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Defining normative side-to-side differences in the distal tibiofibular joint of healthy individuals using weight-bearing CT 3D image analysis

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ABSTRACT

Background and purpose: Accurate quantification of bony malalignment within the ankle syndesmosis is crucial in diagnosing syndesmotic instability, especially when subtle. While three-dimensional (3D) measurement techniques using weight-bearing computed tomography (WBCT) have gained popularity, normative bilateral comparative data still need to be established. This study aimed to identify the side-to-side variations and gender differences in the syndesmotic area and volume among individuals without syndesmotic injury using WBCT.
Methods: Retrospective analysis was conducted on bilateral ankle WBCT imaging of 88 individuals who underwent imaging for non-ankle-related injury or pathology. Two-dimensional area (at 1, 3, and 5 cm proximal to the tibial plafond) and three-dimensional volumetric (from 0.5 mm proximal to the tibial plafond and up to 3 and 5 cm proximally) measurements were obtained for bilateral ankles. Mean (± SD) values, percentage right-to-left differences, and gender differences were analyzed.
Results: Although there were no significant differences between laterality in any of the measurements, the largest right-to-left difference was 8.9 at the syndesmotic area at 3 cm above the tibial plafond in general. Contrarily, significant gender differences were found in the areas and volumes, with the largest difference observed for the 0.5–5 cm volume (8.41 ± 0.87 vs 7.45 ± 1.47 in male vs female, respectively; P = 0.001).
Conclusion: The mean side-to-site variation in the syndesmotic area and volume among individuals without syndesmotic injury is less than 9 %, and a side-to-side volume difference greater than 19 % might be indicative of abnormality. Additionally, gender-specific differences highlight the importance of considering gender norms in ankle syndesmosis evaluation and the need to use the contralateral side as a comparison.

1. Introduction

The ankle syndesmosis is stabilized by a complex of ligaments, including the anterior inferior tibiofibular ligament, posterior inferior tibiofibular ligament, and the interosseous ligament and membrane [1,2]. The incidence of syndesmotic injury is often intermixed with the incidence of ankle sprains, and it has been reported in up to 25 % of them [3]. Likewise, syndesmotic instability has been described in up to 44 % of patients with ankle fractures having a male predominance, with the highest rate among patients aged 18–34 years [4,5]. Furthermore, it is necessary to distinguish the difference between injury and instability of syndesmosis as the latter requires surgical intervention and is related to an increased risk of chronic pain and ankle joint arthritis.

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Substantial anatomic variation of the osseous component of the distal tibiofibular joint has been widely described. Taser et al. evaluated the morphometric characteristics of the fibular incisura on dry bones [6]. They described that 35 % of the cases showed a concave shape (depth of the fibular incisura ≥4 mm), and 65 % had shallow concave fibular incisura (< 4 mm). Contrarily, Ebraheim et al. demonstrated that 60 % of the fibular incisura were significantly concave, and 40 % were shallowly concave [7]. This variability makes it challenging to establish normal boundaries for the distal tibiofibular joint; arbitrarily assuming that one specific criterion would fit every individual [8].

In a retrospective analysis of subjects with no history of syndesmosis injury, Patel et al. reported that lateral translation of the fibula up to 5.27 mm could be found in individuals in the absence of injury [9]. Additionally, they have described subtle differences in the syndesmosis between genders, with the fibula being more laterally translated and externally rotated in males. Although this study provided valuable information and opened the door for the investigation of syndesmotic variability among individuals, syndesmotic instability represents a three-dimensional (3D) entity in which valuable data can be missed when trying to characterize the displacement by the use of discrete, one-dimensional measurements [10,11]. In this regard, volumetric measurements have recently been proven to provide an accurate alternative in the diagnosis of syndesmotic instability [12,13]. However, normative values and side-to-side differences have not yet been established, obscuring the interpretation of these volumetric measurements in current clinical practice.

The purpose of this study was to identify the side-to-side variations and gender differences in the syndesmotic area and volume among individuals without syndesmotic injury using weight-bearing computed tomography (WBCT). Based on these findings, we aim to determine reference range values for the percentage of side-to-side differences. We hypothesized that the mean normal side-to-side difference in subjects without syndesmosis injury is less than 10 %, and there are no significant gender differences in all these measurements.

2. Materials and methods

2.1. Study population

Approval by the Institutional Review Board at the authors' institution was obtained (IRB No. 2015P000464). A total of 663 patients who underwent CT scans for pathologies unrelated to the ankle were identified. Among them, 210 patients had undergone WBCT up to 5 cm above the tibial plafond. Of these, 88 patients with no prior history of ankle injury, who had confirmed bilateral WBCT scans between 2017 and 2021, were included in this study. Similarly, a group of 88 patients who had undergone bilateral WBCT scans for other reasons, including midfoot or forefoot conditions with otherwise healthy ankle were selected as controls in the final cohort. Inclusion criteria were age ≥ 18 years old and having bilateral WBCT extended ≥ 5 cm proximal to the tibial plafond requested for midfoot and forefoot pathology. Exclusion criteria were having a history of ankle surgery or injury, including ankle sprains or distal tibial fractures extending to the incisura. Weightbearing CT images were obtained using PedCAT™ device (CurveBeam AI, Warrington, PA) with the following image protocol and settings: tube voltage: 120 kV; tube current: 5 mAs; pixel size: 0.37 mm; slice thickness: 0.3 mm

2.2. Measurements methods

Axial CT slices were used for the calculation of all measurements. The area of the syndesmosis was measured at 1, 3, and 5 cm proximal to the tibial plafond with reported Intra-class Correlation Coefficient (ICC) for inter-rater agreement of 0.91 (95 % CI: 0.88–0.92), 0.94 (95 % CI: 0.92–0.96), and 0.93 (95 % CI: 0.91–0.95), respectively. Volumetric measurements were made from 0.5 cm proximal to the tibial plafond up to 3 and 5 cm proximally using the method described by Ashkani-Esfahani et al. with reported ICC for inter-rater agreement of 0.93 (95 % CI: 0.89–0.95), and 0.94 (95 % CI: 0.90–0.96), respectively [13]. The syndesmotic area was defined as the interosseous space between the fibula and the tibia delineated by two tangential lines connecting the anterior and posterior cortices of the tibia and the fibula, respectively (Fig. 1) [14]. The formula for volumetric measurements was ($Volume = T \times \sum_1^n A_n$; where "T" is the thickness of WBCT cross-sections [0.3 mm], where "A" is the area of the syndesmosis in each cross-section, and "n" is the number of measured WBCT cross-sections using axial views) [6]. The absolute side-to-side difference Δ (Delta) in the measured values and the percentage of difference of each side as compared to the contralateral side was calculated as well using the following formula [13]:

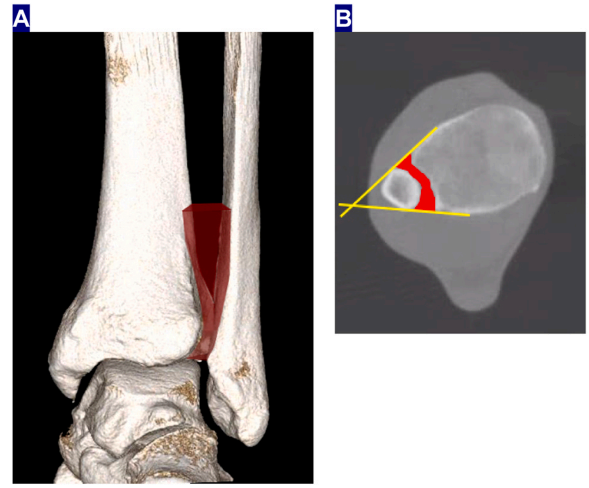

Fig. 1. Weight-bearing CT scan measurements of the volume and area of the distal tibiofibular joint.

$$\Delta \text{ measurement} = |\text{value of the right side} - \text{value of the left side}|$$

$$\textit{Percentage of measurement difference}\,(\%) = \frac{\Delta\text{measurement}}{\text{Average measurement}} \times 100$$

Measurements were performed using Visage™ software (Visage Imaging Inc., Sandiego, CA – version 7).

2.3. Statistical analysis

Descriptive analysis of demographic data was presented as frequencies and percentages for categorical variables and means with standard deviations (SD) or median and interquartile range (IQR) for continuous variables where applicable. Normative ranges for the percentage differences were then defined similarly to previous studies, with normal values defined in a range of the mean ± one SD, "potentially abnormal" values between one to two SD from the mean, and "abnormal" values outside two SD from the mean [9,15]. The Shapiro-Wilk test was used to assess the normal distribution of the demographic data. P value > 0.05 was considered normally distributed. The Chi-square test was used to analyze nominal data (gender) within the group. A one-sample Kolmogorov-Smirnov test was performed to compare the group's numerical data, including age, height, weight, BMI, area, and volume values. An independent sample T-test was used to compare the measurements of the right and left ankles and between genders. All analyses were performed

Table 1
Baseline characteristics of the study population.

Variables	Participants (N = 88)	
Gender*	Female	Male
	67.9 % (n = 60)	32.1 % (n = 28)
Age (years; mean ± SD)	46.95 ± 16.89	45.39 ± 19.48
Weight (kg; mean ± SD)*	75.75 ± 18.49	87.44 ± 20.84
Height (cm; mean ± SD)*	164.96 ± 6.99	174.23 ± 8.24
BMI (kg/m^2; mean ± SD)	27.64 ± 6.07	28.71 ± 5.49

BMI, body mass index; SD, standard deviation
* P-value = 0.09

using Stata 13.0 (Stata Corp LP, College Station, TX), and a p-value < 0.05 was considered statistically significant.

3. Results

The demographic data of the cohort are summarized in Table 1. About two-thirds of the population were female (67.9 % vs. 32.1 %; P = 0.009). There were significant differences between males and females in the area and volumetric measurements, with the largest difference observed for the volume from 0.5 to 5 cm proximal to the tibial plafond (8.41 ± 0.87 vs 7.45 ± 1.47 in male vs female, respectively; P = 0.001). Statistically significant differences between genders were found for all area and volume measurements (Table 2). In contrast, there were no significant differences were found between laterality in any 2D and 3D measurements among the entire cohort. The syndesmotic area at 5 cm proximal to the tibial plafond showed the smallest difference between bilateral sides, with a 6.9 % difference. The volume up to 5 cm proximal to the tibia plafond showed the smallest change, with a 6.5 % difference (Table 3**).** None of these differences in laterality were statistically significant.

4. Discussion

This is one of the largest studies analyzing the normal variation of syndesmosis bilaterally using WBCT [12,14]. Most notably, mean differences between uninjured ankles in subjects without a history of syndesmotic instability never exceeded 9 %. Moreover, the greatest side-to-side difference in the areas was found to be at 3 cm above the tibial plafond, and in the volumes was related to the volume of 0.5–3 cm. These measurements suggested the most sensitive methods for measurement and identifying subtle syndesmotic instability. Potentially abnormal (mean+1 SD) and abnormal (mean +2 SD) values were derived based on these two most sensitive measurement methods. Based on our results, if the percentages of difference of the areas at 1 cm or 3 cm exceed 19 % and 24 %, respectively, they are deemed “abnormal”; moreover, if the volume at 3 and 5 cm exceed 18 %, they should be deemed “abnormal”.

Traditionally, the diagnosis of syndesmotic instability has been supported mainly by plain ankle radiographs. However, syndesmotic instability/malalignment is a multidimensional condition that affects the joint in the coronal, sagittal, and axial planes. The literature has shown the necessity of further imaging that provides detailed, multiplanar information. Conventional CT imaging provides a 3D assessment of bony syndesmotic geometry, which allows for precise evaluation of the syndesmotic alignment [16–18]. Magnetic Resonance Imaging (MRI) also boasts outstanding sensitivity and specificity in diagnosing specific ligamentous damage. However, these imaging modalities do not represent weight-bearing conditions and do not provide bilateral comparisons, potentially underestimating lesion severity. WBCT adds the advantage of a dynamic, physiologic evaluation allowing assessment in the standing position. Patel et al. reported the values of previously described one-dimensional measurements for the diagnosis of syndesmotic injury in 100 healthy individuals with no history of syndesmotic injury using WBCT imaging [9]. The largest side-to-side difference was found at the midpoint distance of the incisura between the fibula and the tibia (3.21 mm vs. 3.29 mm). No significant difference between the right and left ankles was reported in any of the measurements. This study can be considered the starting point to establish reference values of the normal distal tibiofibular joint; however, all the assessed parameters were cross-sectional in one plane only. Unidimensional values leave out a comprehensive evaluation of the syndesmosis, which should be evaluated tree-dimensionally in the coronal, sagittal, and axial planes [19]. Interestingly, they also found significant differences between gender subgroups. More specifically, they showed that the fibulae of men were significantly more externally rotated and more laterally and posteriorly translated. In our study, we were able to assess these gender differences by showing a significantly higher syndesmotic area and volume in men as compared to those in women.

The anatomical variability of the syndesmosis creates a wide range of normal reference values, [20] which makes it much more challenging for the clinician, especially in cases of subtle syndesmotic instability. Patel et al. have found a range of −24.00–6.00 degrees for

Table 2
Absolute values of 2D and 3D weightbearing computed tomography measurements of 88 individuals with uninjured ankle syndesmoses. The mean ± SD of the values are presented.

Variables	Overall	Right	Left	P value†	Male	Female	P value*
Area at 1 cm (cm^2)	0.87 ± 0.27	0.86 ± 0.27	0.87 ± 0.27	0.17	0.97 ± 0.32	0.82 ± 0.22	0.002
Area at 3 cm (cm^2)	1.79 ± 0.38	1.78 ± 0.38	1.80 ± 0.39	0.65	1.98 ± 0.32	1.70 ± 0.38	< 0.001
Area at 5 cm (cm^2)	2.46 ± 0.52	2.43 ± 0.52	2.48 ± 0.53	0.56	2.72 ± 0.44	2.33 ± 0.52	< 0.001
Volume 0.5–3 cm (cm^3)	3.08 ± 0.67	3.09 ± 0.71	3.07 ± 0.63	0.92	3.33 ± 0.54	2.96 ± 0.69	0.004
Volume 0.5–5 cm (cm^3)	7.76 ± 1.38	7.77 ± 1.42	7.77 ± 1.35	0.98	8.41 ± 0.87	7.45 ± 1.47	< 0.001

* Student T-test results

Table 3
Percentage of side-to-side differences for all measurements and derived reference ranges.

Variable	% Difference (Mean ± SD)	Normal reference range*	Potentially abnormal reference range**	Abnormal reference range†
Area at 1 cm	8.2 % ± 5.2	0–13.4 %	13.4–18.6 %	> 18.6 %
Area at 3 cm	8.1 % ± 4.8	0–12.9 %	12.9–17.7 %	> 17.7 %
Area at 5 cm	6.9 % ± 4.7	0–11.6 %	11.6–16.3 %	> 16.3 %
Volume 0.5–3 cm	6.9 % ± 4.3	0–11.2 %	11.2–15.5 %	> 15.5 %
Volume 0.5–5 cm	6.3 % ± 5.0	0–11.3 %	11.3–16.3 %	> 16.3 %

† Defined as > Mean + 2 SD
* Defined as 0 to Mean + 1 SD
** Defined as Mean + 1 SD to Mean + 2 SD

fibular rotation and a range of 1.28–6.89 mm for lateral translation in their cohort of 100 healthy distal tibiofibular joints. [9] Having the contralateral side as a reference narrows down the range of normative values, decreasing the risk of misdiagnosis [21].

The strengths of our study lie in its novel approach to assessing ankle syndesmosis through 3D volume and 2D area measurements, as opposed to the conventional studies on discrete 1D measurements. This study is, to our knowledge, the largest to provide reference values for these measurements. This study offers a practical tool for evaluating the 3D aspect of ankle syndesmosis and using these reference values to differentiate a stable syndesmotic injury from syndesmotic instability. We calculated the right-left percentage difference, which is a straightforward and size-adjusted indicator of abnormal differences. These values enable clinicians to easily compare and interpret the measurements, aiding in diagnosing and managing patients presenting with syndesmotic instability. Additionally, we observed a significant variation between genders, highlighting the importance of considering gender-specific values when assessing ankle syndesmosis. This aspect adds depth to our findings and emphasizes the need for individualized approaches in clinical practice by using the contralateral healthy side as internal control.

Several limitations should be acknowledged. Firstly, the absence of a pathological population (i.e., syndesmotic instability) withholds us from providing a comparison to confirm and validate the observed variations in healthy individuals. Prospective studies should improve upon this by using a matched cohort of patients with syndesmotic instability. Another limitation is the relatively small sample size. While we included 88 individuals (i.e., 166 ankles) in our study, it is important to note that this sample size may not fully represent the entire population. Generalizability may be restricted, and larger studies would be beneficial to confirm and extend our findings. According to a previous study, a minimum of 200 ankles has been shown to present a population-covering sample size [22]. Furthermore, the gender distribution in our study is imbalanced, with a significantly higher number of females as compared to males. This discrepancy may introduce gender-related biases and affect the generalizability of our results to both male and female populations. Future studies should include a more balanced representation of both genders to obtain a comprehensive understanding of the normal values and differences between them. Lastly, our study relied solely on WBCT imaging measurements and did not include additional corroborative imaging techniques (such as ultrasound, MRI, or arthroscopy) to confirm the absence of syndesmotic injury. However, we considered the risk of missed syndesmotic injury to be minimal by limiting the inclusion criteria to those with midfoot and forefoot injuries. Future studies should consider incorporating these imaging techniques to ensure exclusion of syndesmotic injury fully.

5. Conclusions

In this study, to the best of our knowledge, we have established reference values for side-to-side differences in area and volume measurements of the ankle syndesmosis. Mean side-to-side variation among healthy individuals without syndesmotic injury was found to be less than 9 %, and the level found to be most sensitive for differential measurement calculation was 3 cm above the tibial plafond. Results of this study emphasize that the contralateral side provides valuable information as an internal control in suspected syndesmotic instability, and these data strongly suggest that any side-to-side volume difference greater than 19 % is likely to be indicative of instability. Likewise, these results showed a gender-based anatomic variation of the distal tibiofibular joint, and clinicians must consider these differences when suspecting syndesmosis instability.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

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