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Biomechanical investigation of tibial tubercle osteotomy fixed with various screw configurations

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ABSTRACT

Introduction: To date, the effects of various screw configurations on the stability of tibial tubercle osteotomy (TTO) are not completely understood. Hence, the first aim of this study is to evaluate the stability of TTO under various screw configurations. The second aim is to evaluate the internal stresses in the bone and the contact forces on the bone fragment that are developed by the tibia and screws in response to the applied load after the equilibrant is revealed.
Methods: To calculate the biomechanical responses of the bone and screw under loading, finite element (FE) method was used in this study. Six types of screw configurations were studied in the simulation: two parallel horizontal screws placed at a 20 mm interval, two parallel horizontal screws placed at a 30 mm interval, two parallel upward screws, two parallel downward screws, two trapezoid screws, and two divergent screws. The displacement of the bone fragment, contact forces on the fragment, and the internal stress in the bone were used as indices for comparison.
Results: Among all configurations, the configuration of two parallel downward screws yielded the highest stability with the lowest fragment displacement and gap opening. Although the maximum displacement of the TTO with the configuration of two parallel horizontal screws was slightly higher than that of the downward configuration, the difference was only 0.2 mm. The configuration of two upward screws resulted in the highest fragment displacement and gap deformation between the fragment and tibia. The stress of the osteotomized bone fragment was highest with the configuration of two upward screws.
Conclusion: Based on the present model, the current configuration of two parallel horizontal screws is recommended for TTO. If this is inappropriate in a specific clinical scenario, then the downward screw configuration may be used as an alternative. By contrast, the configuration of two parallel upward screws is least suggested for the fixation of TTO.

Introduction

The incidence of total knee arthroplasty (TKA) and revision TKA is continuously increasing [1]. Revision TKA is considered challenging because certain preoperative conditions, such as arthrofibrosis, severe valgus deformity, and limited length of the patellar ligament, make conventional surgical exposures inadequate, increasing the risks of damage to extensor mechanisms [2–4]. Therefore, tibial tubercle osteotomy (TTO) is frequently used because of its larger exposure and field [5], negligible soft tissue

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violation, and predictable recovery through bone healing [6]. Moreover, TTO has been used for treating severe fractures of the distal femur, proximal tibia [7,8], and patella [9] and even widely applied to manage malaligned patellar tracking and patellofemoral incongruence [10].

TTO specifically applied in revision TKA has yielded excellent results [11]; however, it can lead to a relatively high rate of complications, such as nonunion, fracture, and displacement of the tubercle fragment and tibial metaphyseal fracture [12]. Most complications following TTO are related to the fixation of the osteotomy, and several fixation methods have been proposed [13]. Studies have recommended solid bone-to-bone fixation with screws and an adequate size of the osteotomized fragment [13]. In TTO fixation, two parallel horizontal screw fixation is easy to use and has been demonstrated to result in higher stability than wire fixation under static or cyclic loadings [14,15]. However, surgeons have to adjust the screw trajectory based on the bone condition; moreover, fixation using two parallel horizontal screws is often hard to performed in revision TKA due to the interference of the tibial component [16]. To date, only two parallel horizontal screws have been used in the biomechanical testing of TTO, and no mechanical study has investigated the differences between two parallel horizontal screw configuration and other screw configurations.

In addition to the stability of the TTO, the internal bone stress—particularly near the screws in the bone—and contact forces on the fragment from the surrounding bone and screws are rare, as previously reported. Stress and forces are crucial indexes of bone failure and which are difficult to detect because no suitable sensor can be inserted into the bone without affecting it. However, because complications due to fractures of bone fragments—particularly near the junction of the bone and metallic screws—is a primary concern in clinical applications [17,18], internal stress and the forces on the bone should be investigated. Compared to the experimental method, the finite element (FE) analysis, a numerical method and a powerful tool, helps the researchers to determine internal mechanical responses, including stress and strain, in the bone and repair construct model. The FE method has been used in many orthopedic studies concerning complex geometries, complicated loading conditions and contact behaviors, and nonlinear material properties [19–21]. Thus, the first aim of this study was to evaluate the stability of the TTO fixed with various screw configurations. The second aim was to compare the differences for various screw configurations in the internal stresses near the screw holes in the bone and the contact forces from the surrounding bone and screws on the bone fragment. Determining the stability and internal stress of the bone helps surgeons to fix TTO with adequate strength for bone healing and early rehabilitation after surgery.

Materials and methods

To investigate the stability and stability mechanism of an osteotomized tibia fixed with various screw configurations, an FE model comprising an osteotomized tibia fixed with two screws was developed. The tibial component (of knee prostheses) was excluded in the present simulation to clearly confirm the effects of various screw configurations. First, an intact tibia model was created on the basis of the computed tomography images provided by the US National Library of Medicine's Visible Human Project; all methods were performed in accordance with relevant guidelines and regulations. The images were captured in 1-mm increments in the neutral position and subsequently processed using Avizo (Version 6; VSG SAS, Bordeaux, France) to determine the contours of cortical bone. Because the boundary of the cancellous bone at the proximal tibia was not clear, the cancellous bone was created by a 2-mm shrinkage of the cortical contours [22]. The three-dimensional volume was then calculated on the basis of dissociated contour lines and edited to smoothen the complex bony surfaces.

The model was imported to Solidworks 2012 (Dassault Systemes SolidWorks Corp., Waltham, MA, USA) to perform TTO by mimicking the operative procedure of TTO. The tubercle bone fragment was excised from the tibia by using Boolean operation without any gap; the osteotomized bone fragment was 75-mm long and 12-mm thick [13,23] (Fig. 1 (a)). To simulate the procedures performed in our clinical practice, the superior plane of osteotomy was set to 30° to the long axis of the tibia which mimics an oblique crack on the tibial tubercle along the posterior edge of the patellar tendon and extend into the tibia with an angle

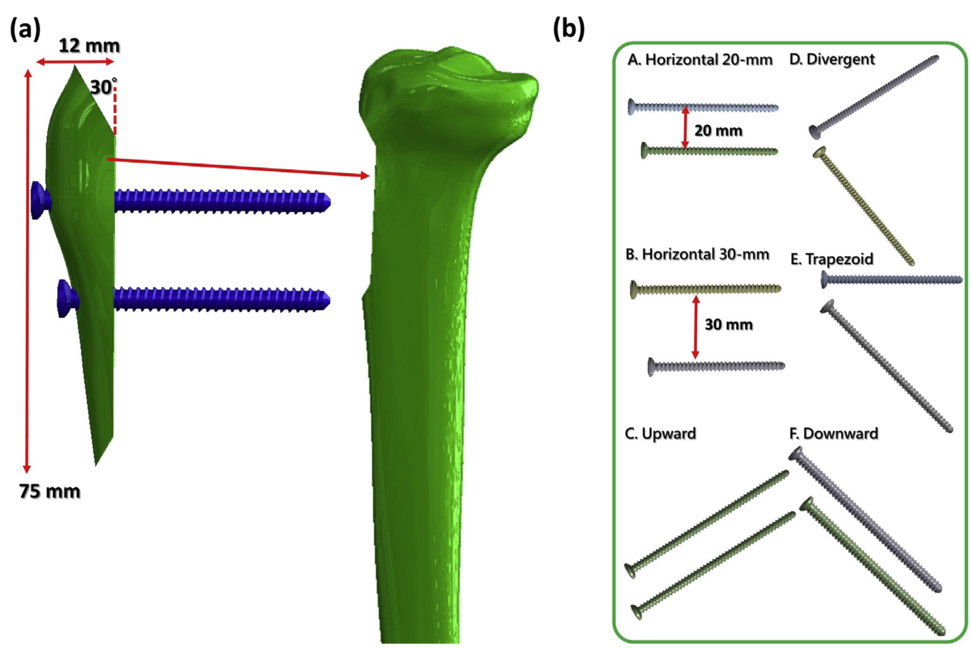

Fig. 1. a -b. TTO model (a) and screw configurations (b) used in this study.

about 30° to the long axis of the tibia. The length and the thickness of the osteotomed fragment were set based on the literature [13,23]. Therefore, no gap existed between the bone fragment and the tibia when the bone fragment was reintroduced to the original position. Two titanium cortical screws (outer diameter, 4.5 mm; DePuy Synthes, PA, USA) were used to stabilize this bone fragment. The pitch and height of the threads of the screws were defined as 2 and 0.75 mm, respectively. Because the tibial component of knee prostheses was not considered in the present study, just screw configuration on the sagittal plane was considered. The screw divergent on the transverse plane was not considered. Six different screw configurations were analyzed, namely two parallel horizontal screws placed at a 20 mm interval, two parallel horizontal screws placed at a 30 mm interval, upward, downward, two trapezoid, and two divergent screws (Fig. 1 (b)). The distinct screw configurations were used to highlight the difference between various configurations. The interval of the two screws was 15 mm in the upward and downward screw configurations, and the angles between the two screws were 45° and 90° in the trapezoid and divergent configurations, respectively. The length of the two parallel horizontal screws was 54 mm (VS401.054), whereas that of the other screws was 76 mm (VS401.076). The length of the screws was defined to ensure that the tip pierced through the far cortex in the horizontal and downward configurations. In the upward configuration, the length of the screws was controlled to reach the inner aspect of the cortex shell at the proximal tibia and to avoid a penetration depth that would pierce through and affect the knee joint. The screws were implanted into the bone by using a Boolean operation in SOLIDWORKS 2012. There was no volume interference between the screw and bone.

The solid model was imported into ANSYS Workbench V14 for meshing and simulation. All parts, including the bones and screws, were meshed with quadratic tetrahedral elements (SOLID 187). The Young's modulus of the cortical and cancellous bones was set to 12.6 GPa and 800 MPa, respectively [24–26]. The Poisson ratio was set to 0.3 and 0.45 for the cortical and cancellous bones, respectively [24,25]. The screws were fabricated from titanium alloy; therefore, the Young's modulus and Poisson ratio were set to 110 GPa and 0.3, respectively [27]. All types of materials were simplified as linear elastic, isotropic, and homogeneous in this study.

All the contact behaviors between the thread surfaces of the screws and surrounding bones (metal-to-bone) and between the osteotomized bone fragment and tibia (bone-to-bone) were defined as frictional surface-to-surface contact behaviors (CONTACT 174 and TARGET 170, respectively; ANSYS). The bone-to-bone and bone-to-metal frictional coefficients were set to 0.46 and 0.3, respectively [28]. Because the screws were inserted into the bone by using a Boolean operation without any interference, which differs from the screw insertion procedure under real conditions, prestress between the screw and the bone was absent at the initial condition.

A vertical–upward 1654 N force was directly applied on the osteotomized tibial tuberosity at twelve small areas (137.8 N per area) to simulate the tension force from the extensor mechanism [Fig. 2(a)]. The purpose of this application was to simulate the worst loading condition in which the TTO sustained a high tension force from the quadriceps and the bilateral end of the tibia was constrained by the ankle and knee joint, such as when initially standing or stepping up. The magnitude of the force was defined according to the failure load in experimental test conducted by Davis et al [14]. To simulate the contact constraint from the distal femur, the superior surfaces of the entire tibia were set to compression-only support using the ANSYS Workbench. The distal end of the tibia was fixed [Fig. 2 (a)]. The contact forces, developed by the applied load, in the vertical direction (the same direction as the applied load) on the osteotomized fragment, including those on the superior and vertical cutting planes of the fragment and superior and inferior screw holes [Fig. 2 (b)], were calculated after the model reached equilibrium under a 1654 N force simulated using ANSYS. In addition, the normal force on the vertical surface of the bone fragment, gap opening at the osteotomized site, displacement of the bone fragment, and bone stress near the screws were examined to evaluate the effects of the various screw configurations.

To verify that the present model is practical, the results of the TTO model with two horizontal screws were compared to Davis's mechanical test [14]. The setting of the mechanical test, which omitted a constraint on the proximal tibia, differed from the present simulation. Therefore, a simulation of the TTO model with two horizontal screws and without the compression-only support was conducted for comparison. For comparison, the

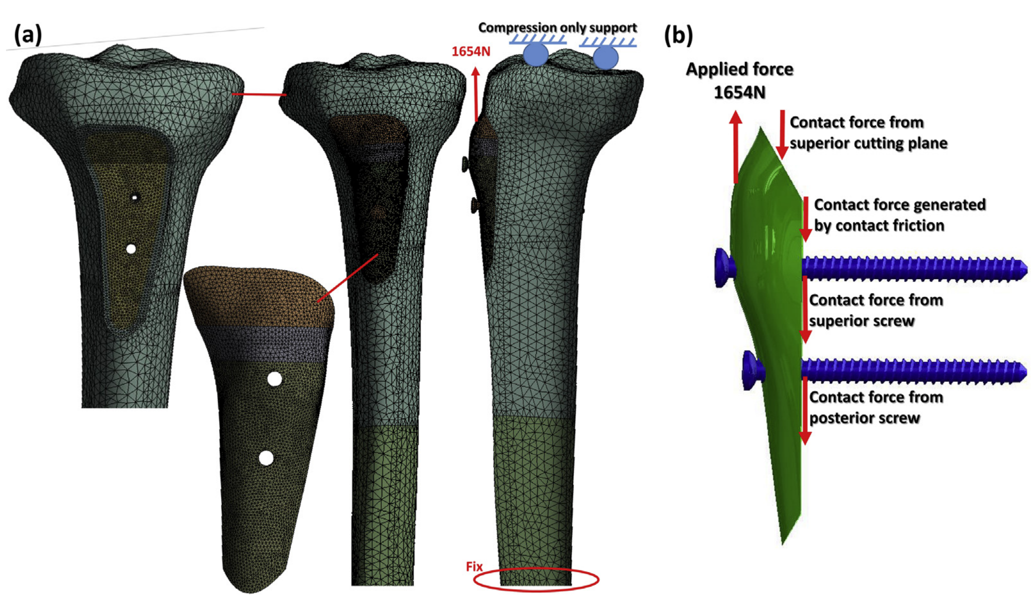

Fig. 2. a –b. The finite element model and boundary condition (a) and the free diagram of the contact forces in the vertical direction on the tibial tubercle fragment under static balance conditions (b).

failure load (1654 N) in the mechanical test was applied to the TTO model and plotted together with the maximum displacement of the tubercle fragment. The maximum displacement was 6.9 (±3.1) mm in the study conducted by Davis and 4.2 mm in the present study [Fig. 3 (a)]. Furthermore, a mesh convergence test was performed with the TTO tibia model with two parallel horizontal screws placed at a 20 mm interval by reducing the element size uniformly and then increasing the number of nodes. The boundary condition was identical to that used in the simulation. The maximum displacement of the fragment under an identical load (1654 N) was 0.41, 0.401, and 0.394 mm with 384 336, 1 153 401 and 1 571 442 nodes, respectively (Fig. 3 (b)). The difference in the maximum displacement of the bone fragment and between the 384 336 and 1 571 442 nodes was 3.9% (0.41–0.394 mm). The contact force on the superior surface of the bone fragment was 767, 786 and 778 N with 384 336, 1 153 401 and 1 571 442 nodes, respectively (Fig. 3 (c)). The difference in the contact force on the superior surface of the bone fragment between the 384 336 and 1 571 442 nodes was 1.41% (767–778 N). The maximum principle stress of the cancellous bone of the fragment near the screw hole was 29.94, 29.04 and 28.83 MPa with 384 336, 1 153 401 and 1 571 442 nodes, respectively (Fig. 3 (d)). The difference in the reaction force on the superior surface of the bone fragment between the 384 336 and 1 571 442 nodes was 3.71% (29.94–28.83 MPa). Finally, an element size identical to that used in the model comprising 384 336 nodes was used in the simulation.

Results

The FE results revealed that the two parallel downward screw configuration resulted in the minimal displacement of the osteotomized bone fragment and gap deformation, whereas the two parallel upward screw configuration resulted in the maximum displacement of the tubercle fragment and gap deformation (Fig. 4 and Table 1). Although the horizontal screw configuration resulted in a little higher displacement of the fragment than did the downward configuration, their difference was only 0.21 mm. The gap openings in the upward screw configuration were 0.755 mm and 0.936 mm between the posterior aspect of the osteotomized bone fragment and vertical cutting plane of the tibia, and between the inferior aspect of the osteotomized bone and inferior cutting plane of the tibia, respectively.

The results indicated that the contact force on the superior surface of the bone fragment from the superior cutting plane of the tibia was higher than the other reaction forces in the two parallel downward and horizontal screw configurations (Table 2). By contrast, in the upward, trapezoid and divergent screw configurations, the contact force on the superior cutting plane of the bone fragment was partially shifted to the two screws. In the two parallel screw configurations, the difference between the contact forces (i.e., the contact forces from the superior cutting plane, the superior screw and the inferior screw) was smaller than that in the other configurations. The maximum differences were 134 N (456 to 590 N), 318 N (418 to 736 N) and 380 N (413 to 793 N) respectively in the downward, upward, and horizontal configurations, whereas the difference increased to 802 N (203 to 1005 N) in the divergent configuration. In addition, the downward screw configuration yielded the highest compressive force of 207 N on the posterior aspect of the fragment between the fragment and the vertical cutting plane of the tibia. The reaction force was very small in the horizontal and upward screw configurations (Table 3).

The upward screw configuration resulted in a higher maximum principle stress around the screw holes in the cancellous bone of the tibia and the bone fragment than did the other screw configurations (Figs. 5 and 6). The divergent screw configuration resulted in a higher maximum principle stress in the cortical bone of the bone fragment than did the other screw configurations (Fig. 7). The downward screw configuration resulted in a lower maximum principle stress in the cancellous bone than did the horizontal screw configuration, whereas the horizontal configuration resulted in a lower maximum principle stress in the cortical bone of the fragment than did the downward configuration. The maximum principle stress in the cortical bone fragment was 184 MPa in the divergent configuration, and those in the tibia and bone fragment in the upward configuration were 58.6 and 81.8 MPa, respectively.

Discussion

This study is the first to investigate the stability of TTO fixed with various screw configurations using a numerical method. The

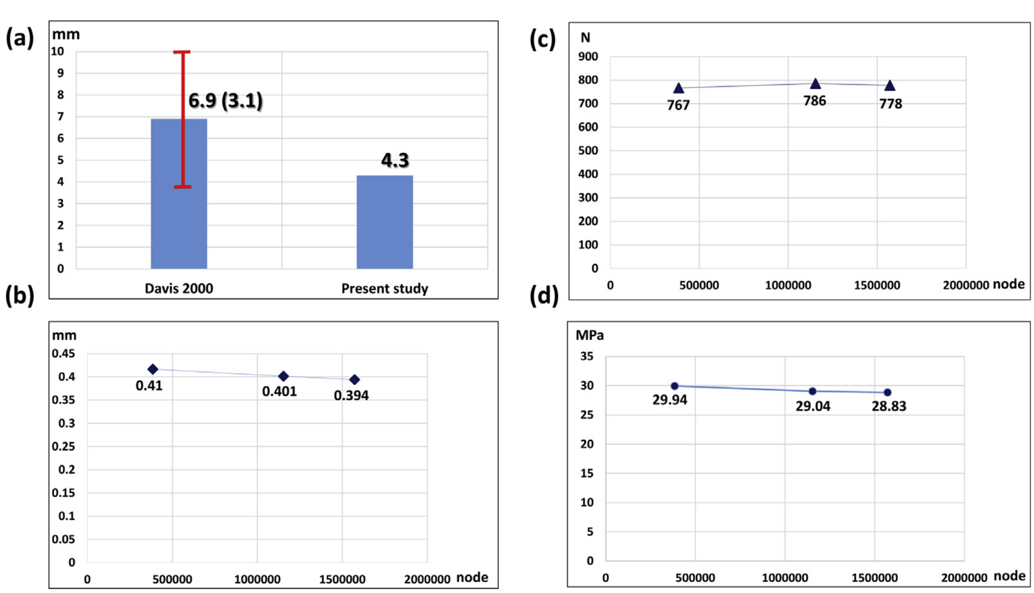

Fig. 3. a –d. Comparison of the structural displacement values in Davis's experiment and the present finite element calculations (a). Relationship between the node and the maximum displacement (b), reaction forces on the superior cutting plane (c) and the maximum principle stress of the cancellous bone in the tubercle fragment (d).

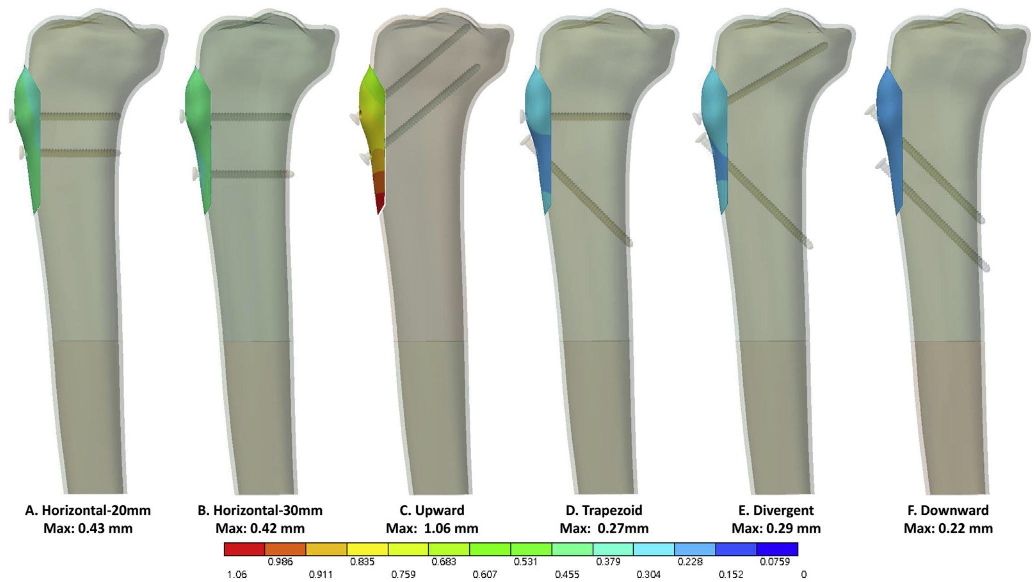

Fig. 4. Total displacement (mm) of the fragment.

Table 1
Maximum gap (mm) between the osteotomized bone fragment and tibia after loading.

	Horizontal-20 mm	Horizontal-30 mm	Upward	Trapezoid	Divergent	Downward
Maximum gap between the posterior aspect of the bone fragment and tibia	0.145	0.133	0.755	0.07	0.092	0.056
Maximum gap between the inferior aspect of the bone fragment and tibia	0.27	0.235	0.936	0.122	0.114	0.086

Table 2
Reaction forces (N) on the tubercle fragment between the tubercle fragment and tibia and screws in the vertical direction.

	Horizontal-20 mm	Horizontal-30 mm	Upward	Trapezoid	Divergent	Downward
Reaction force from superior cutting plane	793	777	500	532	387	532
Reaction force from vertical cutting plane	29	33	10	83	67	89
Reaction force from superior screw	413	419	736	164	203	590
Reaction force from inferior screw	448	458	418	892	1005	456

Table 3
Compressive forces (N) on the vertical cutting surface of the fragment.

	Horizontal-20 mm	Horizontal-30 mm	Upward	Trapezoid	Divergent	Downward
Compressive force on vertical plane of fragment	14	15	2	180	157	207

present study also determined the contact forces, developed by the applied load, on the osteotomized bone fragment to support the fragment and achieve static balance. The results indicate the importance of the superior cutting plane of the tibia in the stability of the osteotomized tibia particularly in the two parallel horizontal and downward screw configurations, while its effect on the stability decreases in the other configurations. Furthermore, the stability of TTO and internal stress of the bone with various screw configurations are demonstrated. Most prior biomechanical studies focused on the different stability between screws and wires. Here, the importance of the cutting plane in each configuration and effects of various screw configurations on the stability of TTO and the internal stress of bone are firstly demonstrated.

The deformed model of the fragment under a tension force from the patellar tendon demonstrates upward translation combined with rotation, enabling the distal part of the fragment to rotate anteriorly away from the proximal tibia (Fig. 8). The upward screw configuration is not suggested for the fixation of TTO because in this configuration no constraining force directly prevents the distal part of the fragment from rotating anteriorly away from the proximal tibia; by contrast, the downward and divergent screw configurations are located distal to the fragment and stop the distal part of the fragment from rotating anteriorly away from the proximal tibia.

In the present study, the superior cutting plane is crucial in the stability of the fragment because the contact force on this plane is large when loading is applied to the fragment following static balance, particularly in the horizontal screw configurations. However, in other configurations like upward, trapezoid, divergent and downward screw placement, the importance of the upper cutting plane declines due to the shift of contact force on this plane to the screws. The upper cutting plane provides a larger contact area with the fragment and generates a strong normal force to the

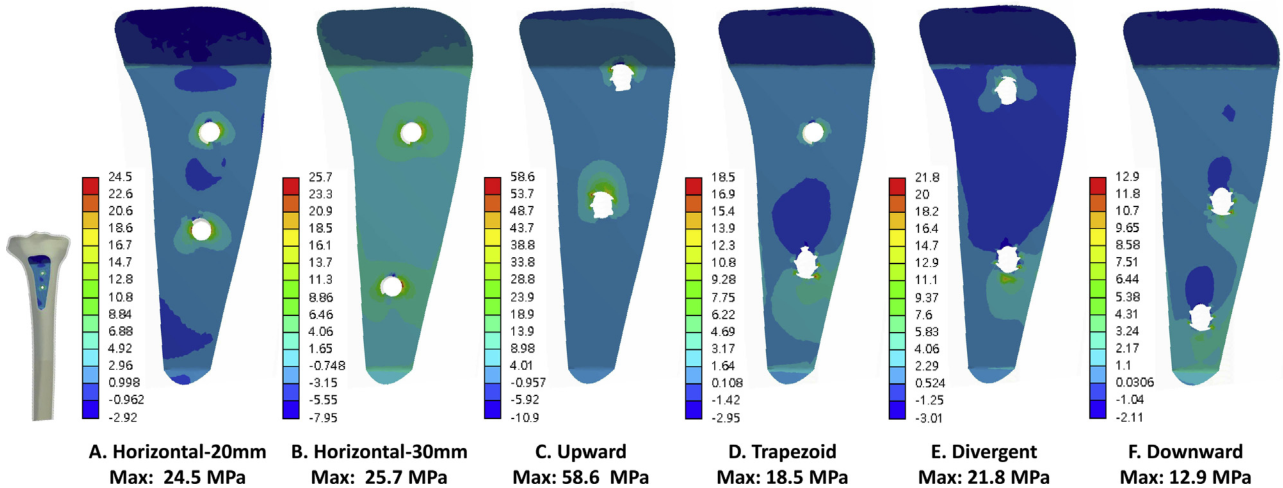

Fig. 5. Maximum principle stress (MPa) of the vertical cutting plane of the tibia. High stress existing around the screw holes.

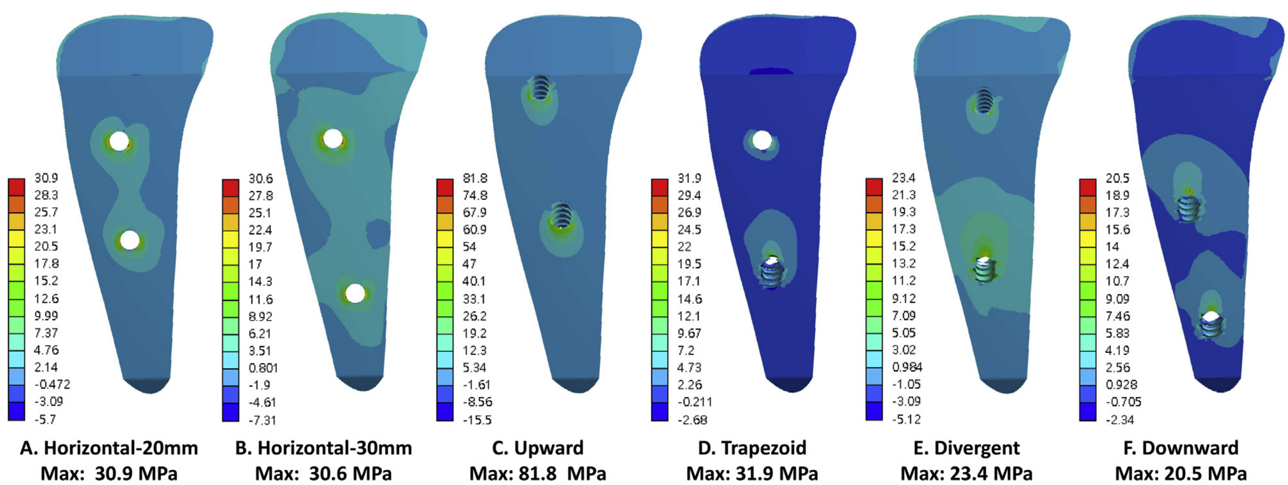

Fig. 6. Maximum principle stress (MPa) in the cancellous bone of the bone fragment. High stress existing around the screw holes.

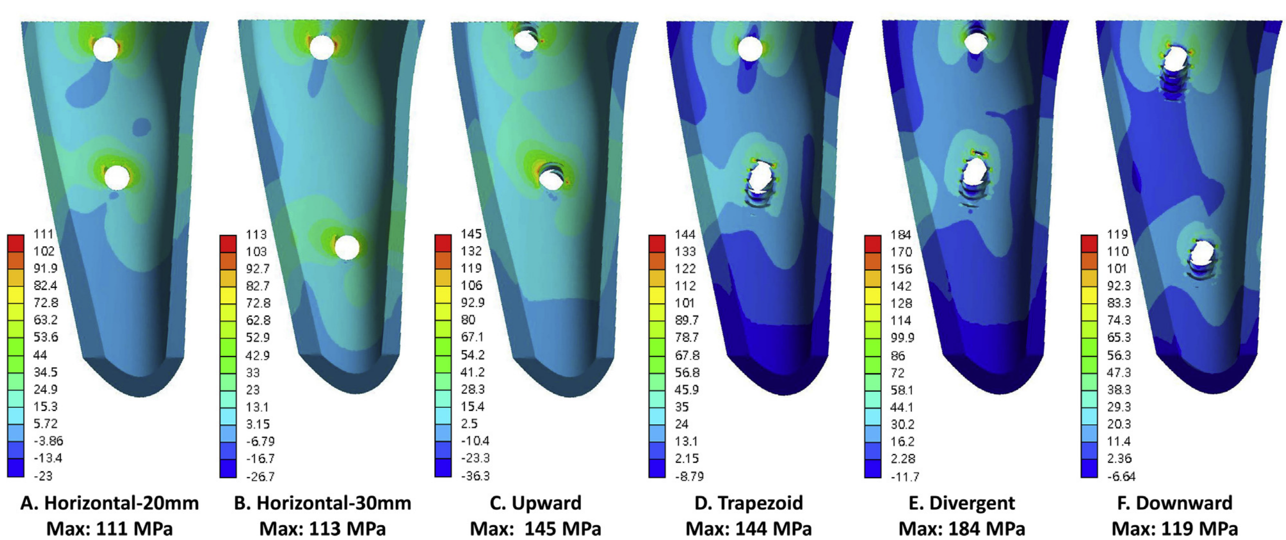

Fig. 7. Maximum principle stress (MPa) in the cortical bone of the bone fragment. High stress existing around the screw holes.

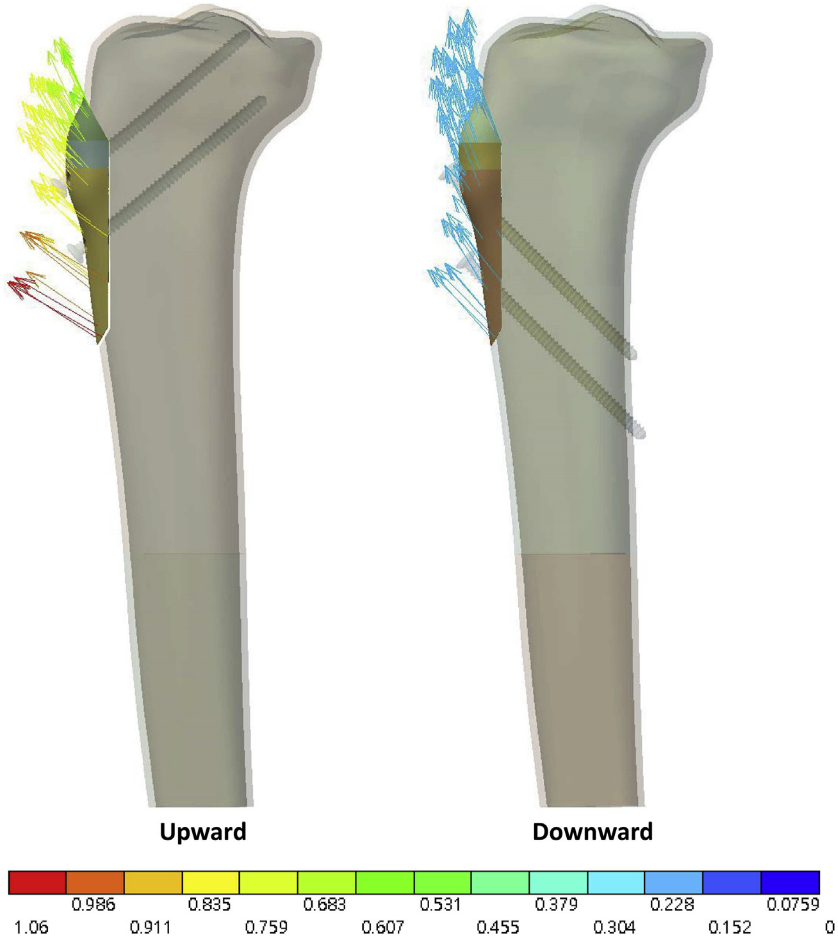

Fig. 8. Vector plot of the total displacement (mm) of the fragment with upward (left) and downward (right) screw configuration.

superior surface of the fragment to stop it from pulling out when loading is added. In addition to this plane, the screws provide resisting force to pull back the fragment when loading is added. In the horizontal screw configurations, the contact force from the screws was relatively low because of their location and direction, and, consequently, the upper cutting plane of the tibia must bear a large load. By contrast, in the downward, upward, trapezoid and divergent screw configurations, the screw provides more than half the force to counterbalance the fragment. Therefore, the superior contact force on the fragment decreased.

The downward and horizontal screw configurations yield a lower difference of force distribution between the screws and the superior cutting plane than the other configurations. From a structural perspective, routinely applying the force distribution average to avoid overloading is a preferable method for avoiding bone failure. By contrast, having a high contact force on one screw, such as in the trapezoid and divergent configurations, is not recommended because of potential overloading of the screw and the surrounding bones. Although the difference in force distribution between the screws and the superior cutting plane in the upward configuration is the second lowest among the screw configurations, the fragment migration and gap deformation is the highest among all configurations. Therefore, the horizontal and downward screw configurations are suggested for the fixation of TTO while the upward screw configuration is not. In addition, another reason to apply the downward screw configuration for TTO is the compressive force on the bone. The downward screw configuration yields a highest compressive force between the vertical cutting plane and tibia. The compressive force between the fragment and vertical cutting plane aids in promoting bone healing because force stimulation facilitates callus formation and ossification [29,30].

Regarding bone stress, the downward screw configuration results in lower maximum principle stress of the cancellous bone than do the other types of screw configurations, whereas the horizontal configuration results in the lowest maximum principle stress of the cortical bone of the fragment among all the configurations. In clinical cases, the stress in the bone is critical for stress fracture; it leads to fixation failure, particularly for osteoporotic bones because their strength is lower than that of the normal bone [31]. Surgeons have to trade-off between horizontal and downward screw configuration based on the individual bone conditions. The stress values of the bone in the present simulation were greater than the failure stress of real bones because the linear elastic material model cannot simulate the breaking of the bone. In reality, bone brakes when it reaches failure stress under such high loadings [14]. Although the stress in the present bone is higher than that in real bone, the tendency of stress to change when the screw configurations are altered has reference value for orthopedic surgeons.

Two parallel horizontal screws, commonly used in clinical applications, yield favorable outcomes. Although the two parallel downward, two trapezoid and divergent screws construed more favorable stability than did the two parallel horizontal screws in the present study, the maximum difference in fragment displacement between the horizontal and downward screw configurations was only 0.21 mm. In clinical applications, higher stability with the downward screw configurations aids in promoting bone healing immediately after TTO, but the high stress elevates the risk of fragment fracture [32,33]; this causes dilemma among surgeons. The suitability of patients for the downward screw configuration must be confirmed on the basis of their condition and bone quality.

As a numerical analysis, the present study has certain inherent limitations. First, only one specific osteotomy with an oblique upper cutting plane was considered in the present study to simulate the common procedures the authors performed. However, the contact forces on the bone fragment and the stability of the TTO may change with the tilt degree of the cutting plane. Second, simplified morphologic features (i.e bony trabeculae, cortical thickness) as well as material properties (i.e linear elastic, homogeneous, and isotropic materials) were used. Therefore, certain important clinical issues detrimental to the final results, such as osteoporosis, defects from previous surgery and/or related implants, following changes in bone structure and mechanical properties after osteotomy and during its healing, and even the common interfragmentary compression techniques are difficult to obtain or simulate using numerical methods under these simplified conditions and assumptions. Third, the applied load was based on the mechanical test of the tibia instead of a direct measurement from human beings. Fourth, to clearly confirm the effects of various screw configurations, certain affecting factors for TTO fixation were excluded in this study, including the diameters and thread patterns of the screw, reinforcing screw-head supports (i.e washers, thin smaller anterior plate) and the tibial component of knee prostheses while revision. However, these mentioned clinical factors might alter the strength of TTO fixation and are worthy of future work. Fifth, soft tissues, including the tendons, ligaments, and muscles, and the contact force between the fragment and the tibia developed during screw inserting were not considered. The tendon force was directed on the tibial tubercle, but the patellar tendon was not modeled.

Conclusion

This is the first study of the TTO to use a numerical method to demonstrate its stability, the contact forces on the bone fragment, and the internal stress on the bone with various screw configurations. In the present simulation, the superior cutting plane of the tibia is important for the stability of TTO because it provides a critical force for maintaining the stability of the fragment. Furthermore, the current two parallel horizontal screw configuration is recommend for TTO; if it is inappropriate for a particular clinical condition then the downward screw configuration is suggested. The two parallel upward screw configuration is not advised for the fixation of TTO.

Ethical approval

This study did not have any ethical issues.

Conflict of interest statement

Each author certifies that he or she has no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article.

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