

Variations of the Posterolateral Tubercle of the Talus: Geometric Analysis, Angular Safe Zones, and Implications for Talar Fixation Using a Three-Dimensional Simulation Model

Orrawan Srinark¹, Rarinthorn Samrid¹, Arada Chaiyamoorn¹, Nichapa Phunchago¹, Chanasorn Poodendaen², Suthat Duangchit³, Sitthichai Iamsaard¹

¹Department of Anatomy and Unit of Human Bone Warehouse for Research, Faculty of Medicine, Khon Kaen University, Thailand, ²Department of Anatomy, Faculty of Medical Science, Naresuan University, Thailand, ³Department of Physiology, Faculty of Medical Science, Naresuan University, Thailand

Correspondence: sittia@kku.ac.th; Tel.: + 66 85 2896363

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Abstract

Objective. To investigate the prevalence of posterolateral tubercle variants and characterize the simulated safe zones and screw insertion angles for posterior-to-anterior talar screw fixation using individual 3D models from a Northeastern Thai skeletal collection. **Materials and Methods.** A total of 1,106 dry tali from 553 skeletons (301 males and 252 females), aged 22–106 years, were classified according to posterolateral tubercle type. Safe zones for posterior-to-anterior (PA) screw fixation were determined for the left and right tali in both sexes using 3D simulation models, and the widest possible screw insertion angles were simulated. **Results.** The posterolateral tubercle was classified into three types: Type 1 (almost absent, 1.36%), Type 2 (normal, 45.48%), and Type 3 (enlarged, 53.16%). In selected individual male talus models, the illustrated safe-zone configurations ranged from 20% to 50% on the left and from 30% to 60% on the right. In selected individual female talus models, the illustrated safe-zone configurations ranged from 20% to 70% on the left and from 20% to 50% on the right. **Conclusion.** The enlarged posterolateral tubercle was the most prevalent variant in the Northeastern Thai skeletal sample. The selected individual models illustrated differences in simulated safe-zone configurations and insertion angles according to side and sex. These findings may provide anatomical reference information for preoperative planning of screw fixation involving the posterolateral region of the talus.

Key Words: Talus ■ Posterolateral Tubercle ■ Talar Screw Fixation ■ Simulation Model ■ Northeastern Thai Skeletal Collection.

Introduction

The talar bone, or talus, plays a major role in transferring body weight through the ankle joint and is surrounded by many ligaments that help stabilize the ankle. Injury to the talus can significantly affect foot structure and ankle function (1, 2, 3). General fractures of the talus occur predominantly due to high-energy trauma, such as motor vehicle accidents or falls from a height (2, 3). The most common location for talar fractures is the talar neck, accounting for approximately 50% of all talus fractures (4, 5). Such fractures often result from axial loading forces when the talus is forced against the tibia during impact. Due to the complex

structure and unique vascular supply of the talus, these fractures carry a high risk of complications, such as avascular necrosis (6, 7). Additionally, fractures of the talar body and posterolateral tubercle have been reported (8).

The treatment of talar fractures is based on the severity and displacement of the fracture fragments. Conservative treatment with immobilization is generally used for nondisplaced talar fractures, whereas displaced fractures usually require reduction and surgical fixation to restore anatomical alignment and joint function (1, 9, 10). Common surgical techniques include the use of pins, plates, and screws for internal fixation.

Among these methods, screw fixation is commonly used because it can provide stable compression across the fracture site and facilitate bone healing (10). Cannulated screws are commonly used for talar neck fracture fixation, with both anterior and posterior insertion techniques described in clinical practice (11, 12). This consideration includes variations in the posterolateral tubercle of the talus (13). During talar fracture fixation, careful planning of the screw trajectory is crucial to avoid damage to the surrounding soft tissues and articular surfaces, particularly when selecting between anterior and posterior screw insertion approaches (2, 14, 15, 16). Identifying safe zones for screw placement may help reduce the risks of joint penetration, vascular injury, and cartilage damage. Advances in three-dimensional imaging technology have improved anatomical visualization and may assist with preoperative planning for screw placement (14). Three-dimensional reconstruction has also been used to define safe zones, screw entry points, and insertion trajectories for posterior-to-anterior talar screw fixation (14).

However, data on talar morphometric parameters, posterolateral tubercle types, safe zones for talar fixation, and screw insertion angles from Thai skeletal samples remain limited. Therefore, this study aimed to investigate posterolateral tubercle morphology, talar morphometric characteristics, and simulated safe zones for posterior-to-anterior talar screw fixation in a Northeastern Thai skeletal collection.

Materials and Methods

Samples and Ethical Considerations

3D scanning and data analysis were performed from May 2023 to August 2024. This study was conducted on completely dried tali from both left and right sides collected from the Unit of Human Bone Warehouse for Research (UHBWR), Department of Anatomy, Faculty of Medicine, Khon Kaen University, Khon Kaen, Thailand. The inclusion criteria were complete tali without evidence of previous surgery or congenital or

acquired deformities. Specimens with fractures, severe osteoporosis, osteolytic lesions, or osteophyte formation were excluded. The study included 553 skeletons, comprising 301 males and 252 females, corresponding to a total of 1,106 tali. Demographic information, including biological sex and age at death, was obtained from the documented donor records accompanying the skeletal specimens in the Unit of Human Bone Warehouse for Research (UHBWR). The records were based on official donor documentation, including identification and death records, and, where available, hospital records. These documented data were used for sample characterization and were not independently re-estimated from skeletal morphology in the present study. The study sample included adults aged 22–106 years. Age was summarized using the mean, standard deviation, median, and range for the overall sample and by sex. This study received ethical approval from the Khon Kaen University Ethics Committee for Human Research (Ref. No. HE651493), and the requirement for informed consent was waived. The sample size was determined based on the sample size calculation described by Gogtay (17), using the standard deviation (SD) and mean differences derived from a previous study by He et al. (18). A confidence level of 95% and a statistical power of 90% were used. For males, the SD was 3.62, and the mean difference was 0.59, based on the reported mean values of 53.48 and 54.07. The calculated minimum sample size was 396 tali, corresponding to 198 skeletons when both left and right tali were considered. For females, the SD was 2.62, and the mean difference was 0.58, based on the reported mean values of 49.15 and 48.57. The calculated minimum sample size was 215 tali, corresponding to 108 skeletons.

Classification of Talar Posterolateral Tubercle Types

The posterolateral tubercle of the talus was classified into three types: Type 1 (almost absent), Type 2 (normal), and Type 3 (enlarged posterolateral tubercle, also known as Stieda's process), based

on the classification described by Kalbouneh et al. (13). The original classification included a fourth type, represented by the os trigonum. However, Type 4 was excluded from the present study because the specimens consisted of completely dried skeletal tali, and the os trigonum could not be reliably identified as a separate accessory ossicle after skeletal preparation. Therefore, only the three morphological types that could be consistently identified in the dry talus specimens were included in the analysis. Specimens were classified as Type 1, Type 2, or Type 3 when the distance between the posterior border of the talar articular surface and the tip of the posterolateral tubercle was ≤ 1 mm, 1.01–4.99 mm, or ≥ 5.00 mm, respectively (Figure 1).

Posterolateral tubercle classification and safe-zone simulation were performed on the same individual talus specimens. Tubercle type was used to characterize the morphology of the posterior process, whereas the safe-zone simulation was performed using the predefined geometric procedure described below. Tubercle type was not included as a variable in the statistical analysis of safe-zone dimensions or screw insertion trajectories.

Determination of the Safe Zone. To determine the safe zone for talar screw fixation, three-dimensional models of the tali were created using a handheld 3D scanner (Shining 3D EinScan HX, SHINING 3D, China). In Laser Scan mode, the manufacturer reports a scanning accuracy of up to

0.04 mm and a minimum point distance of 0.05 mm, which was used as the scanner's point-spacing specification in the present study. The scanner was calibrated according to the manufacturer's recommended procedure before scanning. Each talus was scanned from multiple orientations to capture the complete external surface, with markers used for alignment during scanning. The resulting three-dimensional models were reconstructed using EXScan Pro software (Figure 2) and subsequently processed using Inspect 3D and imported into Solid Edge for screw insertion simulation. All 1,106 tali underwent individual three-dimensional reconstruction and complete simulation-based analysis. Each talus was analyzed separately

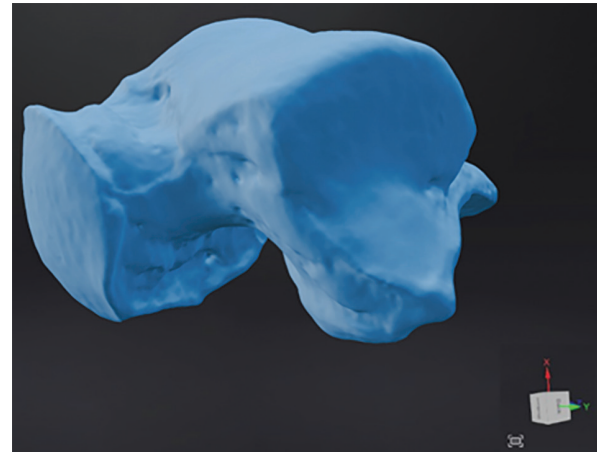


Figure 2. Complete simulation model of a talus scanned with a 3D scanner using the EXScan Pro software.

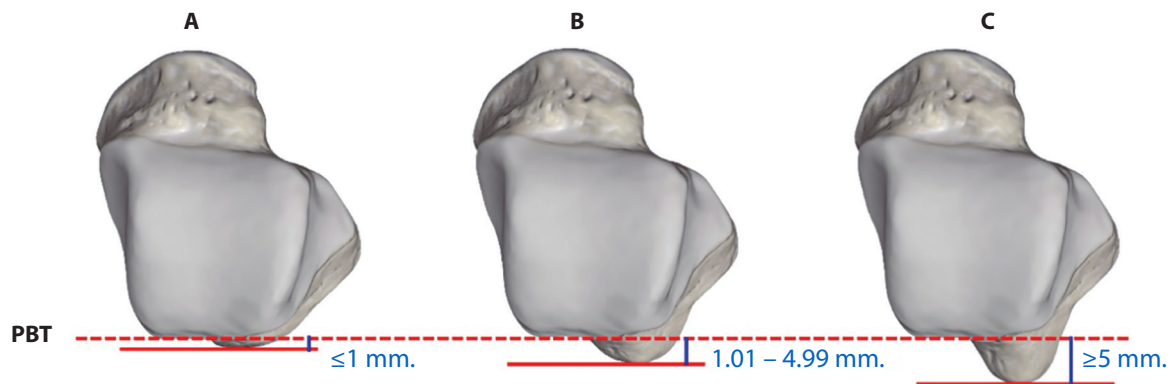


Figure 1. Classification of the posterolateral tubercle types of Thai dry talus. A) Almost absent (Type 1); tubercle length ≤ 1 mm. B) Normal (Type 2); tubercle length between 1.01–4.99 mm. C) Enlarged (Type 3); tubercle length ≥ 5.00 mm; PBT (posterior border line of the talar articular surface).

using the same predefined geometric procedure. The selected individual talus models presented in Figures 4 and 5 were chosen to provide clear visual examples of the geometric configuration of the simulated safe zones and screw insertion angles according to sex and side. These models were selected for graphical illustration rather than as representative or average models of the respective groups. The selected models were not averaged or combined to create composite or population-average 3D models.

Each talus model was sectioned at the coronal plane of the talar neck, and an inner parallel line was created 4 mm from the outer cortical boundary. The 4-mm offset used to define the inner boundary of the safe zone was adopted from the previously described methodology of Wu et al. (11). The safe zone was defined as the area within the inner boundary and above the dotted line representing the roof of the sulcus tali, as previously described (11).

For each talus, the anterior aspect was represented by a rectangular boundary based on the most protruding points, superiorly, inferiorly, medially, and laterally. Nine vertical lines were then drawn along the y-axis to divide the surface into 10 equal columns. Each column represented 10% of the predefined talar surface, with percentage values ranging from 10% to 100%. These percentage values represented the relative position of the potential screw entry region along the predefined anterior talar surface rather than an absolute distance in millimeters. Thus, a safe zone of 20–50% indicated that screw entry trajectories originating within the second through fifth 10% columns were within the predefined geometric safe region under the simulation conditions. The potential safe zone was determined from the area within the inner boundary and above the dotted line representing the roof of the sulcus tali, as described previously (11).

Clinically, these percentage-based zones should be interpreted in relation to the individual talar anatomy and the anatomical landmarks used to establish the simulation boundary. The entry point should be selected within the simulated zone after considering fracture morphology, reduction, screw diameter, screw length, and the intended fixation

trajectory. Therefore, the percentage values should not be applied as absolute surgical coordinates to every talus.

To assess intra-observer reproducibility, 50 talar 3D models were randomly selected from the study sample. All measurements were performed by the same observer. MTH, MTL, MTW, and HTT were measured twice using the same predefined measurement protocol with a 2-week interval between the two measurement sessions. Measurement error was assessed using the technical error of measurement (TEM) and relative TEM

Evaluation of the Safe Zone and Screw Insertion Angles

To evaluate the simulated safe zone for talar screw fixation, all complete simulation models of the talus were analyzed using the Inspect 3D software to simulate screw insertion within the designated safe zone. A 4.0-mm-diameter screw was used in the simulation; the screw length was not used as a fixed parameter because the analysis focused on the safe entry region and insertion trajectory. The screws were inserted in a posterior-to-anterior direction, with the entry point located at the middle of the posterolateral talar tubercle. After the safe zone was identified, the first screw was simulated at the inferior-most predefined safe point, located 4 mm below the outer edge of the talar neck. The second screw was simulated at the superior-most predefined safe point, located 4 mm above the sulcus tali. The area between these two screw positions was defined as the simulated safe zone, and the widest possible screw insertion angle was measured.

The widest screw insertion angles were evaluated descriptively using selected individual talus models for visualization. No inferential statistical comparison was performed for screw insertion angles. Sex-related comparisons of the morphometric parameters were performed using independent-samples t-tests, with the Welch correction applied when equal variances were not assumed. Mean differences, 95% confidence intervals, exact p-values, and effect sizes were calculated for these sex-related comparisons.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics version 28.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean $\pm$ standard deviation (SD). The normality of continuous variables was assessed using the Shapiro–Wilk test, and the homogeneity of variance was assessed using Levene’s test. Because the left and right tali originated from the same skeletons, left–right comparisons were treated as paired observations, with each skeleton representing a matched pair. Therefore, paired-samples *t*-tests were used for side-to-side comparisons. Mean differences were reported with 95% confidence intervals (CIs), and effect sizes were calculated as Cohen’s *dz* for paired comparisons and Cohen’s *d* for independent-group comparisons. For categorical comparisons of posterolateral tubercle types between males and females, Pearson’s chi-square test was used. All statistical tests were two-sided, and a *p*-value <0.05 was considered statistically significant.

Results

The skeletal sample comprised adults aged 22–106 years. The mean age was 64.57 ± 13.95 years, with a median age of 65 years. Male specimens had a

mean age of 66.46 ± 13.08 years (median, 67 years; range, 22–93 years), whereas female specimens had a mean age of 62.30 ± 14.65 years (median, 61 years; range, 24–106 years).

The prevalence of posterolateral tubercle types in Thai dry tali is shown in Table 1. Pearson’s chi-square test was used to compare the distribution of posterolateral tubercle types between males and females. The highest prevalence was observed for Type 3 (53.16%), whereas Type 1 had the lowest prevalence (1.36%). The distribution of posterolateral tubercle types differed significantly between males and females (Pearson’s chi-square test, $\chi^2=45.805$, $P=1.13 \times 10^{-10}$; Table 1). Type 2 was the most frequent variant among females (56.55%), whereas Type 3 was the most frequent variant among males (62.13%).

Paired comparisons of the left and right tali showed small but statistically significant differences in all four morphometric parameters. The left talus was significantly larger than the right for MTH (mean difference, 0.45 mm; 95% CI, 0.06–0.84; $P=0.023$), MTL (0.42 mm; 95% CI, 0.13–0.72; $P=0.005$), MTW (0.23 mm; 95% CI, 0.01–0.46; $P=0.042$), and HTT (0.57 mm; 95% CI, 0.25–0.89; $P=0.00054$). The corresponding effect sizes were small (Cohen’s *dz* = 0.087–0.148). The detailed results are presented in Table 2.

Table 1. Types of Posterolateral Tubercle According to Sex in Northeastern Thai Dry Tali

Types of the posterolateral tubercle	Total (N=1106)	Females (N=504)	Males (N=602)	χ^2	P-value
Almost absent (Type 1)	15 (1.36%)	5 (0.99%)	10 (1.66%)	45.805	1.13×10^{-10}
Normal (Type 2)	503(45.48%)	285 (56.55%)	218 (36.21%)		
Enlarged (Type 3)	588 (53.16%)	214 (42.46%)	374(62.13%)		

Type 1: Tubercle length ≤ 1 mm; Type 2: Tubercle length between 1.01–4.99 mm; Type 3: Tubercle length ≥ 5.00 mm; N=Number of tali.

Table 2. Paired Comparison of Talar Morphometric Parameters Between the Left and Right Sides

Parameter	Left, mean $\pm$ SD (mm)	Right, mean $\pm$ SD (mm)	Mean difference (L–R), mm	95% CI	P-value	Cohen’s <i>dz</i>
MTH	55.31 $\pm$ 4.36	54.86 $\pm$ 4.24	0.45	0.06–0.84	0.023	0.097
MTL	39.02 $\pm$ 3.20	38.59 $\pm$ 3.19	0.42	0.13–0.72	0.005	0.121
MTW	30.43 $\pm$ 2.32	30.19 $\pm$ 2.45	0.23	0.01–0.46	0.042	0.087
HTT	50.24 $\pm$ 3.72	49.66 $\pm$ 3.51	0.57	0.25–0.89	0.00054	0.148

MTH= Maximum talar height; MTL=Maximum talar length; MTW=Maximum talar width; HTT=Distance from the anterior surface of the head of the talus to the posterior boundary of the tibial articular surface.

A comparison of talar morphometric parameters showed that male tali had greater values than female tali on both sides. The mean differences, 95% confidence intervals, p-values, and effect sizes for the sex comparisons are presented in Table 3.

Intra-observer reproducibility was assessed using repeated measurements of 50 randomly selected talar 3D models. All four morphometric parameters showed low measurement error. The TEM values ranged from 0.12 to 0.19 mm, and the relative TEM values ranged from 0.33% to 0.40%. The results indicated good reproducibility of the talar morphometric measurements (Table 4).

Figure 3A demonstrates the lateral aspect of the simulated talus model and the predefined boundaries used for screw insertion. The first screw was simulated at the inferior-most predefined safe point, located 4 mm below the outer edge of the talar neck, whereas the second screw was simulated at the superior-most predefined safe point, located 4 mm above the sulcus tali (Figure 3A).

The screw insertion simulation was performed using Inspect 3D software. The simulation results showed that all simulated screw tips remained within the predefined safe zone and that the screw bodies did not pass through the sulcus tali (Figure 3 A and B).

Figure 4 shows selected individual talus models from the study sample, cut at the coronal section of the talar neck to illustrate the location of the simulated safe zone. All 1,106 tali were individually reconstructed and analyzed using the same predefined simulation procedure. The models shown in Figures 4A–D were selected only to illustrate examples of the geometric configuration of the safe zone according to sex and side. In the selected male talus model, the safe zone was between 20% and 50% on the left and between 30% and 60% on the right (Figures 4A and B). In the selected female talus model, the safe zone was between 20% and 70% on the left and between 20% and 50% on the right (Figures 4 C and D). These percentage ranges

Table 3. Comparison of Talar Morphometric Parameters Between Males and Females

Parameter	Side	Mean±SD (mm)		Mean difference (Male – Female) mm	95% CI	P-value	Cohen's dz
		Male (N=301)	Female (N=252)				
MTH	Left	57.30 ± 3.57	52.93 ± 4.01	4.37	3.73–5.01	2.50×10^{-35}	1.16
	Right	57.48 ± 3.22	51.73 ± 3.02	5.75	5.23–6.27	2.35×10^{-75}	1.84
MTL	Left	40.22 ± 2.64	37.56 ± 3.20	2.66	2.16–3.16	1.67×10^{-23}	0.91
	Right	40.48 ± 2.33	36.33 ± 2.55	4.15	3.74–4.56	2.23×10^{-65}	1.71
MTW	Left	31.39 ± 1.92	29.27 ± 2.23	2.12	1.77–2.47	9.88×10^{-29}	1.03
	Right	31.60 ± 2.02	28.51 ± 1.76	3.09	2.77–3.41	2.31×10^{-63}	1.62
HTT	Left	52.12 ± 2.82	48.00 ± 3.41	4.12	3.59–4.65	2.07×10^{-43}	1.33
	Right	51.80 ± 2.77	47.10 ± 2.42	4.70	4.27–5.13	8.11×10^{-74}	1.80

MTH=Maximum talar height; MTL=Maximum talar length; MTW=Maximum talar width; HTT= Distance from the anterior surface of the head of the talus to the posterior boundary of the tibial articular surface; CI=Confidence interval; SD=Standard deviation.

Table 4. Intraobserver Measurement Error and Reproducibility of Talar Measurements

Parameter	N	Mean±SD Measurement 1 (mm)	Mean±SD Measurement 2 (mm)	TEM (mm)	Relative TEM (%)
MTH	50	55.21 ± 4.18	55.18 ± 4.17	0.18	0.33
MTL	50	38.76 ± 3.16	38.79 ± 3.17	0.13	0.34
MTW	50	30.28 ± 2.36	30.30 ± 2.37	0.12	0.40
HTT	50	49.87 ± 3.52	49.91 ± 3.53	0.19	0.38

MTH=Maximum talar height; MTL=Maximum talar length; MTW=Maximum talar width; HTT=Distance from the anterior surface of the head of the talus to the posterior boundary of the articular surface of the tibia; TEM=Technical error of measurement.

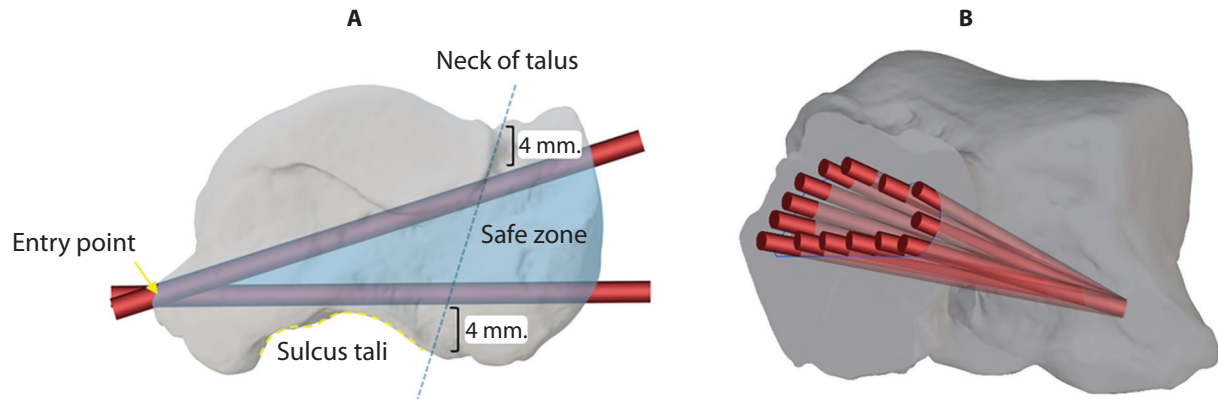


Figure 3. Lateral aspect of the safe zone (light blue area) for talar screw fixation after hypothetical screw insertion (A). Testing of the screw insertion using many screws at an entry point, performed using Inspect 3D software (B).

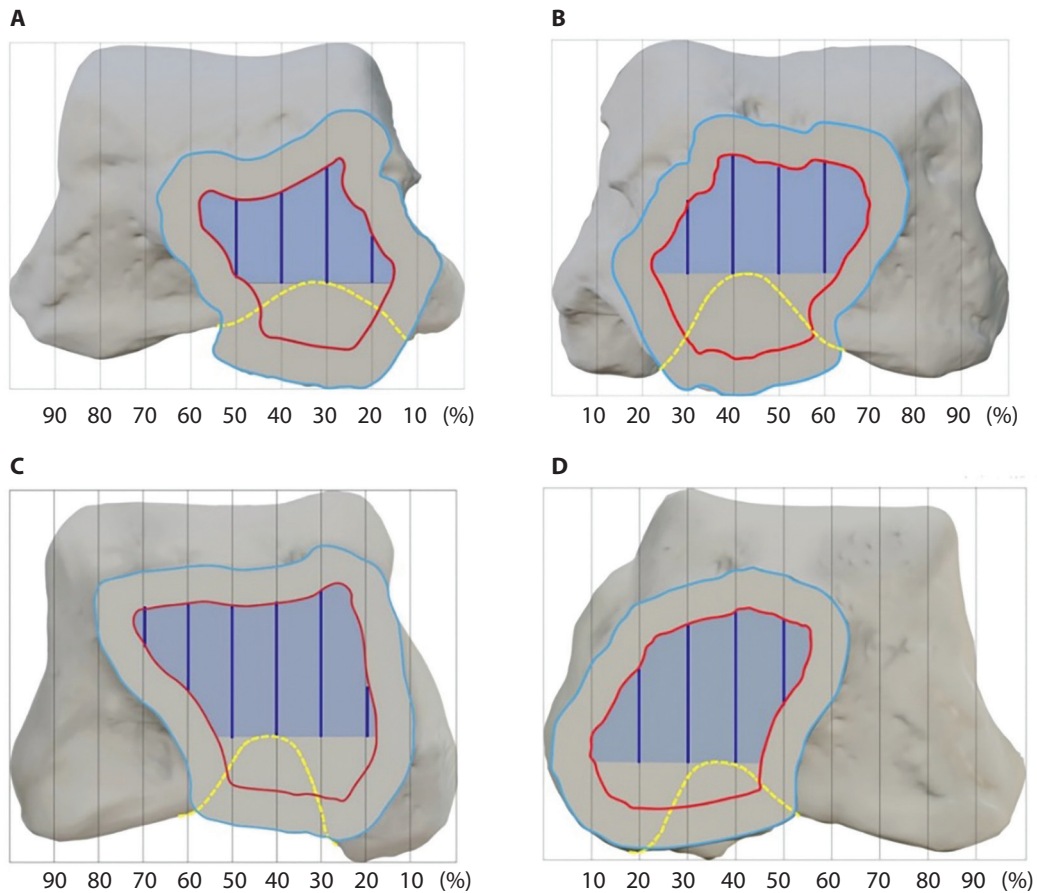


Figure 4. Simulated safe zones for talar screw fixation using selected individual 3D talus models. A) The safe zone on the left side of a male talus was between 20% and 50%, and B) on the right side was between 30% and 60%. C) The safe zone on the left side of a female talus was between 20% and 70%, and D) on the right side, it was between 20% and 50%. The illustrated models are individual specimens selected from the full study sample for visualization. The reported safe-zone ranges apply only to the selected models shown and do not represent population-level estimates or averaged safe-zone values.

describe the selected individual models shown in the figure and should not be interpreted as population-level estimates or values representing all specimens within each sex-side group. Because the safe-zone boundary was not analyzed as a quantitative outcome across the full sample, no population-level mean, range, or variability estimate was calculated for the safe-zone parameters. The values shown in Figure 4 therefore represent selected individual examples rather than the distribution of safe-zone boundaries across all 1,106 tali.

Figure 5 presents the widest simulated posterior-to-anterior screw insertion angles obtained from selected individual talus models for illustrative purposes. The angular values shown in Figure 5 represent the selected models and were not calculated as population-level estimates. In both selected models, the simulated insertion angle was wider on the left than on the right. Because these values were obtained from the selected simulation models, they are presented as descriptive simulation results rather than inferential statistical comparisons. The simulated insertion angles were $21.25 \pm 0.24^\circ$ on the left and $19.94 \pm 0.21^\circ$ on the right in females, and $22.68 \pm 0.13^\circ$ on the left and $20.37 \pm 0.17^\circ$ on the right in males (Figure 5).

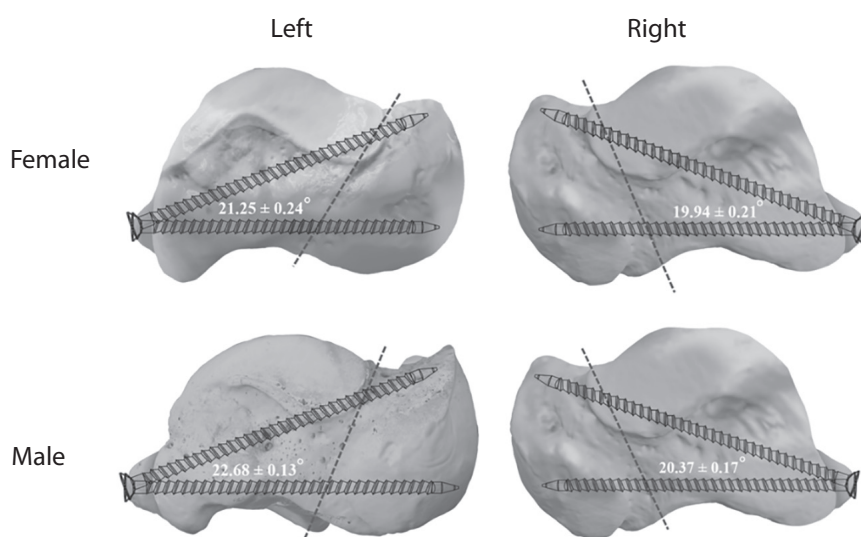


Figure 5. Widest simulated posterior-to-anterior screw insertion angles within the possible safe zones of selected individual talus models according to sex and side. The illustrated angles are descriptive measurements from the selected individual models and do not represent population-level estimates or inferential statistical comparisons.

Discussion

The main finding of this study was that the posterolateral tubercle of the talus showed anatomical variation, while the selected individual models illustrated differences in the geometric configuration of the simulated safe zones according to sex and side in the Northeastern Thai skeletal collection. These differences should be considered during preoperative planning for talar screw fixation. As previously described, the posterolateral tubercle of the talus can be classified into four morphological types (13). The present study included three types because Type 4, corresponding to the os trigonum, could not be reliably identified as a separate accessory ossicle in the dry skeletal specimens. This difference in classification should be considered when comparing the present findings with studies based on CT imaging or other methods that can identify the os trigonum separately. In the present study, three types were identified: Type 1 (almost absent), Type 2 (normal), and Type 3 (enlarged). Type 3 was the most prevalent (53.16%), followed by Type 2 (45.48%) and Type 1 (1.36%). Type 3 was also more common in males (62.13%) than in females (42.46%). The posterolateral tubercle and the simulated safe zone are anatomically located within the posterior talar region; however, the present study did not test whether tubercle type was associated with the dimensions or location of the simulated safe zone. Therefore, no direct relationship between tubercle type and screw trajectory can be inferred from the present data. In the present study, the tubercle was classified according to its morphological size, whereas the safe zone was determined using a predefined geometric procedure based on the individual talar anatomy. The findings should

therefore be interpreted as complementary anatomical observations rather than evidence of a direct statistical relationship between tubercle type and safe-zone parameters. Compared with previous studies, the prevalence of Type 3 in the present Thai sample (53.16%) was higher than the prevalence of an enlarged lateral tubercle reported by Zwiers et al. (19) in ankles without an os trigonum (34.9–36.5%). However, these findings should be interpreted with caution because the two studies used different study populations and classification approaches. The prevalence of Type 1 in the present Thai sample (1.36%) was lower than that reported in the Jordanian population (7.3%) by Kalbounieh et al. (13). These findings provide anatomical reference information from a Northeastern Thai skeletal collection and may be useful for preoperative planning of screw fixation involving the posterolateral region of the talus.

This study investigated the geometric safe zone for talar screw fixation in a Northeastern Thai skeletal sample using dry tali and 3D simulation models. The selected individual models illustrated differences in simulated safe-zone configurations between sexes and sides. Compared with a previous study of 15 Chinese male patients using CT images (11), which reported a safe zone of 30%–60%, the present study showed a similar range in the selected right male model. A previous three-dimensional CT-based study by Mao et al. also demonstrated that computer-assisted three-dimensional analysis could be used to define safe zones and screw trajectories for posterior talar process fixation (14). However, that study evaluated posterior talar process fractures using 3.0-mm screws, whereas the present study used a predefined 4.0-mm screw diameter and a different geometric definition of the safe zone. Therefore, the findings are not directly comparable. However, this comparison should be interpreted with caution because the previous study used CT images from a clinical population, whereas the present study used dry-bone 3D models from a skeletal collection. The findings of the present study may provide anatomical reference information for preoperative planning of talar screw fixation based on this Northeastern

Thai skeletal collection. However, they should not be directly generalized to other Thai regions or non-Thai populations because the sample was obtained from a single skeletal collection. Therefore, the findings should be interpreted as sample-derived anatomical data from the studied skeletal collection rather than as representative estimates for the Northeastern Thai population as a whole.

The clinical applicability of the simulated safe zones is primarily related to posterior-to-anterior screw fixation for talar fractures, in which the posterolateral region is used as the screw entry site. The identified zones may assist preoperative planning by providing anatomical reference locations for selecting a possible screw entry point and trajectory. However, these zones should be considered anatomical reference ranges rather than fixed surgical boundaries. The actual safe trajectory depends on individual talar morphology, fracture pattern, reduction quality, screw diameter, screw length, and the selected fixation technique. Therefore, the percentage-based safe zones should be interpreted in relation to the individual talus and the anatomical landmarks used to establish the simulation boundary.

Age may also influence talar morphology and should be considered when interpreting the present findings. The skeletal sample included individuals aged 22–106 years, representing a broad adult age range. Age-related bone remodeling and degenerative changes, including possible osteophyte formation and changes in articular or cortical morphology, may contribute to variation in bone dimensions and surface morphology and could influence the observed morphometric parameters and simulated safe-zone geometry. However, age-related differences were not specifically analyzed because the present study focused on posterolateral tubercle morphology, sex- and side-related anatomical variation, and simulation-based safe zones and screw trajectories. Therefore, the potential influence of age-related remodeling and degenerative changes cannot be excluded. Future studies using age-stratified analyses or multivariable models are needed to determine whether talar morphology and simulated safe zones vary across adult age groups.

Several limitations should be considered when applying these simulated safe zones. First, the safe zones were derived from dry-bone 3D models and did not include surrounding soft tissues, neurovascular structures, cartilage, or other anatomical conditions encountered during surgery. Second, the screw trajectories were evaluated using computer-based simulation rather than cadaveric surgical testing or clinical imaging. No cadaveric or clinical validation was performed in the present study. The scanner was calibrated according to the manufacturer's recommended procedure; however, independent validation of the scanning accuracy against a reference object or established measurement standard was not performed. Therefore, the reported scanner accuracy represents the manufacturer's specification rather than an independently validated accuracy estimate for the present scanning protocol.

Although all 1,106 tali underwent individual safe-zone simulation, a full statistical assessment of safe-zone boundary variability across all individual specimens was not performed. The use of selected individual models limits the interpretation of the reported safe-zone ranges because these values cannot be used to estimate the typical or full range of safe-zone configurations in the study sample. Differences illustrated between sexes or sides should therefore be interpreted as examples of individual anatomical variation rather than evidence of systematic sex- or side-related differences across the entire sample. Clinically, these simulated configurations may illustrate how individual talar morphology can affect the available screw entry region, but they should not be used as universal or fixed surgical coordinates. Therefore, the safe-zone configurations and screw insertion angles presented in Figures 4 and 5 should be interpreted as illustrative individual simulation results rather than population-level estimates. The simulated boundaries should not be considered clinically validated safety margins. Third, the simulations were based on a predefined screw diameter and geometric criteria and may not directly apply to other implant sizes or fixation configurations. Finally, the specimens were obtained from a single institutional

skeletal collection and should not be assumed to represent the full morphological variation of the Northeastern Thai population or other Thai populations. In addition, interobserver reliability was not assessed because all measurements were performed by a single observer. Therefore, the reproducibility results reflect intra-observer reliability only, and future studies involving multiple observers are needed to assess inter-observer reliability.

Previous 3D simulation studies have also reported differences in talar screw safe zones and insertion angles between sexes (11, 14). In the present study, the insertion angles shown in Figure 5 were obtained from selected individual models and are therefore presented as descriptive simulation findings rather than population-level estimates or inferential statistical comparisons. Biomechanical studies have reported that posterior-to-anterior (PA) screw fixation can provide good mechanical stability (15). Therefore, the screw insertion angle is an important factor to consider during PA fixation. However, the angle should be considered together with the screw entry point, screw length, safe zone, and fixation technique (11, 12, 16). Sex- and side-related anatomical variation may also be considered during preoperative planning to help select an appropriate screw trajectory. Previous studies have also reported an association between the anatomical safe zone and the mechanical properties of talar fixation in finite element analyses (15).

The safe-zone parameters defined in this study are primarily applicable to posterior talar fractures managed with posterior-to-anterior headed screw fixation. These findings should not be directly extrapolated to talar neck fractures treated with anterior-to-posterior screw trajectories, in which the posterolateral tubercle is not the primary entry point. Similarly, headless compression screws inserted beneath the talar dome articular surface, typically outside the posterolateral tubercle region, represent another situation in which the safe-zone definitions may have limited direct clinical applicability. Further studies using quantitative analysis of individual safe-zone measurements, cadaveric testing, and clinical validation are required to determine the reproducibility and clinical usefulness

of the simulated safe zones in surgical practice. Therefore, the findings should be interpreted as sample-derived anatomical data from the studied skeletal collection rather than representative estimates for the Northeastern Thai population as a whole.

Conclusion

In conclusion, the enlarged posterolateral tubercle was the most prevalent variant in the studied Northeastern Thai skeletal collection. The selected individual models illustrated differences in simulated safe-zone configurations according to side and sex. Because the association between tubercle type and safe-zone dimensions was not directly tested, these findings should be considered complementary anatomical information rather than evidence of a direct relationship between tubercle morphology and screw trajectory. The simulated safe zones should not be regarded as clinically validated surgical boundaries and require further validation using cadaveric and clinical studies.

What Is Already Known on This Topic:

Talar fractures, most commonly involving the talar neck, require precise screw fixation planning to avoid neurovascular complications. 3D imaging technology has been shown to improve the preoperative simulation of safe screw trajectories. Anatomical variations of the posterolateral tubercle of the talus have been documented in some populations, with safe zones for talar screw fixation previously reported primarily in Chinese male patients.

What This Study Adds:

This study provides sample-derived anatomical data on posterolateral tubercle morphology and simulated geometric safe zones from a Northeastern Thai skeletal collection. The enlarged tubercle (Type 3) was the most prevalent variant, particularly in males. Selected individual models illustrated differences in simulated safe-zone configurations and insertion angles according to side and sex. In the selected models shown in Figure 5, the simulated insertion angle was wider on the left than on the right in both sexes. These angular findings are descriptive observations from selected individual models and do not represent population-level estimates or systematic side- or sex-related differences.

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