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Optimal double screw configuration for subtalar arthrodesis: a finite element analysis

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Abstract
Purpose The subtalar arthrodesis using screws has been performed to manage traumatic subtalar arthritis. Even though clinically there might not have been big difference between using single screw or double screws for subtalar arthrodesis, a double screw fixation is expected to bring a better initial stability in a mechanical view. This study aimed to assess the optimal configuration of double screw fixation for subtalar arthrodesis.
Methods From the CT-scanned images of an ankle of a Korean male (21 year old), polygon models of the talus and calcaneus were reconstructed. The polygon models were converted to tetrahedron finite elements. Young's modulus was assigned locally to each element based on the Hounsfield unit, and a Poisson's ratio of 0.4 was commonly. Four fixation configurations of double screw subtalar arthrodesis were modeled by combination of a same placement of a neck screw and one of four different placements of a dome screw, i.e., anterolateral (AL), anteromedial (AM), posterolateral (PL), and posteromedial (PM) placements. External and internal rotation torques of 4 N-m were applied when evaluating the stability of each fixation configuration.
Results Among the four fixation configurations, the fixation configuration of a neck screw plus a PM dome screw had the least translation of 0.9 and 0.8 mm for external and internal rotational torques of 4 N-m, respectively. The fixation configuration of a neck screw plus a PM dome screw showed the least rotation of 5.0° and 4.8° for external and internal rotational torques of 4 N-m, respectively. The divergence angle or the contact length did not solely match well to the better stability. However, the integration of both the divergence angle of 2 screws and the contact length between screw and bones were proportionally related to the better rotational stability.
Conclusion A posteromedial dome screw combined with a neck screw can be the best surgical choice, which will bring out excellent union rate of the subtalar arthrodesis as well as the best mechanical stability.

Keywords Ankle · Calcaneus · Talus · Subtalar arthrodesis · Screw fixation · Finite element analysis

Introduction

Isolated subtalar arthrodesis has been an established treatment of hindfoot problems in adults [9, 10, 13, 18, 24]. The most common indication for subtalar arthrodesis is painful post-traumatic subtalar arthrodesis after fractures of the calcaneus or talus and painful subtalar instabilities [12]. One of most common method of subtalar arthrodesis involves using screws to unite calcaneus and talus. Many mid-term or long-term clinical studies has testified favorable union rate of the talus and the calcaneus, which varies 82–99% [4, 7, 9, 27]. Even though the union rate is favorable, efforts should be taken to find the best and

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uniform surgical technique for better union rate for patients, if possible.

The union rate of the subtalar arthrodesis would be influenced by surgical or technical fixation factors, which can be categorized into the anatomical conditions, the pathologic factors, the surgical choices, and the fixation configuration factors. The anatomical conditions include fracture types, ligament soundness, and preoperative malalignment [19, 26]. The pathological factors include smoking level, age, presence of avascular necrosis, bone quality, and history of diabetics [1, 4, 13]. The surgical choices include open reduction or arthroscopic treatment and options in bone grafting of articular surface [14, 24]. And the fixation configuration factors include number of screws, staples, length of thread, diameter of screws, calcaneal or talar or plantar approach in screw insertion, and screwing torque, and alignment of screws [2, 6, 9, 11, 16, 22, 23, 25]. Optimal fixation configurations would improve the initial stability of the subtalar arthrodesis and then will consequently induce the higher union rate postoperatively.

Finding an optimal screw alignment is of great importance. Bone healing can be enhanced by keeping sufficient contact pressure and minimizing the movements of fused areas [9]. There have been several biomechanical studies that investigated the effects of the screw insertion approach, the screw alignment, and the number of screws on the initial stability of subtalar arthrodesis [9, 11, 15, 16, 22, 23]. Chuckpaiwong et al.'s study [6] revealed that double screw configuration showed significantly greater rotational stability than single screw configuration in the subtalar arthrodesis using the calcaneal screw approach. In their study, the double diverging screw placement composed of one screw toward the talar neck and another toward the talar dome showed higher compression and rotational stability than any single screw placement or parallel double talar dome screws. From Chuckpaiwong et al.'s finding [6], the authors of the current study get to have a curiosity on what is the best diverging screw alignment for the double screw subtalar arthrodesis. Finding an optimal screw alignment of double screw subtalar arthrodesis is a provision of the best surgical guide line for more reliable clinical outcomes.

Hence, the current study aimed to assess the optimal screw configuration for the subtalar arthrodesis. It was hypothesized that the larger divergence angle of the double screw configuration will bring about the better stability for subtalar arthrodeses. In a sense of the best comparison, the finite element analysis can compare only the effects of screw alignment in a most fare way since we can use a same model and loading conditions, without need of normalization of size or material properties.

Materials and methods

Left foot of a normal Korean male (20 years old) was scanned by a computerized tomography (CT) scanner (Brilliance 64, Philips Electronics, the Netherlands). The CT scanning was executed with a setting of 140 kV, 309 mA, and the field of view of 275 mm × 275 mm. The CT images were finally obtained to have the resolution of 0.54 mm × 0.54 mm and the slice interval of 0.69 mm, rebuilt using the smooth gradient algorithm. From the CT-scanned images, three-dimensional polygon models of the talus and calcaneus were reconstructed, using Mimics V13 (Materialise, Belgium). The critical Hounsfield unit for bone contour was basically set as 300 HU over which the gray area was segmented as cortical bone. Inside the bone contour was fully filled.

Double screw configurations

The simulation models analyzed were four kinds of double screw fixation configurations for subtalar arthrodesis, as precise submodels of that of Chuckpaiwong et al.'s study [6].

Each of 4 double screw configurations is composed of a neck screw and a dome screw. The simulated screws were cannulated screws of the diameter 5 mm and thread length 20 mm. A dome screw was inserted from the lateral posteroinferior calcaneal tuberosity to one of quadrants of the talar dome, i.e., anterolateral (AL), anteromedial (AM), posterolateral (PL), and posteromedial (PM) portions of talar dome (Fig. 1). A neck screw was inserted from the central posteroinferior calcaneal tuberosity to the anteromedial junction of the talar neck body and was commonly used for 4 different configuration models.

Finite element mesh

The polygon models of the four screw fixation configurations were converted to tetrahedron finite mesh. Mechanical stiffness of the bones was encoded with Young's modulus. Young's modulus was assigned based on the value of Hounsfield unit (HU) of each pixel on CT images. The relationship between apparent bone density and HU was found by calibrating a standard quantitative CT (QCT) phantom, i.e., QCT-Bone Mineral Phantom (Image Analysis Inc., KY, USA). A linear relationship between HU and QCT-based bone mineral density (BMD, ρ_{QCT}) was formulated (Eq. 1).

$$\rho_{QCT}\ (\mathrm{kg/m^3}) = 0.9011 * \mathrm{HU} + 6.637 \quad (1)$$

The relationship between compressive elastic modulus (E_C) and BMD (ρ_{QCT}) was obtained from a literature [20]

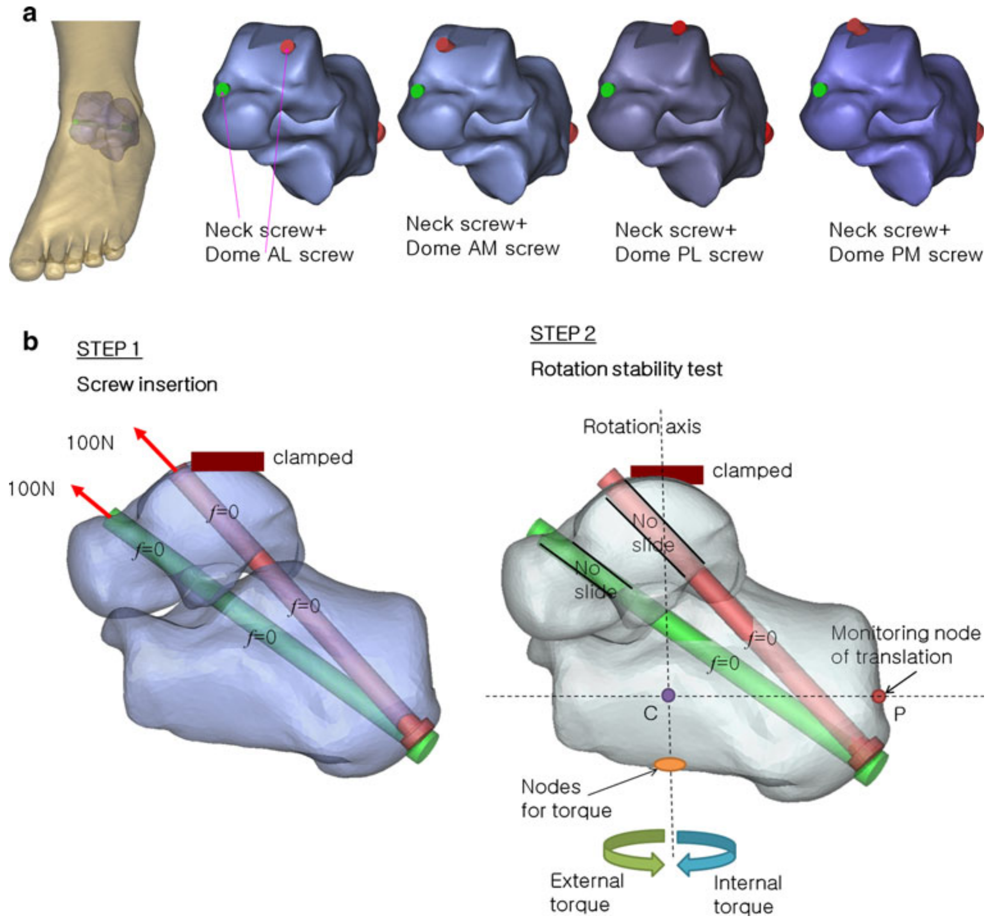

Fig. 1 Double screw configurations for subtalar arthrodesis. Superior articular surface of the talus was artificially made to use it a clamping fixture during rotational torques, when performing the finite element analysis. **a** A schematic of each double screw configuration, **b** superior and lateral views of an integrated model, which includes all the four configurations

that experimentally determined the relationship between E_C and ρ_{QCT}. The mechanical features of the cortical and cancellous bones were assigned with Young's modulus locally to each element based on local BMD. An equation of Young's modulus was functioned as the average line of E_C & ρ_{QCT} relationship with metabolic lesion and that without metabolic lesion [20].

$$E_C\,(\text{MPa}) = 15 \times \rho_{QCT} \qquad (2)$$

For verification of reliable mesh size, a convergence test was performed to guarantee that our numerical model reached the converged results and that no further mesh refinement was necessary. Based on the PL double screw model (i.e., a neck screw + a PL dome screw), without screws. The finite element meshes of the model were generated with linear tetrahedral elements whose maximal edge size is 1 mm. From this 1-mm mesh model, mesh models of 1.5, 2, 2.5, or 3 mm were created by converting mesh sizes, with limiting each mesh model's geometric error less than 0.1 mm from the 1-mm mesh model. The 3, 2.5, 2, 1.5, and 1-mm mesh models had 95666, 164282, 320351, 760479, and 2597182 tetrahedron elements, respectively. The models were constrained at the proximal flat surface of the talus that was artificially cut flat to set up an identical constraint for all configuration models (Fig. 2). The top flat plane, the artificially cut flat of the talus, was clamped firmly. The maximum translation of the calcaneus was reviewed for convergence within the five mesh patterns. The tolerance level for convergence was set as the change of less than 1%. The change of translation from the 2.5-mm mesh model to the 2.0-mm mesh model was 1.5% and that from 2.0-mm mesh model to 1.5-mm mesh model was 0.9%, which was less than the tolerance level for mesh convergence 1%. Hence, analysis model was constructed into finite element meshes whose maximum edge length is less than 2 mm.

Finite element analysis models of the double screw subtalar arthrodesis

Talocalcaneal finite element models for analysis were made with 4-node tetrahedron elements, using Mimics 11 (Materialise Group, Leuven, Belgium) and Patran 2005 (MSC Software Co., CA, USA). Maximum and minimum edge lengths of tetrahedron elements were set to 2.0 and 0.1 mm, respectively. The maximum mesh size of 2.0 mm was chosen based on the result of the mesh conversance test.

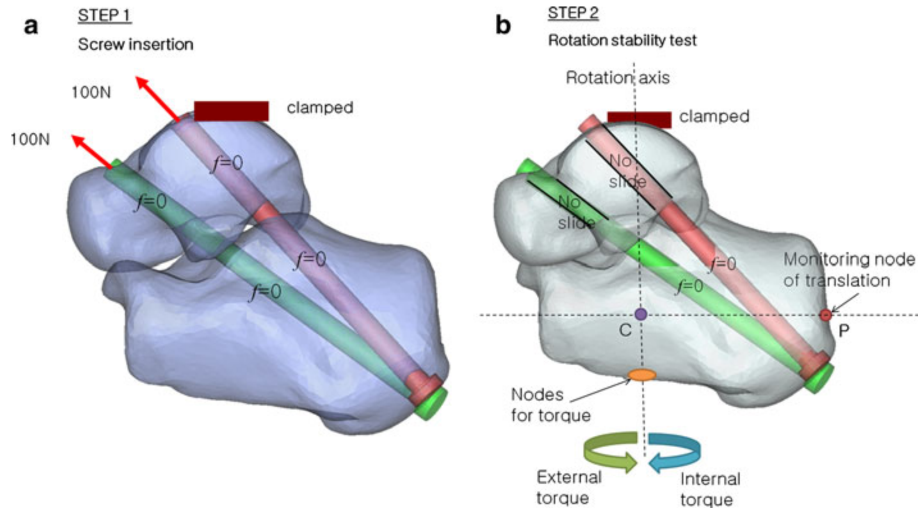

Fig. 2 Finite element analysis through the screw insertion step and the rotational stability test step. The *f* and *T* represent the coefficient of friction (COF) and torque, respectively. $f = 0$ means that there is no friction between contacting surfaces; **a** *STEP 1* the screw insertion, the double screw insertion was simulated by pulling 2 screws toward the talus along the path of each screw hole, **b** *STEP 2* rotational stability tests, the models were subjected to internal or external torque of 4 N-m as an extension of the screw insertion step

By Eq. 2, Young's modulus for the talocalcaneal model was calculated as 0.01–30.0 GPa. Young's modulus was grouped into 30 sets to each of which 0.1–29.0 MPa was assigned with increment of 1 MPa. Even though Poisson's ratio of bone varies in the range of 0.30–0.56 depending on direction and microstructure, current study used a constant Poisson's ratio of 0.4 independently on bone's microstructure [8]. And the contact between the talus and calcaneus was almost ignorable, i.e., the coefficient of friction (COF) $f = 0.1$.

Boundary conditions for the finite element analysis

Simulation of the finite elements analyses was performed in two steps, i.e., the double screw insertion step mimicking screw insertion in the subtalar arthrodesis, and the external or internal rotational stability test step mimicking clinical palpational diagnoses of rotational stability (Fig. 2).

The double screw insertion was simulated by pulling 2 screws toward the talus along the path of each screw hole. A pulling force of 100 N was applied normally to the end face of each screw's threaded part. The force was smoothly increased from 0 to 100 N using RAMP option of ABAQUS, rather than STEP option applying a sudden force at time zero. In this step, it was assumed that there is no friction between bones and screws, i.e., COF $f = 0$.

Once the double screw insertion step has completed, the rotational stability test is simulated. That is, the models were subjected to internal or external torque of 4 N-m as an extension of the screw insertion step [6]. In this step, it was assumed that there is no slide between screws and the talus (i.e., COF $f =$ infinite) while no friction between screw and the calcaneus (i.e., COF $f = 0$).

Translational and rotational dislocations as stability evaluators

Mechanical stability of each model was evaluated by the displacement of the calcaneus with respect to the talus. Translational displacement, as a stability evaluator, represents the linear movement of the calcaneus with respect to the talus. It is calculated as the translation of that monitored node (P) that located posterior facet of the calcaneus (Fig. 2), i.e., the translational change arisen during each analysis step. Rotational displacement, as another stability evaluator, represents the resultant angular movement of the calcaneus with respect to the talus. It is calculated as the angular rotation of the P–C line about the superior-inferior axis (i.e., the rotation axis in Fig. 2), i.e., the angular rotation occurred during each analysis step. The point C is the normal projection of the point P onto the superior-inferior axis.

Results

Translational displacement

When subjected to screw pulling force of 100 N, translational displacements of calcaneus were in the range of 0.9–1.4 mm. The translational displacement of the calcaneus was calculated as the change of location after the screw insertion. When subjected to the external or internal torques, "Neck screw + Dome PM screw" showed the least translational displacements, which were 0.9 and 0.9 mm under the external and internal torques, respectively (Fig. 3a). "Neck screw + Dome AL screw" and "Neck screw + Dome PL screw" showed translational displacements of 1.2–1.3 mm. "Neck screw + Dome AM

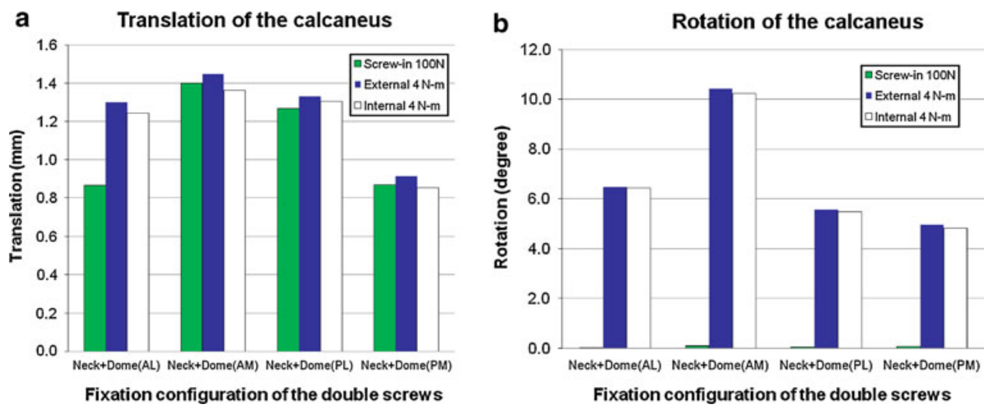

Fig. 3 Displacement of the calcaneus with respect to the talus when being subjected to internal or external torques, **a** translations due to rational torques, **b** rotations due to rational torques

screw" moved the most, 1.5 and 1.4 mm under the external and internal torques, respectively.

Rotational displacement

By the screw pulling force of 100 N, the rotational displacement of the calcaneus was less than 0.1° in all the configuration models. The rotational displacements due to external and internal torques were least for "Neck screw + Dome PM screw", which were 4.7° and 4.8°, respectively (Fig. 3b). The rotational displacement of "Neck screw + Dome PL screw" model was 5.6° and 5.5° due to external and internal torques, respectively. And the rotational displacements of "Neck screw + Dome AM screw" model were 10.0° and 10.2° due to external and internal torques, respectively. In contrast, "Neck screw + Dome AL screw" rotated 6.5° and 6.4° due to external and internal torques, respectively, which were considerably larger than those of other models.

Discussion

The most important finding of the present study was that the optimal configuration for rotational stability was revealed as the combination of a neck screw and posterior medial dome screw. The current study assessed the optimal double screw configuration for the subtalar arthrodesis, by performing the finite element analysis, which is the best method for fair comparison. Fair experimental boundary condition is critical for comparison of the tension band wiring techniques with different fixation configurations. It is difficult to keep fair testing conditions throughout subsequent tests and specimens in controlling rotational torque, anatomic variation, etc. Only under same model and boundary conditions, fair comparisons among different fixation configurations can be achieved. This is why the current study chosen the finite element analyses. The finite element analysis can assess the effect of a unique single factor because other factors can be standardized. This multiscale modeling of micro cancellous structure through limb frame and easy change of mechanical properties enable a more accurate characterization of bone fracture behavior and assessment of the effects of aging, osteoporosis and drug treatment [5].

The double screw fixations in the current study simulated the calcaneal screw approach. The authors of the current study clarify the terms of screw approaches into three, i.e., talar, calcaneal, and plantar screw approaches [9, 11, 16, 22, 23]. The talar screw approach (so called, the anterior approach or the talar approach) inserts screws from the talar body toward the posteroinferior calcaneus [11, 22, 23]. The calcaneal screw approach (so called, the posterior approach or the calcaneal approach) inserts screws from the posteroinferior calcaneus toward the talar body [3, 9, 21, 23]. The plantar screw approach (so called, the plantar approach) inserts screws from the plantar aspect of the calcaneus toward the talar body [16, 22]. The plantar screw approach is provoked as an alternative approach for revision arthrodesis since it makes a fixation screw possible to avoid the same path of cancellous bone as the primary arthrodesis [16] that were performed using the talar or calcaneus screw approach. Among them, the calcaneal screw approach has been widely adopted for the primary subtalar arthrodesis, preferably over the talar screw approach since the talar screw approach may cause anterior ankle impingement or a stress riser at the neck of the talus [15]. Because the calcaneal screw approach has the largest bone mass along the path that the whole length of a screw or threaded part of the screw passes, it may provide the best initial stability than other approaches [17].

'Neck screw + Dome PM screw' was appeared to be the best double screw configuration for the subtalar arthrodesis. In the most similar study to the current study, Chuckpaiwong et al. [6] reported that the posterolateral (PL) talar dome showed the worst rotational stability among several single talar dome screw fixation configurations while the anteromedial (AM) or posteromedial (PM)

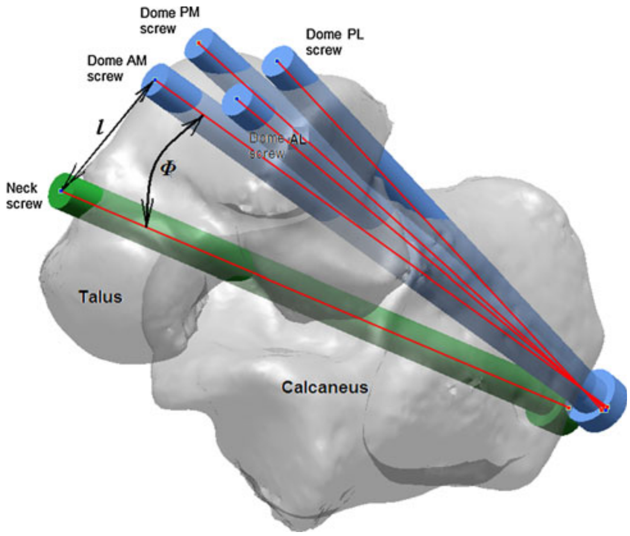

Fig. 4 The dimensions related to divergence between the talar neck screw and the talar dome screw. l and Φ represent the distance and the included angle between centers of the proximal end surface of screws, respectively. The proximal end of screws extruded out of anterosuperior surface in the analysis models because extruded screw length will not change the comparison results in terms of translations and rotations of the calcaneus. In practical subtalar arthrodeses, the screws never get out of the anterosuperior talar surface not to interfere ankle articulation

single dome screw fixation did the best rotational stability. Seeing the figures in their manuscript, it is thought that "Diverging double screws = Neck screw + Dome AL screw" showed better stability than "Parallel double screws = Dome AM screw + Dome AL screw" [6]. Because our study revealed the optimal double screw configuration, we can postulate that 'Neck screw + Dome PM screw' would give better stability over any divergent, parallel double talar dome screws or any single screw.

There are several things that care should be taken to when comparing our results with Chuckpaiwong et al.'s [6]. Because the model of the current study does not include graft bone stock model, we looked at only rotational stability whereas Chuckpaiwong et al. looked at compression and rotational stability since they used normal talocalcaneal cadaveric models. In addition, there is ambiguity in placement and direction of screws in their study [6]. We can understand that there is limitation in comparing same kinds of studies of different research groups since the model and protocol are not identical among the groups. Hence, the model used in the current study is described with clear definitions of landmarks and rotation axis and the finite element modeling may well be better way of looking at stability in a fair way. Furthermore, we used the same bone for a fair comparison study among different fixation models.

The hypothesis that the larger divergence angle of the double screw configuration will bring about the better stability for subtalar arthrodesis did not match to the results of the finite element analysis. The divergence angle and the contact area are geometric stability factors, which can contribute the subtalar arthrodesis stability. In Fig. 4,Φ represents the divergence angle between a dome screw and the neck screw. l represents the distance between centers of the proximal end surface of screws and the neck screw and is proportional to the divergence angle. By scaling the divergence angle (Φ) by the maximum value among them, i.e., scaling that of 'Neck screw + Dome PL screw' ($\Phi = 18.7°$) to 50 contribution points, the contribution of each divergence angle (Φ) can be scored (Table 1). Figure 5 demonstrates the contact length (C_{cal}) between the calcaneus and a dome screw and the contact length (C_{tal}) between the talus and a dome screw. The contact area between a screw and a bone can be directly estimated because screws are inserted into bones with interference forced contact. The contact length can also be scored with respect to the length of 'Neck screw + Dome AM screw' (75 mm), i.e., scaling 75 mm to 50 contribution points. In the total 100 points in contribution scoring system, the dome PM screw has the highest contribution score of 94 while the dome AM screw does the lowest of 81. Here, it should be clearly recognized that the divergence angle or the contact length does not solely match well to the less displacement. In other words, the rotational stability is contributable to the integration (the total contribution score in Table 1) of the divergence angle and contact length. However, surprisingly the higher total contribution score including contributions of both the divergence angle and the contact length matches well to the less displacement of the finite element analysis (Fig. 3).

Table 1 Stability contributors

Configuration	Divergence dimensions		Contact length of a dome screw with			Contribution score		
	l (mm)	Φ (°)	C_{cal} (mm)	C_{tal} (mm)	$C_{cal} + C_{tal}$ (mm)	Φ (50)	$C_{cal} + C_{tal}$ (50)	Total (100)
Neck screw + Dome AM screw	19.5	11.7	48	27	**75**	31	**50**	81
Neck screw + Dome AL screw	27.0	13.3	48	25	73	36	49	84
Neck screw + Dome PM screw	28.0	17.6	45	25	70	47	47	94
Neck screw + Dome PL screw	33.6	**18.7**	39	17	56	**50**	37	87

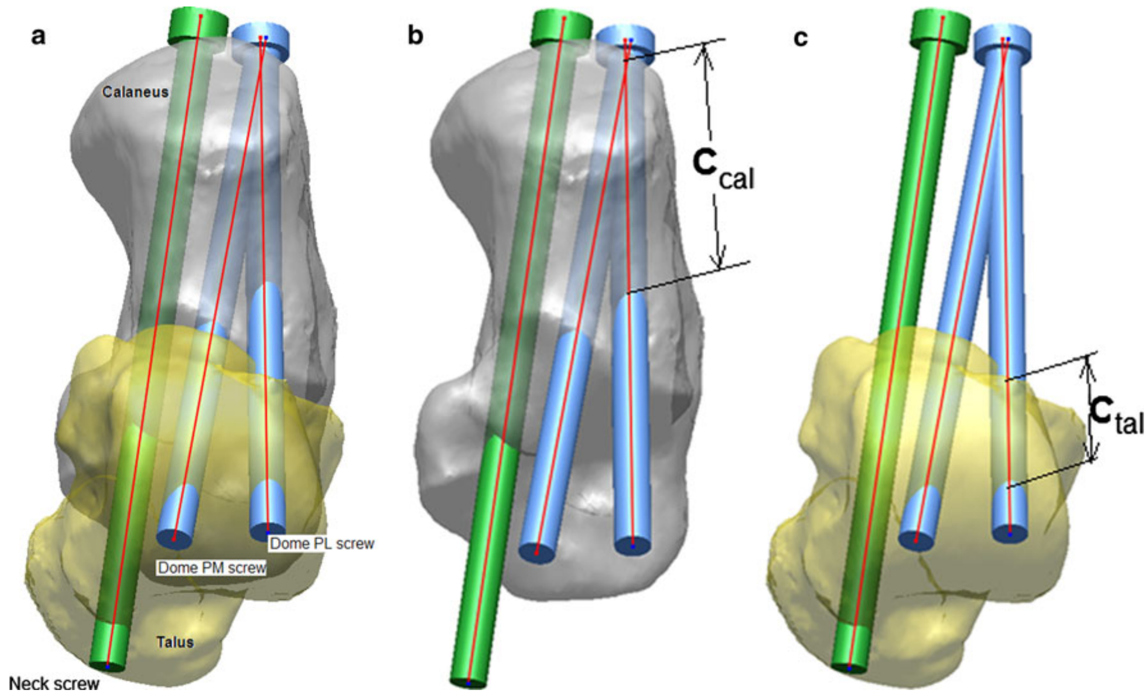

Fig. 5 Comparisons of contact areas between the dome PL screw and the dome PM screw. **a** The superior view of the model representing the talocalcaneus and the neck and two dome talar screws, **b** the model demonstrating contact length (C_{cal}) between the calcaneus and the dome PM screw or the dome PL screw, and **c** the model demonstrating contact length C_{tal} between the talus and the dome PM screw or the dome PL screw. The dome PM screw has larger contact areas with the calcaneus and the talus than the dome PL screw

The current study has a limitation in that it did not simulate the bone grafting into talocalcaneal articulation space. The bone grafting will recover ankle height and provide better subtalar joint stability. Fusion compression of a subtalar arthrodesis will be affected by quality of graft bone, packing density and screwing torque and would be different from that of intact talocalcaneal joint. The current study does not deal with compression because it was not possible to make a grafted talocalcaneal model with numerous chopped bone fragments. Because Chuckpaiwong et al.'s [6] used only normal talus and calcaneus rather than fractures ones, and their compression measurements also may be different from real grafted subtalar arthrodesis. Hence, the current study could compare purely the effects of double screw configurations on the subtalar joint arthrodesis, without need to consider other factors.

It is not that practical application of the findings always brings about expected clinical outcomes, since initial instability and union of subtalar arthrodesis can be affected by surgical choices, anatomical variance, life habit during rehabilitation, or physiological conditions of patients. Also, accurate placement of screw to a target location is difficult to achieve. With help of navigation-assisted surgery systems, stereographic C-arm X-ray images or new anatomical guiding tools, the accurate surgical application of the findings can be realized.

Foot patients with diabetes or vascular disease would have poorer union rates of the subtalar arthrodesis. For them, a double screw arthrodesis will mechanically provide a better stability rather than a single screw configuration. However, foot surgeons including the author (J. Y. Lee) have been questioning about the right placement of double screw and the answer was difficult to be found due to complex anatomy of the talocalcaneus. When it comes to the question, the current study is the first one that gives the answer through performing the biomechanical assessment. Clinical application of the optimal double screws replacement can be the best surgical choice, which will bring out excellent union rate of the subtalar arthrodesis as well as the best mechanical stability.

Conclusions

The best double screw configuration for the subtalar arthrodesis was revealed as the combination of a talar neck screw and a posteromedial dome screw. In contrast, the combination of a talar neck screw and an anterolateral dome screw should be avoided if possible. Harmony of the divergence angle and contact area is considered as important operation factors in determination of the best double screw configuration for subtalar arthrodesis.

Conflict of interest None.

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