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Anatomical characteristics and coordinate-based mapping of neurovascular structures within the ankle flexor retinaculum in Vietnamese cadavers

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Abstract

Purpose

This study aimed to characterize the anatomical features of the ankle flexor retinaculum and to provide a coordinate-based mapping of tibial nerve and posterior tibial artery branching points in Vietnamese cadavers.

Methods

A descriptive cadaveric study was conducted on 60 lower leg and foot specimens from Vietnamese adult cadavers preserved in formalin. Anatomical measurements were obtained using calibrated electronic calipers. The branching points of the tibial nerve and posterior tibial artery were mapped using an O–xy Cartesian coordinate system, with the medial malleolus serving as the reference landmark.

Results

The mean length of the medial malleolus–calcaneus axis was 66.3 ± 6.8 mm. Branching within the flexor retinaculum was observed in 76.7% of specimens for the tibial nerve and 100% for the posterior tibial artery. The mean coordinates of tibial nerve branching points were (26.8 ± 8.5; 16.4 ± 11.9), while those of the posterior tibial artery were (36.8 ± 6.1; −2.6 ± 8.6). Significant sex differences were identified in most anatomical measurements ($p < 0.05$). A high-density branching zone was consistently located approximately 25–40 mm distal to the medial malleolus.

Conclusion

This study provides the first coordinate-based mapping of neurovascular branching within the ankle flexor retinaculum in a Vietnamese population. The findings offer clinically relevant anatomical references that may enhance surgical planning, improve the precision of regional anesthesia, and reduce the risk of iatrogenic injury during ankle procedures.

INTRODUCTION

The tarsal tunnel is a complex anatomical structure located posterior and inferior to the medial malleolus and plays an important role in protecting the neurovascular and tendinous structures passing through this region. The ankle flexor retinaculum stabilizes the flexor tendons and helps maintain the functional stability of the ankle joint [7]. This structure consists of strong fibrous bands, typically triangular or trapezoidal in shape [1], extending from the medial aspect of the medial malleolus to the medial surface of the calcaneus, forming the roof of the tarsal tunnel [7]. Beneath the flexor retinaculum run the tibial nerve and its branches, along with the posterior tibial artery and veins, and several flexor

tendons. Tarsal tunnel syndrome occurs when the structures passing through the tarsal tunnel, particularly the tibial nerve and its branches, are compressed by the flexor retinaculum [5, 9]. Clinically, this syndrome presents with pain around the medial malleolus radiating to the plantar foot and heel, accompanied by paresthesia and sensory disturbances in the distribution of the tibial nerve, significantly affecting patients' quality of life [10].

Although surgical decompression of the flexor retinaculum has been demonstrated to be an effective treatment with success rates ranging from 79% to 95% [3, 9, 10], the diagnosis and management of this condition remain challenging. One of the reasons is the complex anatomical structure of the ankle flexor retinaculum, whose superior and inferior boundaries are often difficult to clearly define. Anatomical variations in this region may produce distinct clinical manifestations, requiring detailed anatomical knowledge for accurate diagnosis. In addition, clinical interventions such as calcaneal fracture fixation or surgical procedures involving the ankle joint often require precise anatomical knowledge of the flexor retinaculum and the underlying structures to ensure surgical safety and avoid injury to neural branches. Moreover, heel pain is a common clinical symptom but is often overlooked in practice, which may result in ineffective treatment [10]. These considerations highlight the importance of detailed anatomical investigations of the flexor retinaculum and its associated structures in the ankle region.

In Vietnam, detailed studies on the ankle flexor retinaculum and its related structures remain limited. This lack of data not only poses challenges for clinical application but also restricts the optimization of treatment strategies. However, no previous study has applied a standardized coordinate-based system to map neurovascular branching patterns within the flexor retinaculum in a Southeast Asian population. Therefore, this study was conducted to describe the anatomical characteristics of the ankle flexor retinaculum and its relationship with surrounding structures in Vietnamese adult cadavers.

MATERIALS AND METHODS

Study design and specimens

A descriptive cadaveric study was conducted on 60 lower leg and foot specimens obtained from 30 Vietnamese adult cadavers preserved in formalin at the Department of Anatomy and Embryology, University of Health Sciences – Vietnam National University Ho Chi Minh City, and the Department of Anatomy, Pham Ngoc Thach University of Medicine. Both lower limbs from each cadaver were included. Each limb was treated as an independent anatomical unit for analysis, as commonly performed in cadaveric anatomical studies.

Inclusion and exclusion criteria

Cadavers were included if they were Vietnamese individuals aged 18 years or older, with intact lower leg and foot regions and no prior dissection. Specimens with a history of congenital deformities, trauma, or surgical interventions involving the lower leg or foot were excluded. Cadavers with severe tissue

degradation, fibrosis, adhesions, or decomposition that could interfere with anatomical dissection were also excluded.

Dissection procedure and anatomical measurements

A posteromedial approach to the ankle was employed. The specimens were placed in the supine position, and the medial aspect of the distal leg, ankle, and foot was carefully dissected to preserve the normal anatomical relationships of the medial ankle region.

A longitudinal skin incision was made approximately 8–10 cm proximal to the medial malleolus and extended distally to a point inferior to the medial malleolus. Additional short incisions, nearly perpendicular to the main incision, were created to facilitate reflection of the skin.

The skin was carefully reflected while preserving the superficial fascia, which was subsequently removed to expose the underlying neurovascular structures. Care was taken throughout the procedure to avoid distortion of anatomical relationships.

The flexor retinaculum and surrounding bony landmarks, including the apex of the medial malleolus and the medial aspect of the calcaneus, were clearly identified. The boundaries of the flexor retinaculum were delineated prior to measurement.

Anatomical measurements were obtained using a calibrated electronic caliper. The following parameters were recorded:

- Length of the medial malleolus–calcaneus axis
- Perpendicular distance from the superior border of the flexor retinaculum to the apex of the medial malleolus
- Perpendicular distance from the inferior border of the flexor retinaculum to the apex of the medial malleolus
- Perpendicular distance from the terminal point of the superior border of the flexor retinaculum (at the Achilles tendon region) to the medial malleolus–calcaneus axis
- Perpendicular distance from the terminal point of the inferior border of the flexor retinaculum (at the abductor hallucis muscle) to the medial malleolus–calcaneus axis

All measurements were performed twice by a single experienced anatomist on separate occasions, and the mean values were used for analysis.

Neurovascular assessment and coordinate mapping

After completion of the measurements, the flexor retinaculum was carefully released from its tibial attachment to expose the underlying structures extending into the plantar region. The tibial nerve,

posterior tibial artery, and associated structures were identified.

The presence or absence of branching of the tibial nerve and posterior tibial artery within the flexor retinaculum was recorded. The distances from the branching points of these structures to the apex of the medial malleolus were measured.

To standardize spatial analysis, branching points were mapped using an O–xy Cartesian coordinate system. The origin (O) was defined as the apex of the medial malleolus. The x-axis (Ox) corresponded to the medial malleolus–calcaneus axis, and the y-axis (Oy) was defined as the line passing through the medial malleolus and perpendicular to the x-axis. Coordinates were expressed as A (x, y), where x and y represent perpendicular distances to the respective axes. (Fig. 1)

Statistical analysis

Data were entered, coded, and analyzed using SPSS Statistics version 20.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD), and categorical variables were presented as frequencies and percentages.

Independent t-tests were used to compare anatomical measurements between males and females. Although both limbs from the same cadaver were included, each limb was analyzed as an independent anatomical unit, consistent with common practice in cadaveric anatomical studies. Given that the primary objective was to describe anatomical variation at the limb level, this approach was considered appropriate. Nevertheless, the potential effect of within-cadaver correlation was taken into account when interpreting the results.

A p-value < 0.05 was considered statistically significant.

Ethical considerations

This study was conducted on donated cadavers. The identity and personal information of the specimens were kept confidential and replaced with research codes. Ethical approval was obtained from the Institutional Ethics Committee of Pham Ngoc Thach University of Medicine (Decision No. 1332/TĐHYKPNT-HĐĐĐ).

The authors hereby confirm that every effort was made to comply with all local and international ethical guidelines and laws concerning the use of human cadaveric donors in anatomical research.

RESULTS

A total of 60 lower leg and foot specimens were examined, with an equal distribution between left and right sides. The mean age of the specimens was 67.1 ± 8.4 years, and 60% were male.

Anatomical characteristics of the flexor retinaculum

Table 1
Anatomical measurements of the flexor retinaculum

	Overall (n = 60)	Male (n = 36)	Female (n = 24)	p-value
	Mean ± SD	Mean ± SD	Mean ± SD	
Length of the medial malleolus–calcaneus axis (mm)	66.3 ± 6.8	68.5 ± 6.8	63.1 ± 5.5	**0.002**
Perpendicular distance from the superior border of the flexor retinaculum to the apex of the medial malleolus (mm)	9.0 ± 3.5	10.0 ± 3.6	7.6 ± 2.7	**0.005**
Perpendicular distance from the inferior border of the flexor retinaculum to the apex of the medial malleolus (mm)	12.0 ± 5.3	13.1 ± 5.4	10.3 ± 4.6	**0.036**
Perpendicular distance from the terminal point of the superior border of the flexor retinaculum to the medial malleolus–calcaneus axis (mm)	38.6 ± 9.9	37.8 ± 11.0	39.8 ± 7.9	0.438
Perpendicular distance from the terminal point of the inferior border of the flexor retinaculum to the medial malleolus–calcaneus axis (mm)	32.6 ± 9.2	36.2 ± 7.8	27.2 ± 8.4	**p < 0.001**

The mean length of the medial malleolus–calcaneus axis was 66.3 ± 6.8 mm.

The mean distance from the inferior border of the flexor retinaculum to the apex of the medial malleolus was greater than that from the superior border. In contrast, the mean distance from the superior border of the flexor retinaculum to the medial malleolus–calcaneus axis was greater than that from the inferior border.

Overall, most anatomical measurements were larger in males than in females, with statistically significant differences observed in the majority of parameters.

Relationship between the flexor retinaculum and surrounding neurovascular structures

The tibial nerve branched within the flexor retinaculum in 46 specimens (76.7%), whereas the posterior tibial artery branched within the flexor retinaculum in all specimens (100%).

Table 2
Distances from branching points to the apex of the medial malleolus

	Overall (n = 60)	Male (n = 36)	Female (n = 24)	p-value
	Mean ± SD	Mean ± SD	Mean ± SD	
Tibial nerve (mm)	31.3 ± 10.6	33.0 ± 10.0	28.9 ±11.4	0.160
Posterior tibial artery (mm)	32.2 ± 9.6	33.8 ± 8.6	29.9 ± 10.2	0.130

The mean distances from the branching points of the tibial nerve and posterior tibial artery to the apex of the medial malleolus were 31.3 ± 10.6 mm and 32.2 ± 9.6 mm, respectively. Although these values were higher in males than in females, the differences were not statistically significant.

Coordinate distribution of branching points

Table 3
Mean coordinates of branching points in the O–xy coordinate system

Tibial nerve (mm)	Mean x-coordinate of branching points	Mean y-coordinate of branching points
	26.8 ± 8.5	**16.4 ± 11.9**
Posterior tibial artery (mm)	36.8 ± 6.1	-2.6 ± 8.6

The tibial nerve branching point was located at a mean coordinate of (26.8 ± 8.5, 16.4 ± 11.9), whereas the posterior tibial artery branching point was located at (36.8 ± 6.1, − 2.6 ± 8.6). Compared with the tibial nerve, the posterior tibial artery was located farther along the medial malleolus–calcaneus axis and at a lower vertical position relative to the origin.

The branching points of the tibial nerve and posterior tibial artery were further mapped using the O–xy coordinate system, as illustrated in Fig. 2.

The branching points of the tibial nerve were primarily concentrated within the high-density region, corresponding to approximately 25–35 mm along the medial malleolus–calcaneus axis and 5–25 mm along the perpendicular axis.

Similarly, the branching points of the posterior tibial artery were mainly located at or slightly inferior to the medial malleolus–calcaneus axis, at a distance of approximately 30–40 mm from the apex of the medial malleolus.

DISCUSSION

Anatomical characteristics of the flexor retinaculum

The medial malleolus–calcaneus axis has been widely used as a reference line in anatomical studies of the lower leg and foot, including the classification of tibial nerve branching patterns [8]. However, quantitative data on the length of this axis remain limited. In a study conducted in Thailand, Inthasan et al. [6] reported a mean length of 77.22 ± 5.56 mm, which is greater than the value observed in our study (66.3 ± 6.8 mm). This discrepancy may be explained by multiple factors. First, ethnic and anthropometric differences may contribute to variation in skeletal dimensions. Second, the relatively high mean age of our specimens may have influenced anatomical measurements due to age-related changes or potential tissue shrinkage associated with formalin fixation. Third, minor methodological differences in landmark identification may also have contributed to the observed variation. Further studies in diverse populations are required to clarify these differences.

Sex-related differences were observed in most anatomical parameters, with males demonstrating larger measurements than females. This finding is consistent with general anatomical principles, as males typically have larger skeletal dimensions, which may result in a longer medial malleolus–calcaneus axis and greater associated distances.

Regarding the anatomical extent of the tarsal tunnel, previous studies have suggested that this structure extends approximately 1–2 cm proximal and distal to the medial malleolus–calcaneus axis [2, 4]. In the present study, the superior and inferior borders of the flexor retinaculum were located at relatively considerable distances from both the medial malleolus and the reference axis, suggesting that the flexor retinaculum may cover the entire tarsal tunnel region.

Relationship between the flexor retinaculum and surrounding neurovascular structures

Branching pattern of the tibial nerve

To date, most studies have focused on the branching of the tibial nerve within the tarsal tunnel rather than within the flexor retinaculum itself. Previous reports, including those by Havel et al. [4] and Bilge et al. [2], have demonstrated that tibial nerve branching occurs within or at the level of the tarsal tunnel in approximately 84–93% of cases.

In our study, 76.7% of tibial nerves branched within the flexor retinaculum, which is consistent with the general trend reported in the literature. Differences in reported rates may be attributed to variations in anatomical definitions, as our study defined branching relative to the flexor retinaculum (the roof of the tarsal tunnel), whereas other studies focused on the tarsal tunnel itself. In addition, population differences and methodological variations, including cadaveric dissection versus imaging-based studies, may also contribute to these discrepancies.

Notably, in 23.3% of cases, the tibial nerve branched proximal to the flexor retinaculum. This finding has important clinical implications. When branching occurs proximally, terminal branches may be exposed before entering the typical ankle region, thereby increasing the risk of iatrogenic injury during procedures

such as regional anesthesia, tarsal tunnel release, or endoscopic surgery. Conversely, when branching occurs within the tarsal tunnel, multiple nerve branches may be compressed simultaneously, potentially resulting in more complex clinical manifestations. These findings highlight the importance of individualized preoperative assessment, rather than relying solely on population-based averages.

Branching pattern of the posterior tibial artery

The posterior tibial artery demonstrated branching within the flexor retinaculum in all specimens (100%). This finding is consistent with the general anatomical understanding that the posterior tibial artery typically divides into medial and lateral plantar arteries near the level of the medial malleolus.

Yang et al. [11] reported that 71.7% of posterior tibial arteries branched around the medial malleolus–calcaneus axis, approximately 1 cm distal to this axis. The higher proportion observed in our study may reflect differences in the definition of the flexor retinaculum boundaries or variations in anatomical interpretation.

The mean distance from the branching point of the posterior tibial artery to the apex of the medial malleolus (32.2 ± 9.6 mm) was comparable to that reported by Kim et al. [8] (30.69 ± 4.11 mm), suggesting relative consistency of this anatomical parameter across different populations, despite some variability.

Quantitative coordinate mapping of neurovascular structures

A key strength of this study is the application of a standardized O–xy coordinate system to describe the spatial distribution of neurovascular branching points relative to consistent anatomical landmarks. Compared with traditional linear measurements, this approach allows for a more precise and reproducible characterization of anatomical variability. Importantly, the identification of a concentrated branching zone for the tibial nerve provides a practical anatomical reference that may assist in clinical decision-making. The coordinate-based approach also facilitates comparison across studies and populations, thereby enhancing the reproducibility and applicability of anatomical data.

The identification of a high-density branching zone for the tibial nerve approximately 25–40 mm distal to the medial malleolus may help guide surgical incision planning for tarsal tunnel decompression. Surgeons may consider initiating the incision slightly proximal to this region to account for proximal branching variations.

Another study by Rodríguez-Merchán and Moracia-Ochagavía [9] described the surgical approach for tibial nerve exploration as being located approximately 15 mm posterior to the apex of the medial malleolus. In contrast, both the present findings and those of Kim et al. [8] suggest that the site of tibial nerve decompression may be located further from this landmark. This discrepancy may reflect ethnic and anthropometric variation, as well as differences in anatomical reference points. Clinically, this

highlights that the direct application of anatomical data derived from other populations may not always be appropriate for Vietnamese patients and may lead to suboptimal surgical planning.

Study limitations

This study has several limitations. First, the relatively high mean age of the specimens may have influenced anatomical measurements due to age-related changes or formalin fixation effects. Second, both lower limbs from the same cadaver were included in the analysis, which may introduce a degree of non-independence between observations. As bilateral anatomical structures may share similar characteristics within the same individual, this could potentially affect statistical comparisons. However, given the primary descriptive and exploratory nature of this study, the impact of this limitation on the overall findings is likely limited. Third, the study did not explore detailed variations in branching patterns or subtypes of neurovascular structures. Fourth, imaging modalities such as ultrasound, radiography, or magnetic resonance imaging were not incorporated for validation of the anatomical findings. Finally, the results may be specific to the Vietnamese population, and further studies in other ethnic groups are needed to enhance generalizability.

CONCLUSION

This study provides a quantitative anatomical characterization of the ankle flexor retinaculum and introduces a standardized coordinate-based approach for mapping neurovascular branching patterns. The identification of a consistent high-density branching zone may support surgical planning and improve the safety of ankle procedures. Further studies integrating imaging modalities and involving diverse populations are needed to validate these findings and enhance their clinical applicability.

Declarations

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Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Research Ethics Committee of Pham Ngoc Thach University of Medicine (Decision No. 1332/TDHYKPNT-HDDD).

Consent to Participate

This study was conducted on cadaveric specimens obtained from the Department of Anatomy and Embryology, University of Health Sciences – Vietnam National University Ho Chi Minh City, and the Department of Anatomy, Pham Ngoc Thach University of Medicine. All cadavers were donated for educational and research purposes in accordance with Vietnamese regulations on body donation. Informed consent was obtained from donors or their families prior to donation.

Consent to Publish

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are not publicly available due to concerns regarding participant confidentiality but are available from the corresponding author on reasonable request.

Author Contributions

Tuan H.N.A: Project development, Data management, Manuscript writing and editing

Trinh N.P: Project development, Data collection, Data analysis

Van N.T: Manuscript editing, Project administration and supervision

Tuyen L.Q: Manuscript editing, Project administration and supervision

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Figures

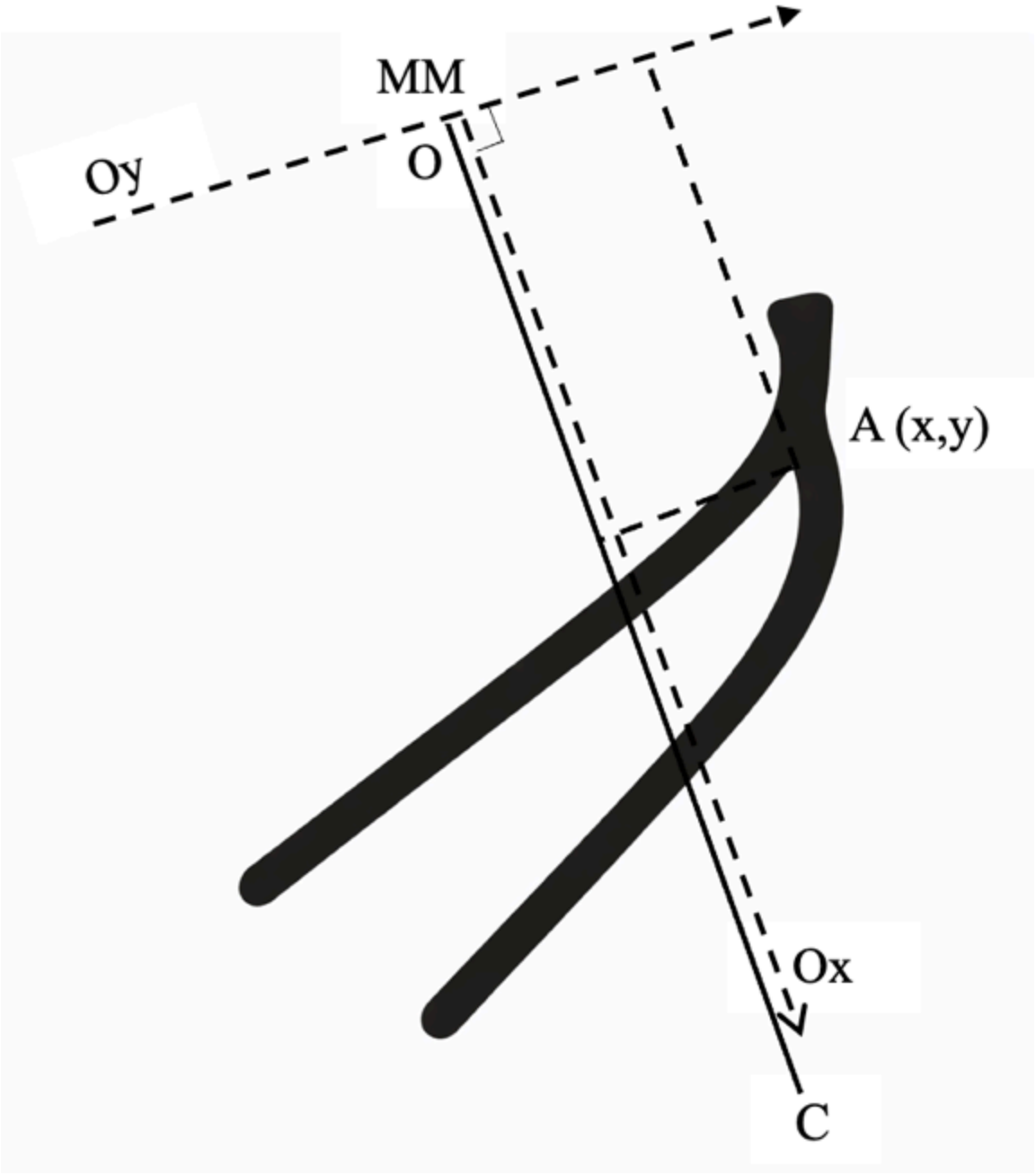


Figure 1

Standardized O–xy coordinate system used to determine the location of neurovascular branching points relative to the medial malleolus (MM) and calcaneus (C)

MM: medial malleolus; C: calcaneus; A: branching points

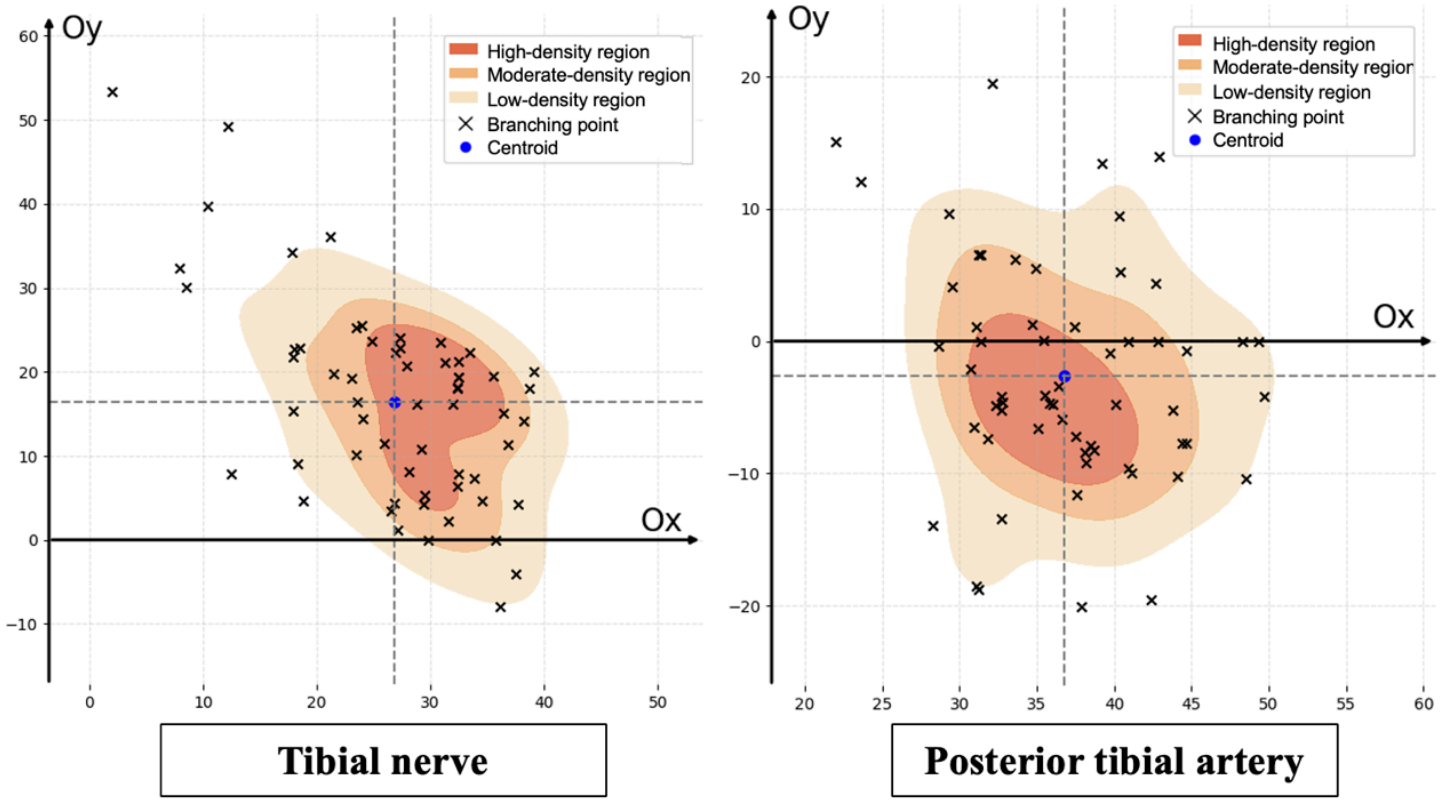


Figure 2

Spatial distribution of tibial nerve and posterior tibial artery branching points in the O–xy coordinate system

Black crosses indicate individual branching points, and blue dots represent the centroids. Shaded regions represent high-, moderate-, and low-density areas