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Prediction of Sustentaculum Tali Sustentacular Screw Length based on Linear Regression Model

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ABSTRACT

Calcaneal fractures present challenges due to the complex anatomy and difficulty in achieving precise screw placement. Traditional methods often rely on empirical screw insertion, leading to complications like joint penetration or nerve damage. We selected 66 adult calcaneus specimens and conducted analyses using micro-CT scanning and anatomical measurement techniques, dividing the calcaneus into the anterior, middle, posterior, and ST regions. The calcaneus was divided into anterior, middle, posterior, and ST regions. Linear regression was used to analyze the relationship between anatomical parameters and the lengths of screws for the posterior facet (PF) and articulatio calcaneocuboidea (AC). The derived models for AC/PF screw length based on CT data are: G1 = -1.96 + 0.71F1 + 0.48F8 + 0.39F9 (AC screw) and G2 = 3.95 + 0.28F1 + 0.59F8 + 0.31F9 (PF screw), with similar results for anatomical data. Predicted screw lengths were validated through Micro-CT imaging, confirming accurate insertion without perforating the medial calcaneal cortex. In conclusion, linear regression models based on Micro-CT and anatomical data can accurately predict AC/PF screw lengths, improving surgical precision and outcomes. Meanwhile, we'll keep collecting more data to validate and improve the models. Additionally, we'll explore new methods like machine learning to enhance prediction accuracy in the future.

Study design: Experimental cadaveric study with anatomical and Micro-CT-based measurements.

Keywords: Sustentacular screw, anatomical measurements, CT-based analysis, linear regression, mathematical modeling.

INTRODUCTION

Calcaneus fractures represent 1-2% of all fractures[1-3]. Roughly 75% of calcaneal fractures are intra-articular[4-6]. Despite the recent innovation in surgical implants and techniques, the best strategy for displace calcaneal fracture remains controversial. Nonetheless, open reduction and internal fixation (ORIF) by application of locking plate through an extended lateral approach or the sinus tarsi approach remain the current standard[7-12].

For treatment of Sanders type II or III calcaneal fractures, a posterior facet (PF) screw is typically placed in the most anterior part of the posterior facet and runs subchondral, ideally into the medial end of the ST articulatio calcaneocuboidea (AC) screw can be drilled from the process anterior calcanei into ST. This fragment is essential for surgeons attempting to restore subtalar joint congruity, since it usually maintains its position in relation to the ST via the presence of strong interosseous talocalcaneal ligaments[13-15]. The ST process is a bony structure located in the medial side of calcaneus, which plays a role in supporting body weight, conducting stress and stabilizing foot and ankle balance[16]. The surrounding ligaments and joint capsule and other tough connecting structures keep a stable relationship between talus process and calcaneus after calcaneus fracture, providing anatomic conditions for screw placement[17].

The ST, being small, and combined with the complex three-dimensional structure of the calcaneus, makes laterally applied screws difficult to adequately engage it. The placement of AC and PF screws is challenging. One complication is possible screw penetration of the subtalar joint. Another complication is irritation of medial structures by long screws that penetrate the ST[18].

In such a case, fracture reduction is stable, but the medial anatomical structures are irritated/injured[15]. Complications include peroneal tendon injury, neuritis/neuroma of the sural nerve and injury to the flexor hallucis longus tendon when placing screws through the constant fragment from a laterally based incision where direct visualization is not possible[19-21]. Our previous work indicate screw inserting into ST by 3D print technique[22].

Linear regression models are a cornerstone in the field of statistical analysis and have found extensive application in medical research[23,24], particularly in orthopedics[24]. These models are utilized to establish a linear relationship between one or more independent variables and a dependent variable, allowing for the prediction of outcomes based on measurable characteristics, such as the diameter (outer diameter) of the acetabular prosthesis used in total hip arthroplasty[25]. They serve as a predictive tool that can potentially enhance the precision of surgical interventions, thereby improving patient outcomes and reducing complications associated with malpositioned hardware[26].

The aim of the study is to provide optimal prediction for AC and PF screw lengths by using CT-based measured data during calcaneus fixation to prevent penetration of the subtalar joint, as well as the flexor tendons bundle. So, We hypothesize that a linear regression model based on key calcaneal measurements obtained from standard pre-operative CT scans can accurately predict the optimal length for both AC and PF screws.

MATERIAL AND METHODS

Material

This research has been approved by the authors' affiliated institutions. We collected sixty-six ankle specimens, comprising 32 right calcanei and 34 left calcanei, from our department.

Methods

Inclusion and Exclusion Criteria

Inclusion criteria: Age 18-50; Height of human specimen greater than or equal to 150 cm; Foot length greater than or equal to 18 cm. *Exclusion criteria:* Congenital calcaneal dysplasia, Ankle and hindfoot trauma and surgical scars, Ankle gout, rheumatoid disease and severe osteoarthritis and deformities; Foot and ankle tumors, bone tuberculosis and chronic osteomyelitis. The surveyor divided the calcaneus into anterior, middle and posterior regions. The surveyor then divided each part of the calcaneus into indicators to be measured.

Anatomical and Micro-CT-based Parameters

Both anatomical and Micro-CT-based measure were performed to determine following parameters: f1: ST length; f2: ST width; f3: ST height; f4: maximum width of the anterior calcaneus; f5: minimum width of the anterior calcaneus; f6: maximum width of the posterior calcaneus; f7: minimum width of the posterior calcaneus; f8: maximum width of the posterior articular surface; f9: maximum height of the posterior calcaneus; f10: maximum height of the corpora calcanei; f11: maximum length of the anterior calcaneus;f12: calcaneus body axis.

Anatomical Measure

For anatomical measure, the special calcaneus bracket (Patent number: ZL202010654635.9) was used to fix the calcaneus in the anatomical position. The axes of the calcaneus were marked and an electronic vernier calliper was used to measure the parameters (Figure 1).

Micro CT-based Measure

The isolated calcaneus in anatomical position were scanned using Micro CT (MadicLab Ultra Small Animal CT. Shandong, China), Tube voltage 60 V, Tube current 10 mA. CT scan with a slice thickness of 0.2 mm. DICOM format sections were generated and imported into the PMOD software (PMOD Technologies, Swit). The parameters of calcaneus were measured by using PMOD software (Figure 2).

Linear regression correlation analysis

The corrplot package was employed to analyze the correlation between PF/AC screw length and the measured calcaneal parameters. Variables with correlation coefficients (R values) greater than 0.7 were identified as strongly correlated and selected for subsequent multi-variable linear regression analysis. Through this screening, three key parameters were determined: sustentaculum tali length (f1/F1), maximum width of the posterior articular surface (f8/F8), and maximum height of the posterior calcaneus (f9/F9).

Multi-variable linear regression mathematical model analysis for AC/PF screw length

Based on the results from step 2, different variables were hand-picked to predict AC/PF screw length using the Lm function in R. Namely, to predict G1 (g1) and G2 (g2), F1, F8 and F9 were used for CT-based measure data; f1, f8 and f9 were used for anatomical measure data.

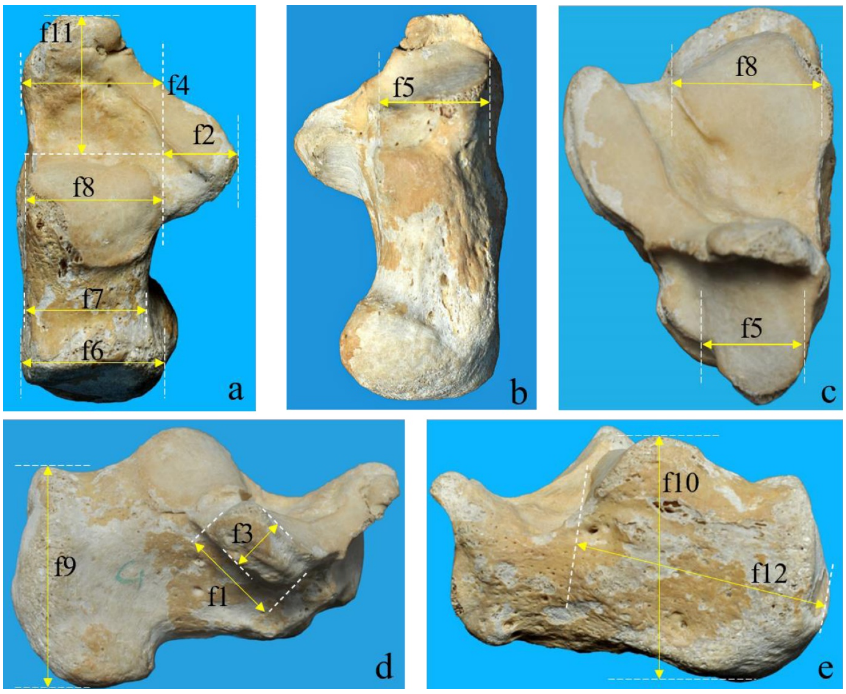

Fig. 1 — a: Top view; b: Bottom view; c: Front view; d: Medial view; e: Lateral view. f1: ST length; f2: ST width; f3: ST height; f4: maximum width of the anterior calcaneus; f5: minimum width of the anterior calcaneus; f6: maximum width of the posterior calcaneus; f7: minimum width of the posterior calcaneus; f8: maximum width of the posterior articular surface; f9: maximum height of the posterior calcaneus; f10: maximum height of the corpora calcanei; f11: maximum length of the anterior calcaneus; f12: calcaneus body axis.

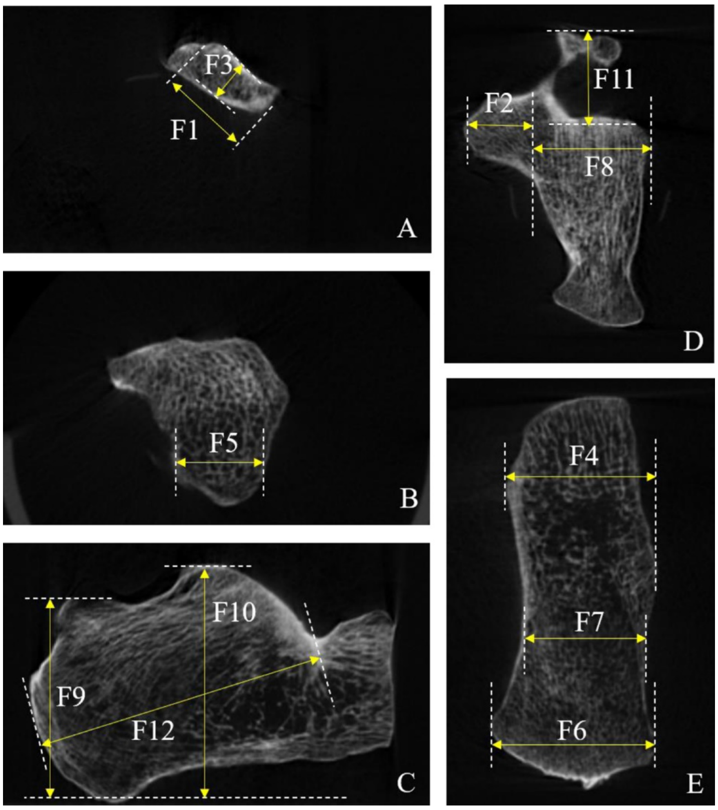

Fig. 2 — CT measure. A: Lateral side of the sustentaculum tali. B: Front view. C: Lateral view. D&E: Top view for the measure.

Building mathematical model

As seen in the step 2 analysis, G1 (g1) and G2 (g2) was also correlated. To further illustrate the relationship, the SPSS function was used to calculate the R value, and Ggplot was used to plot the correlation graph.

Model Validation

To verify the reliability of the constructed models, 10 additional calcaneal specimens were randomly selected. The key parameters (f1, f8, f9 for anatomical measurements; F1, F8, F9 for Micro-CT measurements) were re-measured, and the predicted AC/PF screw lengths were calculated using the above models. Kirschner wires were inserted into the sustentaculum tali according to the predicted lengths, and Micro-CT 3D reconstructions confirmed that all wires were accurately positioned without perforating the medial calcaneal cortex, validating the models' accuracy.

Description of AC and PF

AC: It is located about 10 mm backward from the intersection of the lateral anterior part of the calcaneocuboid joint surface, where the Angle of needle entry is about 20° upward (upper oblique Angle) and 27° backward (posterior oblique Angle).

PF: The needle entry point was located about 10 mm below the posterior articular surface of the calcaneus on the lateral wall of the calcaneus (and on the axis of the fibula), and tilted 27° inward and upward (Figure 3).

Statistical analysis

All statistical analysis and graph plotting were performed using R statistical software. Paired t test was used to determine whether there was a significant difference between anatomical measurements and CT measurements. Multi-variable linear regression model analysis for AC/PF screw length. Based on the results from step 2, different variables were hand-picked to predict AC/PF screw length using the Lm function in R. Namely, to predict G1 (g1) and G2 (g2), f1, f8 and f9 were used for CT-based measure data; f1, f8, and f9 were used for anatomical measure data.

RESULTS

Model Building

Our study aimed to develop prediction models for AC/PF screw lengths based on anatomical and CT-based measurements. The first step was a comparative analysis of these two methods to establish their reliability. As shown in Table I, the results indicated no significant differences between the anatomical and CT-based measurements, with paired t-tests yielding negligible t-values and high P-values (>0.95), suggesting a high degree of consistency between the two sets of measurements.

The benefits of using both methods include increased accuracy in screw length prediction and the ability to use either method depending on the clinical setting. However, limitations exist, such as the need for CT scans in the CT-based method, which may not be readily available in all settings.

To further understand the relationship between screw lengths and anatomical parameters, correlation analysis was conducted. Figure 4 illustrates the strong correlations found between AC/PF screw lengths and specific calcaneal measurements for both anatomical and CT-based data. This analysis was crucial for identifying key parameters that influence screw length.

Based on the linear correlation analysis, three key parameters—sustentaculum tali length (f1/F1), maximum width of the posterior articular surface (f8/F8), and maximum height of the posterior calcaneus (f9/F9)—were identified as the most influential in determining the AC/PF screw lengths. These parameters were subsequently utilized to develop

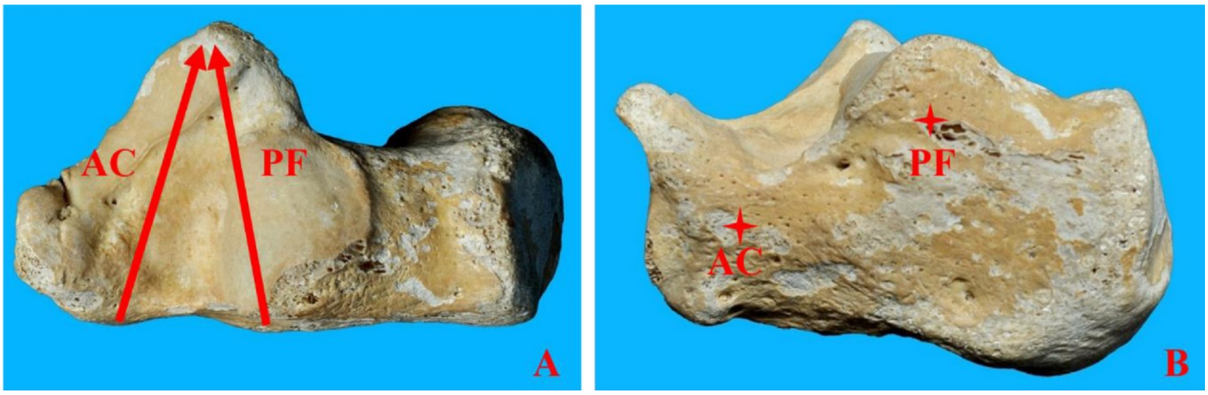

Fig. 3 — (A) Top view; (B) Lateral view.

prediction models for both anatomical and CT-based data sets.

The mathematical models derived for the anatomical data were as follows:

g1 (AC screw length) = -1.96 + 0.71 * f1 + 0.48* f8 + 0.38* f9

g2 (PF screw length) = 3.97 + 0.28*f1 + 0.60*f8 + 0.30*f9

Similarly, for the CT-based data, the models were:

G1 (AC screw length) = -1.96 + 0.71* F1 + 0.48* F8 + 0.39* F9

G2 (PF screw length) = 3.95 + 0.28 * F1 + 0.59* F8 + 0.31 * F9

Model Validation

To validate the accuracy of the developed models, experimental screw placements were conducted using Kirschner wires on 10 additional calcaneal specimens. The screws were inserted into the sustentaculum tali based on the predicted lengths from the models. The results, as visualized in Figure 5 through three-dimensional reconstructions, demonstrated that the screws were accurately positioned without perforating the calcaneal cortex, confirming the effectiveness of the prediction models.

Statistical analysis was performed using R software, employing multi-variable linear regression to predict AC/PF screw lengths. The models were validated

Table I. — Comparison between CT-based and anatomical measure data.

Paired *t*-test	f/g (mean ± SEM)	F/G (mean ± SEM)	$t_{(65)}$	P
f1 vs F1	23.10 ± 0.25	23.10 ± 0.25	0.07	0.95
f2 vs F2	14.59 ± 0.20	14.59 ± 0.19	0.05	0.96
f3 vs F3	10.37 ± 0.16	10.37 ± 0.16	0.05	0.96
f4 vs F4	24.84 ± 0.36	24.84 ± 0.36	0.09	0.93
f5 vs F5	20.33 ± 0.25	20.33 ± 0.25	0.06	0.96
f6 vs F6	30.04 ± 0.38	30.04 ± 0.38	0.06	0.96
f7 vs F7	25.34 ± 0.38	25.34 ± 0.38	0.06	0.96
f8 vs F8	27.92 ± 0.37	27.92 ± 0.37	0.06	0.95
f9 vs F9	44.11 ± 0.44	44.11 ± 0.44	0.08	0.94
f10 vs F10	42.02 ± 0.49	42.02 ± 0.49	0.06	0.95
f11 vs F11	21.82 ± 0.31	21.83 ± 0.31	0.06	0.95
f12 vs F12	51.36 ± 0.62	51.36 ± 0.62	0.07	0.95
g1 vs G1	44.86 ± 0.53	44.86 ± 0.53	0.07	0.95
g2 vs G2	40.39 ± 0.43	40.39 ± 0.43	0.06	0.95

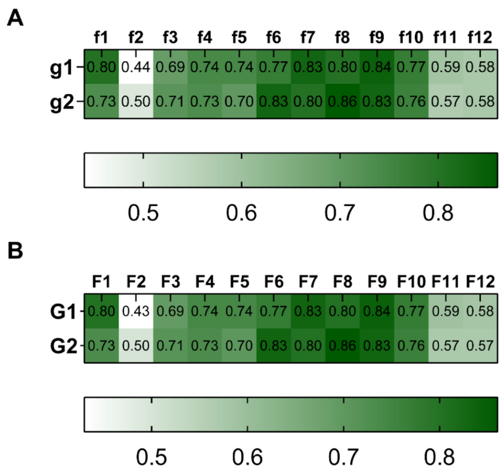

Fig. 4 — Calcaneal linear indicators and focal distance index correlation nailing. ACg1 (G1)/ PFg2 (G2) and the variables (f1 ~ f12) based on anatomical measure data and CT measure data.

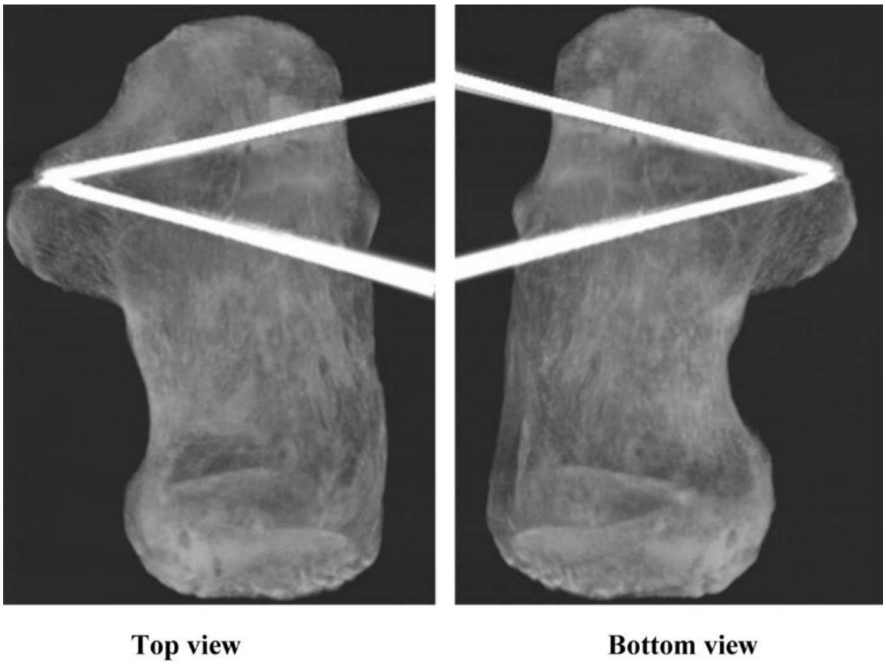

Fig. 5 — Three-Dimensional Reconstruction of Experimental Screw Placement. (Left): Superior view of the calcaneus after three-dimensional reconstruction, showing the experimental screw placement. (Right): Inferior view of the calcaneus post three-dimensional reconstruction, illustrating the position of the experimentally placed screws. Note: The anterior screw is designated as the sustentaculum tali screw 1, and the posterior screw as sustentaculum tali screw 2, with the Kirschner wires placed accurately behind and above the sustentaculum tali without perforation.

using the lm() function, and the results were plotted to visualize the relationships between the variables, as shown in Figure 6 and Figure 7. The scatter plots provided a clear representation of the correlations, further substantiating the accuracy of the prediction models.

DISCUSSION

Through the statistical method of multiple linear regression, after analyzing all the data, we establish a mathematical prediction model, which is multiple regression equation. The construction of mathematical model is beneficial for clinicians to obtain the final screw length by measuring the corresponding indexes on CT after CT scanning. Clinical scan of bilateral ankle can be used to compare screw placement. The mathematical model is only applicable to AC and PF positions, and accurate screw placement of ST is carried out in these two positions. The PF screw placement point is located at the posterior articular surface where the calcaneus and talus meet, and this point is located 1 cm below the midpoint of the lateral margin of the posterior articular surface. The AC is located on the lateral surface of the calcaneus 0.5 cm to 1 cm from the most anteriorly. These two points ensure the accuracy of the offset protruding screw. Clinical nailing from these two points can reduce the injury of vascular, muscle and tendon[17,27].

At present, a number of studies have been reported on the anatomical relationship with the sustentaculum screw length for the calcaneus fracture fixation[28]. Basa et al., measured the coronal and axial plane distance between the lateral cortex and the ST in a Turkish population18. Chun et al., developed a prediction model for determining coronal length of calcaneus using CT. In this study, they predicted the length of screws to be placed in the calcaneus using correlations of neighboring bones such as tatus and cuboid[29]. A single data or adjacent structure after prediction model is established to measure from the Angle of all aspects of the overall characteristics, so after multiple data by filtering using multiple linear regression to establish mathematical model used to can show from the overall Angle of calcaneal nailing specific length, but there may be some defects of mathematic model, So we used the established mathematical model to verify, and finally the model was verified, and from the clinical point of view, it can be concluded that the mathematical model is authentic. We measured many parameter of ST such as length, width, height, maximum/minimum width, maximum/minimum

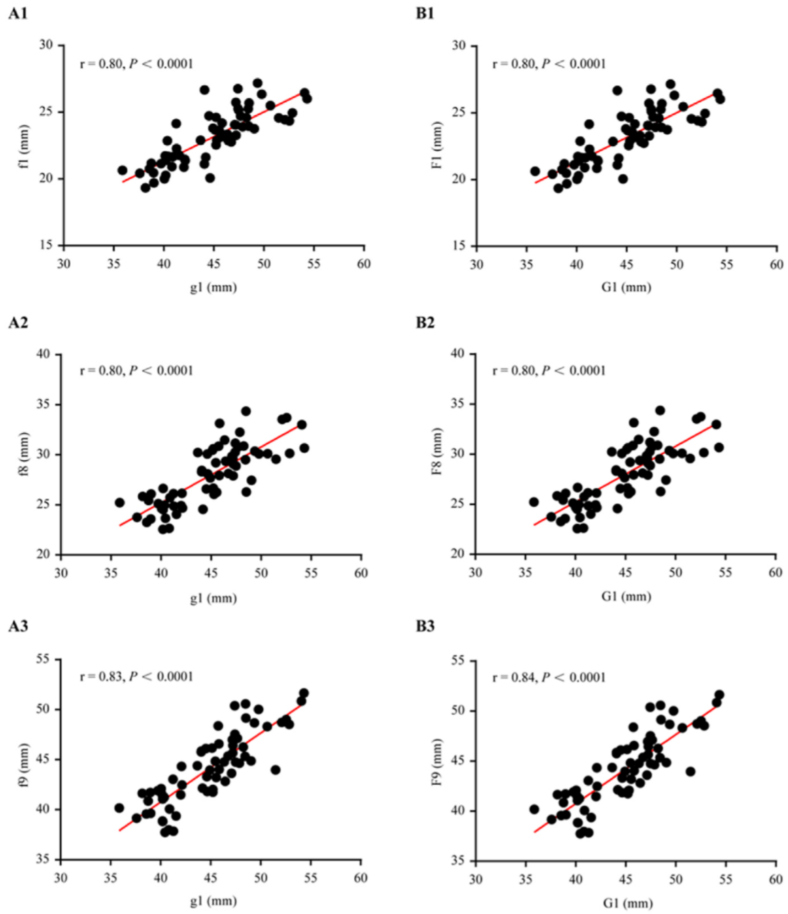

Fig. 6 — Linear Regression Analysis for Sustentacular Screw Length Prediction. A1: Scatter plot illustrating the relationship between the sustentaculum tali screw length (g1) and the sustentaculum tali length (f1) in normal calcanei. A2: Scatter plot showing the correlation between the sustentaculum tali screw length (g1) and the maximum width of the posterior articular surface (f8). A3: Scatter plot depicting the link between the sustentaculum tali screw length (g1) and the maximum height of the posterior calcaneus (f9). B1: Scatter plot for the predicted sustentaculum tali screw length (G1) versus the sustentaculum tali length (F1) based on CT measurements. B2: Scatter plot for the predicted sustentaculum tali screw length (G1) versus the maximum width of the posterior articular surface (F8) based on CT measurements. B3: Scatter plot for the predicted sustentaculum tali screw length (G1) versus the maximum height of the posterior calcaneus (F9) based on CT measurements.

width of the anterior calcaneus, maximum/minimum width of the posterior part, maximum width of the posterior articular surface, lowest anterior, highest posterior, medial lowest, lateral highest, maximum body height, maximum length of the anterior part, calcaneus body axis length using both CT-based measure and anatomical measure.

The data were analyzed to show that AC screw length and PF screw length was highly correlated the following parameters: f1: ST length; f8: maximum width of the posterior articular surface; f9: maximum height of the posterior calcaneus; for CT-based measure. The AC screw length and PF screw length were highly correlated with the following parameters: f1: ST length; f8: maximum width of the posterior articular surface; f9: maximum height of the posterior calcaneus[8].

The multivariable prediction models were derived for guiding surgeons in the estimation of the AC/PF screw length preoperatively. The multivariable prediction models on the screw length were further verified on its effectiveness and feasibility. Its effectiveness and feasibility were confirmed through the 3D reconstruction images of the experimental screw placement of the predicted models using CT measure. Guo[30] and Shi[31] 3 d printing technology is

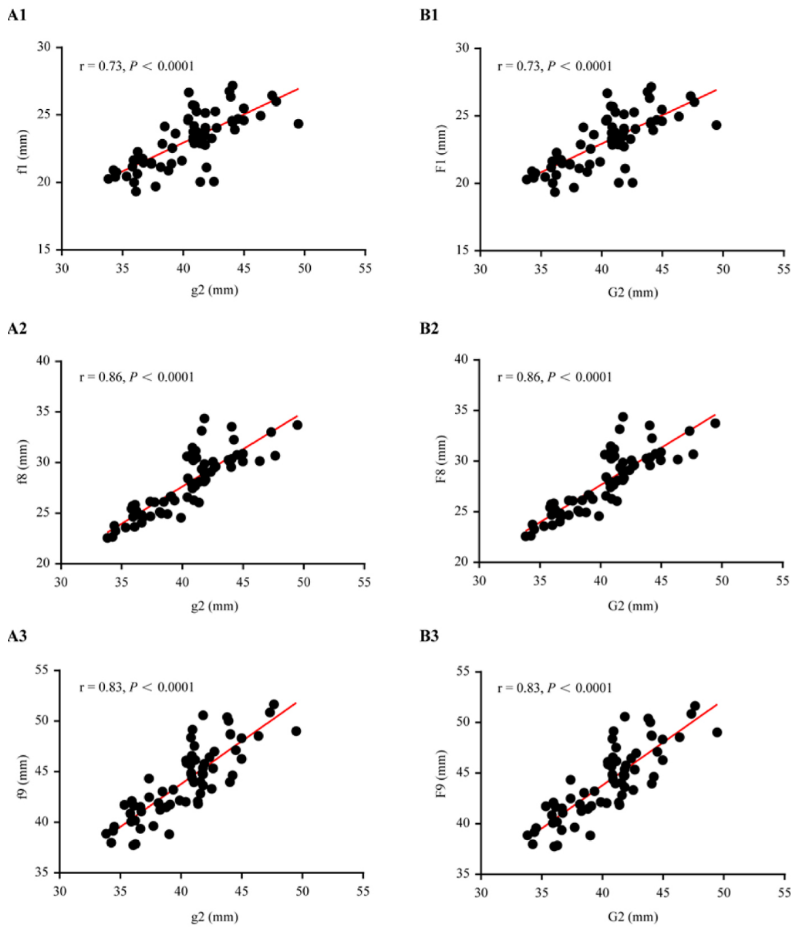

Fig. 7 — Correlation between Anatomical Parameters and Predicted Screw Length (g2 and G2). A1: Scatter plot demonstrating the relationship between the posterior facet screw length (g2) and the sustentaculum tali length (f1) in normal calcanei. A2: Scatter plot correlating the posterior facet screw length (g2) with the maximum width of the posterior articular surface (f8). A3: Scatter plot showing the relationship between the posterior facet screw length (g2) and the maximum height of the posterior calcaneus (f9). B1: Scatter plot for the predicted posterior facet screw length (G2) versus the sustentaculum tali length (F1) based on CT measurements. B2: Scatter plot for the predicted posterior facet screw length (G2) versus the maximum width of the posterior articular surface (F8) based on CT measurements. B3: Scatter plot for the predicted posterior facet screw length (G2) versus the maximum height of the posterior calcaneus (F9) based on CT measurements.

used to determine the calcaneal fractures of the injury, after in surgical treatment, in this study does not need to use under the premise of 3d printing, according to determine the right into the needle point Angle, AC measures corresponding indicators can be directly calculated and the length of the PF nailing.

The study limitation is that the measure was based on unfractured calcanei. The measures might have proved to be different in fractured calcanei. Another limitation is that the complex three-dimensional anatomical shape of the calcaneus may not be entirely captured by the linear parameters used in this study[32,33]. Such shortcomings could be overcome by incorporating 3D measurements on detailed shape models, which can better characterize the intricate morphological features and improve prediction accuracy. The mathematical model provided an effective theoretical basis for the establishment of experimental anatomic measurement and clinical accurate screw placement.

CONCLUSION

The AC/PF screw length can be precisely predicted by the linear regression model. The prediction models for the PA/PF screw length can improve the orthopedic surgeon's precision and limit error and in turn enhance surgical success. In surgical practice, this tool can assist physicians in accurately planning the length and position of screws before surgery, reducing the need for intraoperative adjustments, thereby saving surgical time and enhancing patient safety. To ensure that this tool is widely adopted and has a lasting impact, we will seek partnerships with other research institutions and hospitals to collect additional data to validate and refine our models, and explore new methods such as machine learning to further enhance the accuracy of predictions.

Authors' contributions: Guangsheng Tang and Deguang Wang designed the study and performed the experiments, Bing Wang and Jiangning Sun collected the data, Bing Wang, Jiangning Sun and Yao Xu analyzed the data, Guangsheng Tang and Deguang Wang prepared the manuscript. All authors read and approved the final manuscript.

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Conflict of Interests: The authors declared no conflict of interest.

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