Scholars Journal of Applied Medical Sciences
Abbreviated Key Title: Sch J App Med Sci
ISSN 2347-954X (Print) | ISSN 2320-6691 (Online)
Journal homepage: https://saspublishers.com

OPEN ACCESS

Anatomy

Beyond the Textbook: Morphological Variations of the Soleal Line of the Tibia - A Cadaveric Osteological Study with Clinical Implications

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DOI: https://doi.org/10.36347/sjams.2026.v14i11.008 | **Received:** 05.08.2026 | **Accepted:** 24.09.2026 | **Published:** 16.11.2026

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Abstract | **Original Research Article**

Background: The soleal line is an important anatomical landmark on the posterior surface of the tibia and is closely related to the proximal attachment of the soleus muscle. Although traditionally described as a relatively constant oblique ridge, previous anatomical studies have demonstrated considerable variation in its position, shape, prominence, and extent. ***Method:*** During routine osteological examination and teaching activities in the Department of Anatomy, Adesh Institute of Medical Sciences and Research, Bathinda, Punjab, India, 32 dry tibiae, comprising 17 right-sided and 15 left-sided tibiae, were examined for the morphology of the soleal line. The specimens were assessed for its presence, position, continuity, prominence, and morphological appearance. Most tibiae demonstrated a clearly defined and normally positioned soleal line, while variations included a two-lipped appearance, increased prominence, faint or poorly developed morphology, and complete macroscopic non-identification. Complete macroscopic non-identification of the soleal line was observed in 3 of 32 tibiae (9.38%). ***Conclusion:*** The present observations demonstrate considerable morphological variability of the soleal line, indicating that it should not always be regarded as a sharply defined and consistently positioned bony landmark. Recognition of these variations is relevant to osteological examination, anatomical education, radiological interpretation, and surgical anatomy. However, the morphology of the bony soleal line alone cannot determine the precise pattern of the associated soleus attachment.

Keywords: Soleal line; tibia; soleus muscle; anatomical variation; osteology; posterior compartment; morphological variation.

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INTRODUCTION

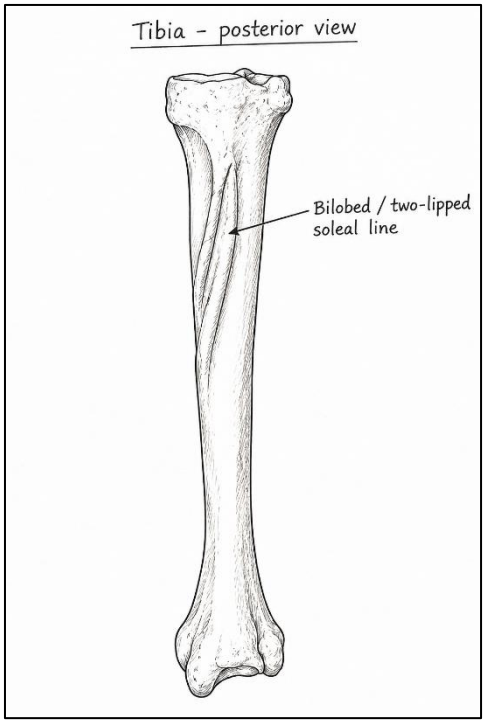
The soleal line, also referred to as the popliteal or soleus line, is an oblique bony ridge situated on the posterior surface of the tibia. Classically, it extends inferomedially from the region of the fibular articular facet towards the medial border of the tibia at approximately the junction of the upper and middle thirds. The region above the line is associated with the origin of the popliteus, whereas the region of the soleal line is closely related to the proximal attachment of the soleus and to the adjacent origins of muscles of the deep posterior compartment, including the flexor digitorum longus and tibialis posterior [1-3].

The soleus is a major component of the triceps surae and is an important plantar flexor and postural muscle. Its proximal attachment is anatomically complex and includes both tibial and fibular components as well as a tendinous arch between the two bones [4-6]. The muscle also has a complex internal architecture, with several aponeurotic and intramuscular tendinous components, which contributes to its important functional role during standing, walking and running [7-9].

The soleus is also clinically important because the calf musculovenous pump contributes substantially to venous return from the lower limb. Cadaveric anatomical studies have demonstrated an extensive venous network within the soleus muscle, emphasizing its contribution to the lower-limb venous pump. [10] Consequently, variations in the anatomy of the soleal line and its proximal attachments may have relevance beyond purely descriptive anatomy.

Although the soleal line is traditionally depicted as a prominent and relatively constant ridge, detailed

osteological examination has demonstrated considerable variation. Mysorekar and Nandedkar examined 330 tibiae and reported that the soleal line frequently differed from the classical textbook description. It could appear as a line, broad line, ridge or groove and was frequently absent in the upper third of the tibia [11].



Variations of the soleus muscle itself have also been reported. These include accessory soleus muscles, additional muscular bellies, multiple heads and unusually extensive fibular origins [12-16]. Such observations indicate that the relationship between the bony morphology of the tibia and the muscular anatomy of the soleus may be more variable than suggested by standard anatomical descriptions.

Despite descriptions of variation in the morphology of the soleal line, relatively limited attention has been given to specimens in which the landmark is faint or macroscopically non-identifiable. Furthermore, the relationship between variation in the bony soleal line and the complex proximal architecture of the soleus remains incompletely understood. Because isolated osteological specimens cannot demonstrate the corresponding soft-tissue attachment directly, careful distinction between absence of a bony landmark and absence of the muscular attachment is necessary.

The present study describes marked variations in the morphology and position of the soleal line, including specimens in which the line was poorly developed or could not be identified.

Materials and Methods

Study Design and Setting

The present study was a descriptive osteological study conducted in the Department of Anatomy, Adesh Institute of Medical Sciences and Research, Bathinda, Punjab. The study involved systematic macroscopic examination of dry tibiae available in the departmental osteological collection for teaching and research purposes.

Specimens

A total of 32 dry tibiae were examined, comprising 17 right-sided and 15 left-sided tibiae. Each specimen was examined individually for the morphology of the soleal line. Specimens with adequate preservation of the posterior surface were included for assessment.

Osteological Examination

The posterior surface of each tibia was examined under adequate illumination with the bone oriented anatomically. The region corresponding to the expected location of the soleal line was inspected visually and assessed by gentle palpation to identify any ridge, groove, or change in surface contour.

The soleal line was assessed with particular attention to its macroscopic identifiability, prominence, configuration, and continuity. Based on the predominant morphological appearance, the specimens were classified into five categories:

1. Normally positioned and clearly defined soleal line
2. Two-lipped soleal line
3. Prominent soleal line
4. Faint or poorly developed soleal line

5. Completely non-identifiable soleal line

A soleal line was considered completely non-identifiable when no discrete ridge, groove, or other recognizable bony landmark corresponding to the expected soleal-line region could be demonstrated on careful visual inspection and palpation.

The findings were recorded separately for right and left tibiae and subsequently summarized for the entire sample.

Data Analysis

The observations were analyzed descriptively. Frequencies and percentages were calculated for each morphological category, both for the total sample and separately for right- and left-sided tibiae. As the study was primarily descriptive and involved a limited number of specimens, no inferential statistical analysis was performed.

Observations

The examination of 32 dry tibiae (17 right and 15 left) demonstrated considerable morphological variation in the appearance of the soleal line.

A clearly defined and normally positioned soleal line was the most common finding, observed in 21 specimens (65.63%), including 11 right tibiae (64.71%) and 10 left tibiae (66.67%). A two-lipped soleal line was observed in 3 specimens (9.38%), with 1 on the right side (5.88%) and 2 on the left side (13.33%).

A prominent soleal line was identified in 3 specimens (9.38%), comprising 2 right tibiae (11.76%) and 1 left tibia (6.67%). In 2 specimens (6.25%), the soleal line was faint or poorly developed, with one specimen on each side. Of particular interest, the soleal line was completely non-identifiable in 3 specimens (9.38%), including 2 right tibiae (11.76%) and 1 left tibia (6.67%). In these specimens, the posterior surface of the tibia appeared relatively smooth in the region where the soleal line would ordinarily be expected.

The morphological variations were observed on both right and left tibiae, although their frequency differed between the two sides. The findings are summarized in Table 1.

No attempt was made to infer the precise muscular attachment solely from the observed bony morphology, as the present study was conducted on isolated dry tibiae.

The findings are summarized in Table 1.

Table 1: Morphological variations of the soleal line in the examined tibiae

Morphological appearance	Right tibiae, n (%)	Left tibiae, n (%)	Total, n (%)
Clearly defined and normally positioned	11 (64.71%)	10 (66.67%)	21 (65.63%)
Having two lips	1 (5.88%)	2 (13.33%)	3 (9.38%)
Prominent	2 (11.76%)	1 (6.67%)	3 (9.38%)
Faint/poorly developed	1 (5.88%)	1 (6.67%)	2 (6.25%)
Completely non-identifiable	2 (11.76%)	1 (6.67%)	3 (9.38%)
Total	**17 (100%)**	**15 (100%)**	**32 (100%)**

The variation was observed on both sides; however, the degree of variation differed between individual specimens. No attempt was made to infer the exact muscular attachment from the bony morphology alone because the present observations were performed on isolated dry tibiae.



Image 1: Posterior view of tibia showing a normally developed soleal line



Image 2: Posterior view of tibia demonstrating a soleal line with two lips



Image 3: Prominent Soleal line



Image 4: Posterior view of tibia demonstrating a faint or poorly developed soleal line



Image 5: Posterior view of tibia demonstrating complete non-identification of the Soleal line

DISCUSSION

The Soleal line is an important anatomical landmark of the posterior tibia, but its morphology appears to be considerably more variable than suggested by conventional textbook illustrations. The most relevant comparison for the present observation is the study by Mysorekar and Nandedkar, who examined 330 tibiae, including 167 left and 163 right tibiae. They reported that the soleal line frequently failed to conform to the classical description. It could begin well below the fibular facet, terminate closer to the middle of the tibia and show different morphological forms, including a line, broad line, ridge or groove. They also observed that the line was frequently absent in the upper third, while in the middle and lower thirds it could appear either as a ridge or depression.[11]

The observations in the present study are consistent with this concept of substantial morphological variability. In our specimens, the soleal line was not uniformly represented as a sharp oblique ridge. Differences in its position, prominence and continuity were observed, and some specimens demonstrated complete macroscopic non-identification. This finding is important because the absence of a visible ridge on an isolated tibia should not automatically be interpreted as an abnormality or developmental defect.

The anatomical significance of the soleal line is largely related to its relationship with the soleus muscle. The soleus has both tibial and fibular origins. The tibial component is traditionally described in relation to the soleal line and medial border of the tibia, while the fibular component arises from the head and proximal part of the fibula. A tendinous arch connects these proximal attachments and overlies important structures of the deep posterior compartment. [4-6]

Importantly, variation in the soleal line may coexist with variation in the soleus itself. Barberini *et al.,* reported an unusual bilateral extension of the fibular origin of the soleus in a 73-year-old female cadaver. In that specimen, the soleus arose from the fibular head, neck and proximal two-thirds of the medial crest of the fibula, demonstrating that the fibular component can be considerably more extensive than the conventional description.[12]

Similarly, additional muscular bellies of the soleus have been reported. Singh *et al.,* described bilateral additional bellies of the soleus muscle and emphasized their anatomical and clinical significance. [13] A cadaveric study of 100 specimens also identified a three-headed soleus muscle consisting of tibial, fibular and intermediate heads. [14] These observations demonstrate that variation in the proximal architecture of the soleus is not restricted to the tibial attachment.

Accessory soleus muscle represents another well-documented variation. It has been described in cadaveric and clinical studies and may arise in relation to the soleal line, posterior tibia, fibula or the deep surface of the soleus [15-19]. Although accessory soleus is anatomically distinct from the present finding, its existence supports the broader concept that the morphology of the soleus and its attachments can vary substantially between individuals.

The possibility that a poorly developed or absent soleal line could be associated with altered distribution of the soleus attachment is therefore anatomically plausible. However, this relationship cannot be established from an isolated dry tibia alone. The present study therefore proposes that the absence of the soleal line may reflect variation in the pattern or degree of development of the associated muscular and fascial attachment, rather than claiming that the soleus must necessarily originate from another specific site.

This distinction is important. The soleus does not depend exclusively on the bony soleal line for its proximal attachment. Its origin involves the posterior fibula, fibular head, medial border of the tibia and the tendinous arch between the tibia and fibula. [4-6] Therefore, an absent bony ridge does not necessarily indicate absence of the tibial component of the soleus attachment.

The functional significance of the soleus also increases the importance of recognizing anatomical variations. The soleus is predominantly involved in plantar flexion and postural control, and its architecture is adapted to sustained force production. Modern imaging studies have demonstrated considerable compartmentalization of the muscle and complex fascicular architecture. [7-9] In addition, the soleus contains an extensive venous network and forms an important component of the calf musculo-venous pump. [10]

Anatomical variation can also be relevant during surgical procedures involving the proximal leg. An unusually extensive fibular origin of the soleus, for example, may alter the surgical field when approaching the proximal fibula and may influence the relationship with the neurovascular structures of the posterior compartment. [12] Similarly, accessory soleus muscles may mimic soft-tissue masses or contribute to exertional pain and neurovascular compression around the ankle. [15-19]

Levine *et al.,* described the prominent soleal line as a normal anatomical variant that may produce a pseudoperiosteal appearance along the posterior aspect of the proximal tibial shaft. Such an appearance can potentially mimic a pathological periosteal reaction on radiographs. The authors noted that this pseudoperiostitis is associated with an otherwise normal underlying bony architecture, helping to distinguish it from true pathological hyperostotic changes [20]. These observation highlights the importance of recognizing variations in the morphology and prominence of the soleal line to avoid misinterpretation during radiological assessment.

The present observation therefore reinforces an important principle in clinical anatomy: the absence of a textbook landmark does not necessarily indicate the absence of the anatomical structure or its associated function. Rather, surrounding bony, muscular, fascial and neurovascular relationships should be considered collectively.

Anatomical interpretation of the observed variations

The morphological diversity observed in the present series may be understood in the context of the complex proximal anatomy of the soleus and its relationship with the posterior tibial surface. The soleal line is not an isolated anatomical structure but represents a surface landmark within a region of multiple muscular, tendinous and fascial relationships. The proximal soleus has both tibial and fibular components, which are connected by a tendinous arch, and its attachment therefore extends across a relatively broad anatomical area rather than being restricted to a single discrete ridge.

The variation from a clearly defined ridge to a broad, prominent, two-lipped, faint or non-identifiable structure may reflect differences in the configuration of this attachment region and the degree to which the underlying cortical surface expresses the associated bony landmark. One possible explanation is that variation in the distribution of musculotendinous attachment and associated mechanical loading may influence the degree of cortical expression of the soleal-line landmark. However, this remains a hypothesis because the corresponding soft tissues and individual biomechanical history were not available for assessment. Differences in mechanical loading and subsequent cortical remodeling may also contribute to variation in the prominence of the landmark. However, these mechanisms remain hypothetical in the present study because the corresponding muscles, tendons and fascial attachments were not available for direct examination.

The presence of a two-lipped soleal line may represent further variation in the contour of the attachment-related region rather than a completely separate anatomical structure. Similarly, a prominent soleal line may represent increased expression of the normal bony landmark. In contrast, the faint and completely non-identifiable patterns observed in the present study demonstrate that the classical sharply defined ridge is not an obligatory feature of every tibia.

Importantly, failure to identify a discrete soleal line should not be equated with absence of the soleus attachment. The proximal origin of the soleus is distributed between the tibia, fibula and intervening tendinous arch, and the bony morphology of the tibia alone cannot establish the exact configuration of the associated musculotendinous attachment. For this reason, the three specimens in which the soleal line was completely non-identifiable macroscopically should be interpreted as demonstrating absence of a recognizable bony landmark rather than proven absence of the anatomical attachment.

From a functional perspective, the broad and complex proximal architecture of the soleus is consistent with its role in sustained plantar flexion and postural control. Its proximal tendinous arch also forms an important anatomical relationship with the neurovascular structures of the deep posterior compartment. Consequently, recognition of variation in the bony morphology of the soleal region may be relevant not only

to osteological identification but also to radiological interpretation and surgical anatomy.

Clinical and Anatomical Significance

The findings of the present report have several implications:

First, the soleal line should not always be considered a sharply defined and consistently positioned landmark during osteological examination.

Second, variation in the soleal line may be important when interpreting radiographs or CT images of the proximal tibia because an apparently absent ridge may represent normal anatomical variation.

Third, knowledge of variation in the soleal line may assist surgeons operating around the posterior proximal tibia and proximal fibula, particularly when the expected muscular attachments are being used as anatomical landmarks.

Fourth, the findings emphasize the need for correlation between bony morphology and soft-tissue anatomy. The morphology of the soleal line alone cannot determine the exact pattern of the soleus origin.

Finally, this observation provides an anatomical basis for further cadaveric studies examining whether the degree of development of the soleal line correlates with the area and pattern of attachment of the soleus muscle.

Limitations

The principal limitation of this report is that the observations were made on isolated tibiae. The corresponding soleus muscles, fascial attachments and tendinous structures were not available for direct correlation. Therefore, the precise relationship between absence of the soleal line and the pattern of soleus origin cannot be established.

In addition, the sex, age and laterality of all individual specimens may not have been available, limiting assessment of demographic associations. Future studies combining osteological examination with cadaveric dissection, morphometry, CT or three-dimensional imaging could determine whether specific patterns of soleal-line morphology correspond to variations in the soleus attachment.

CONCLUSION

The soleal line of the tibia demonstrates considerable morphological variability in its position, continuity, prominence and form. The present observations include specimens in which the line was displaced, poorly developed or completely non-identifiable. These findings support previous anatomical evidence that the soleal line does not invariably conform to the classical textbook description.

Because the soleal line is closely related to the proximal attachment of the soleus and other structures of the posterior leg, recognition of its variability is important in anatomical education, osteological examination, radiological interpretation and surgical anatomy. However, absence of the bony landmark should not by itself be interpreted as absence of the corresponding muscular attachment. Further cadaveric and imaging-based studies are required to determine whether specific patterns of soleal-line morphology are associated with variations in the proximal attachment of the soleus muscle.

DECLARATIONS

Ethical approval

The present report was based on examination of anatomical specimens available in the Department of Anatomy for teaching and research purposes. No living human participants were involved. The study was conducted in accordance with the institutional policies governing the use of human anatomical specimens.

Conflict of interest: The authors declare no conflict of interest.

Funding: No external funding was received for this work.

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