国際医療福祉大学審査学位論文（博士）

大学院医学研究科博士課程

A novel categorization of the muscular branches of the tibial nerve within the popliteal fossa

（邦題：ヒト膝窩部脛骨神経筋枝の新しい分類の提案）

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医学専攻　基礎医学研究分野　解剖学領域

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題目：ヒト膝窩部脛骨神経筋枝における新しい分類

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要旨

目的：本研究の目的は、ヒト膝窩部における脛骨神経の筋枝分岐のパターンとその基本的な法則を明らかにすることである。

対象と方法：対象は、正常人体解剖実習にて使用されたご遺体 31 体 62 肢とした。肉眼解剖学的解析として、脛骨神経本幹からの分岐の方向を記録した。組織学的解析として、軸索の断面積と軸索数を計測した。

結果：腓腹筋内側頭（MH)、腓腹筋外側頭（LH)、ヒラメ筋（So）筋枝は、脛骨神経の後面へ分岐し、足底筋（Pl)、膝窩筋（Po）筋枝は、前面へ分岐した。次に、脛骨神経から LH と So の共通枝として分岐した。組織学的解析では、MH 筋枝よりも LH と So の共通枝が、軸索の断面積、軸索数ともに大きく、LH 筋枝よりも So 筋枝の方が、軸索の断面積、軸索数ともに大きかった。

結語：筋枝分岐の方向によって後方群（MH、LH、So）と前方群（Pl、Po）に分類できた。また、今まで LH の筋枝と表記されていた筋枝は、LH と So の共通枝と表記することが望ましい。

キーワード：筋枝分岐パターン、脛骨神経筋枝、筋枝分岐の順序、解剖学的変異

Title: A novel categorization of the muscular branches of the tibial nerve within the popliteal fossa

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Abstract

Background: The muscular branches of the tibial nerve within the popliteal fossa innervate the gastrocnemius, soleus, plantaris, and popliteus muscles. Various branching patterns have been described in textbooks; however, the underlying fundamental rules explaining the patterns remain unclear. Understanding the fundamental rule explaining the branching pattern of the innervating nerves is essential for understanding the ontogeny of skeletal muscles. Therefore, this study aimed at establishing a theory to explain the branching pattern of the muscular branches of the tibial nerve within the popliteal fossa.

Materials and Methods: The branching patterns of the muscular branches of the tibial nerve within the popliteal fossa were examined macroscopically in 62 lower limbs derived from 31 adult cadavers (22 males and 9 females, aged 49-95 years). The cross-sectional are and total number of axons were examined from 8 samples, which were randomly picked up among 62 lower limbs.

Results: The branch to the medial head of the gastrocnemius muscle invariably arose from the posteromedial side of the tibial nerve. The branches to the soleus muscle and lateral head of the gastrocnemius muscle had a common trunk in all the lower limbs and invariably arose from the posterolateral side. The branches to the plantaris and popliteus muscles arose anteriorly from the tibial nerve in this order (plantaris branch first, followed by the popliteus branch). These branches invariably arose more distally than the branch to both the heads of the gastrocnemius and soleus muscles.

Conclusions: Based on these fundamental branching patterns, we suggest a novel branching categorization. The branches could be categorized into a posterior group and an anterior group, which has independent branches to the plantaris and popliteus muscles. This fundamental branching pattern and novel categorization contribute to the understanding of the ontogeny of the skeletal muscles around the flexor compartment of the leg.

Keywords: Branching pattern, Muscular branches, Branching order, Anatomical variations

Index

1. Introduction

The tibial nerve (TN) has an articular branch (to the posterior knee joint capsule), a cutaneous branch, and muscular branches within the popliteal fossa. The articular branch is the medial inferior genicular nerve, which supplies the medial part of the knee joint capsule. The cutaneous branch is the medial sural cutaneous nerve, which typically descends between the heads of the gastrocnemius muscle, and pierces the crural fascia distally in the popliteal fossa (Pailsen et al., 2011; Standring, 2021). The muscular branches that arise within the popliteal fossa innervate the medial and lateral heads of the gastrocnemius muscle (MH and LH), the soleus muscle (So), plantaris muscle (Pl), and popliteus muscle (Po). We can easily find these branches in many scholarly sources; however, various branching patterns in this region have been described in different anatomy and surgery textbooks (Drake et al., 2015; David and Peter, 2017; Magee, 2013; Netter, 2018; Standring, 2021). More importantly, the rules underlying the choice of these different descriptions of the branching patterns remain unclear. Previous studies have reported variations in the branching pattern of both heads of the gastrocnemius muscle and So (Benjamin et al., 2020; Hwang et al., 2008; Hwang et al., 2003; Prathapamchandra et al., 2019). However, all the descriptions did not include the branches to the Pl and Po. To understand comprehensive ontogeny of the muscles, relationship between the muscular branches within the popliteal fossa must be considered. Moreover, there is still a controversy regarding the origin of the Pl; whether it develops from the deep muscle anlage of the leg (Okamoto et al., 2013) or arises proximal to the So and the tibial side of the LH (Bardeen, 1906; Jin et al., 2017). The knowledge of the common branching order and pattern, with the underlying rule explaining the pattern, may be useful estimator of skeletal muscle grouping (Kudoh and Sakai, 2007) or to understand the ontogeny of the muscles. Furthermore, the knowledge of branching pattern could also be useful for clinical diagnosis and treatment techniques.

Therefore, this study aimed at suggesting a rule for the branching patterns (direction, level, and order) of the muscular branches of the TN within the popliteal fossa.

2. Materials and methods

2.1. Ethical approval

This study was approved by the Research Ethics Review Committee of the International University of Health and Welfare (Approved number: 20-Im-001-02). All donors had agreed to donate their bodies to the International University of Health and Welfare for medical education and research in their living will.

2.2. Materials

The TN (and its branches within the popliteal fossa) of 62 lower limbs obtained from 31 Japanese adult cadavers (22 males, 9 females, aged 49-95 years) were macroscopically examined during routine dissection of cadavers for undergraduate medical school programs at the International University of Health and Welfare. These cadavers were embalmed with 3.7% formaldehyde and 34.0% ethanol. None of the lower limbs revealed any evidence of previous surgical procedures or trauma involving the examined regions. The total number of lower limbs containing both Pl and Po branches was reduced to 47 limbs (obtained from 26 adult cadavers [17 males and 9 females]) due to the absence of the Pl in some limbs and the exclusion of the lower limbs where these branches were destroyed (during the dissection process).

2.3. Procedures of dissection and measurement

The TN and its muscular branches (within the popliteal fossa) alongside the muscles innervated by these branches were displayed by careful dissection and delineation of the surrounding structures. The MH and LH were incised and reflected bilaterally to verify the pattern of the nerve branches to the So, Pl, and Po. These branches were separated manually as proximally as possible. The branching patterns (branching directions, levels, and orders) were manually recorded. The horizontal line connecting the superior border of the medial and lateral condyles of the femur was designated as the baseline level (level 0). The distance between the branches and level 0 was measured using a vernier caliper. The branching levels from the TN proximal and distal to level 0 were indicated as positive and negative, respectively (Fig. 1).

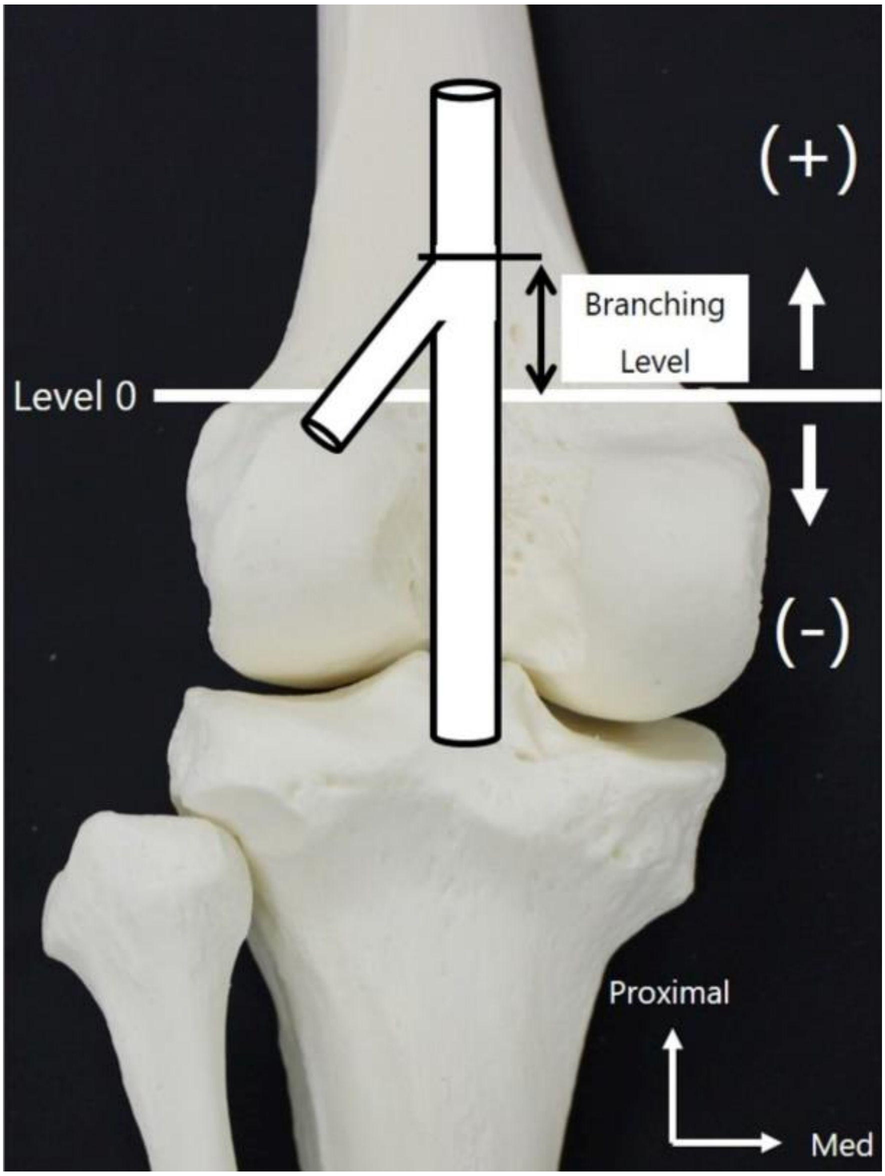

Fig. 1. Measurement of the muscular branches within the popliteal fossa. The photograph is that of the posterior view of the left popliteal fossa. Level 0 is an imaginary line connecting the superior borders of the medial and lateral epicondyles of the femur. The branching levels from the TN proximal and distal to level 0 were indicated as positive and negative, respectively.

2.4. Histological measurements and statistical analyses

Specimens of the branches to the MH, LH, and So, and of the common trunk of the LH and So were randomly collected from eight samples among the 62 lower limbs. The specimens were collected, as proximally as possible, to detect the sizes of the branches and the number of axons. Excised branches were embedded in paraffin and sectioned transversely at a 5-μm thickness, using a microtome (Retoratome REM-710; Yamato Kohki Industrial, Saitama, Japan). The sections were then stained with hematoxylin and eosin, and digital images of the full sections were recorded using a BZ-X810 microscope (KEYENCE, Osaka, Japan). The total cross-sectional area of each nerve bundle was measured, and the number of axons within each nerve bundle was counted from the digital images using the BZ-H4M software (KEYENCE, Osaka, Japan). The mean values of the total cross-sectional areas and the total number of axons, which were measured three times, were calculated and then analyzed using the unpaired *t*-test. The analysis was done between the branch to the MH and common trunk of the LH and So, and the branches to the LH and So. Statistical significance was set at $p < 0.05$. All data were analyzed using the software Free JSTAT for windows version 13.0 (programmed by M. Satoh; Vector Inc., Tokyo, Japan).

3. Results

3.1. Branching patterns of the branches to the MH, LH, and So

A typical branching pattern of the muscular branches of the TN within the popliteal fossa, which were the branches to the MH, LH, So, Pl, and Po, is shown in Fig. 2. The branch to the MH arose from the posteromedial side of the TN (Fig. 2A). The branch to the LH and So arose as a common trunk from the posterolateral side of the TN. The mean branching levels of the branch to the MH and the common trunk of the LH and So were 13.1 ± 17.4 mm and 10.1 ± 19.6 mm, respectively, from level 0.

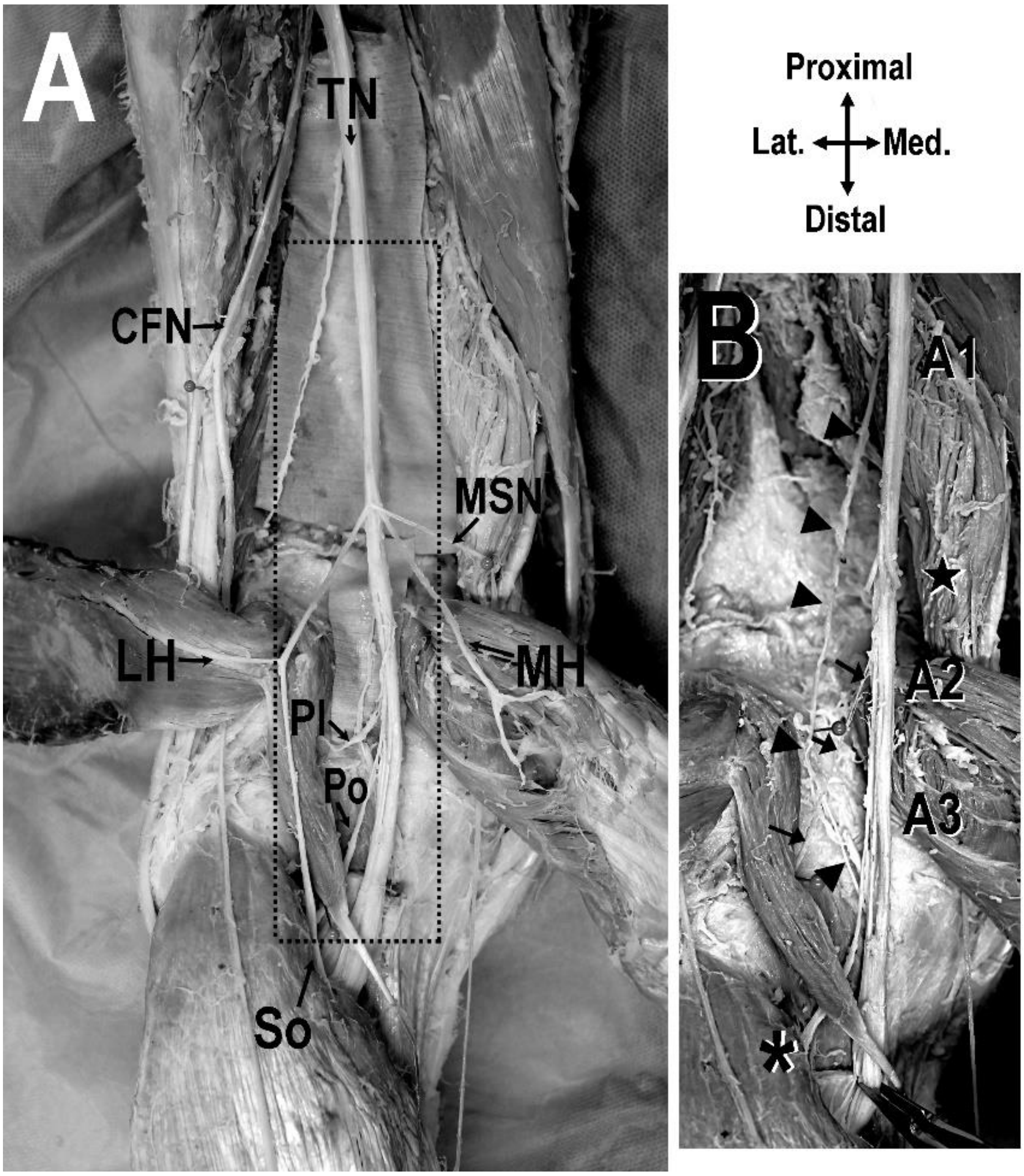

Fig. 2. Posterior view of the tibial nerve in the left popliteal fossa. (A) The medial and lateral heads of the gastrocnemius muscle (MH and LH) were incised and reflected to the medial and lateral sides, respectively. After the tibial nerve (TN) bifurcates with the common fibular nerve (CFN), the TN branches to the medial sural cutaneous nerve (MSN), the medial head of the gastrocnemius muscle (MH), the lateral heads of the gastrocnemius muscle (LH), and the soleus muscle (So). The dotted line in (A) is magnified and photographed from the posterolateral aspect in (B). (B) We observed three major branches which arose anteriorly in the distal popliteal fossa; these were the articular branch (A1 with arrowheads), the branch to the plantaris muscle (Pl) (A2 with arrows), and the branch to the popliteus muscle (Po) (A3 with an asterisk), in the proximal-distal order. These branches were moved laterally using two pairs of tweezers. The star indicates the branching level of the MSN, the branch to the MH, and the branch to the LH and So (B).

The branching patterns of the branch to the MH and the common trunk of the LH and So were classified into three types (Fig. 3). In most of the cases (39 lower limbs [62.9 %]), the branching level of the branch to the MH was equal to that of the common trunk of the LH and So (Type 2). This Type 2 included 20 lower limbs (32.3 %) that had a common trunk to the branch of the MH and to the common trunk of the LH and So. The mean branching level of this common trunk in type 2 was 16.9 ± 17.5 mm. In 21 lower limbs (33.9 %), the branching level of the branch to the MH was located more proximally than the branching level of the common trunk of the LH and So (Type 1). The mean branching levels of the branch to the MH and the common trunk of the LH and So in this type were 6.8 ± 15.7 mm and -2.3 ± 17.7 mm, respectively. In two limbs (3.2 %), the branching level of the branch to the MH was located more distally than the branching level of the common trunk of the LH and So (Type 3). The mean branching levels of the branch to the MH and the common trunk of the LH and So in this type were 3.4 ± 19.3 mm and 7.7 ± 20.0 mm, respectively.

The common trunk of the LH and So could be observed in all the lower limbs. Its mean length, which is the distance between its origin and its bifurcation point to the LH and the So, was 35.1 ± 15.3 mm (Type 2 in Fig. 3).

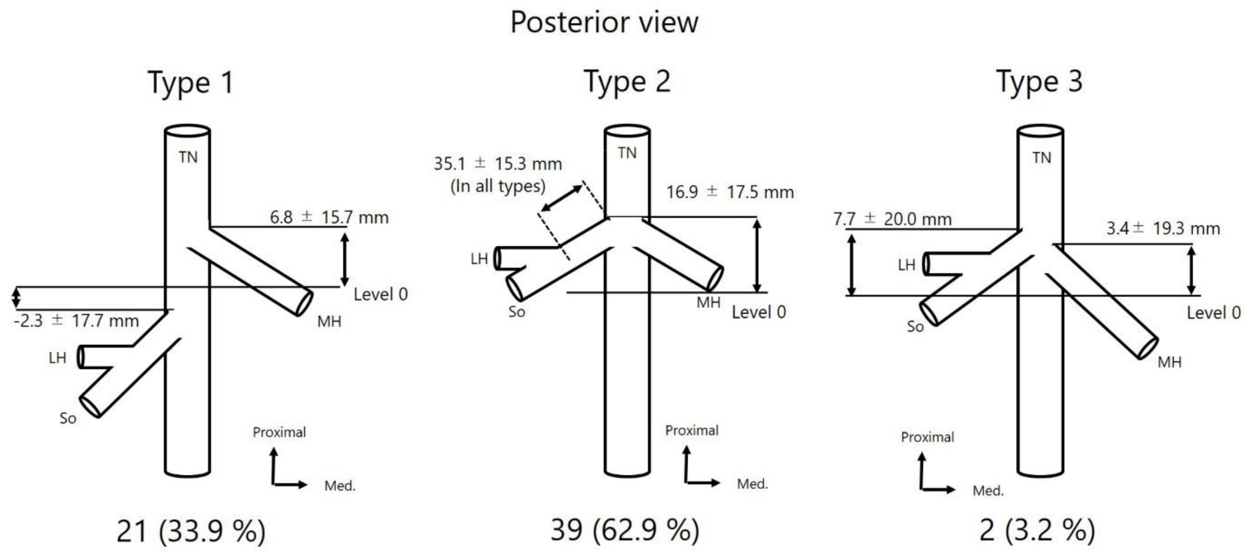

Fig. 3. Branching patterns of the branch to the MH and the common trunk of the LH and So. Based on the branching levels of these branches, the branching patterns of the posterior branches were classified into three types: type 1 (21 lower limbs, 33.9 %) where the branch to the MH is proximal to the common trunk of the LH and So, type 2 (39 lower limbs, 62.9 %) where both arise at the same level, and type 3 (2 limb, 3.2 %) where the common trunk of the LH and So arises proximally to the branch to the MH. The branching levels, equivalent to the length (mm), are indicated as the mean ± standard deviation.

3.2. Histological analyses of the branch to the MH, common trunk of the LH and So, branch to the LH, and branch to the So

Representative microscopic structures of the branch to the MH, the common trunk of the LH and So, and the branches to the LH and So are shown in Fig. 4. The mean cross-sectional area of the branch to the MH and the common trunk of the LH and So were 0.4 ± 0.2 mm^2 and 0.8 ± 0.2 mm^2, respectively (Table 1), and their mean number of axons were 1386.0 ± 118.9 and 2817.5 ± 1026.0, respectively (Table 2). Both the cross-sectional area and number of axons of the common trunk of the LH and So were significantly larger than those of the branch to the MH (p = 0.0011 and 0.0037, respectively). The mean cross-sectional area of the branches to the LH and So were 0.3 ± 0.2 mm^2 and 0.7 ± 0.3 mm^2, respectively and their mean numbers of axons were 767.8 ± 283.2 and 1990.8 ± 689.9, respectively. The branch to the So was significantly larger (p = 0.0051) and contained significantly more axons (p = 0.0012) than the branch to the LH (Tables 1 and 2).

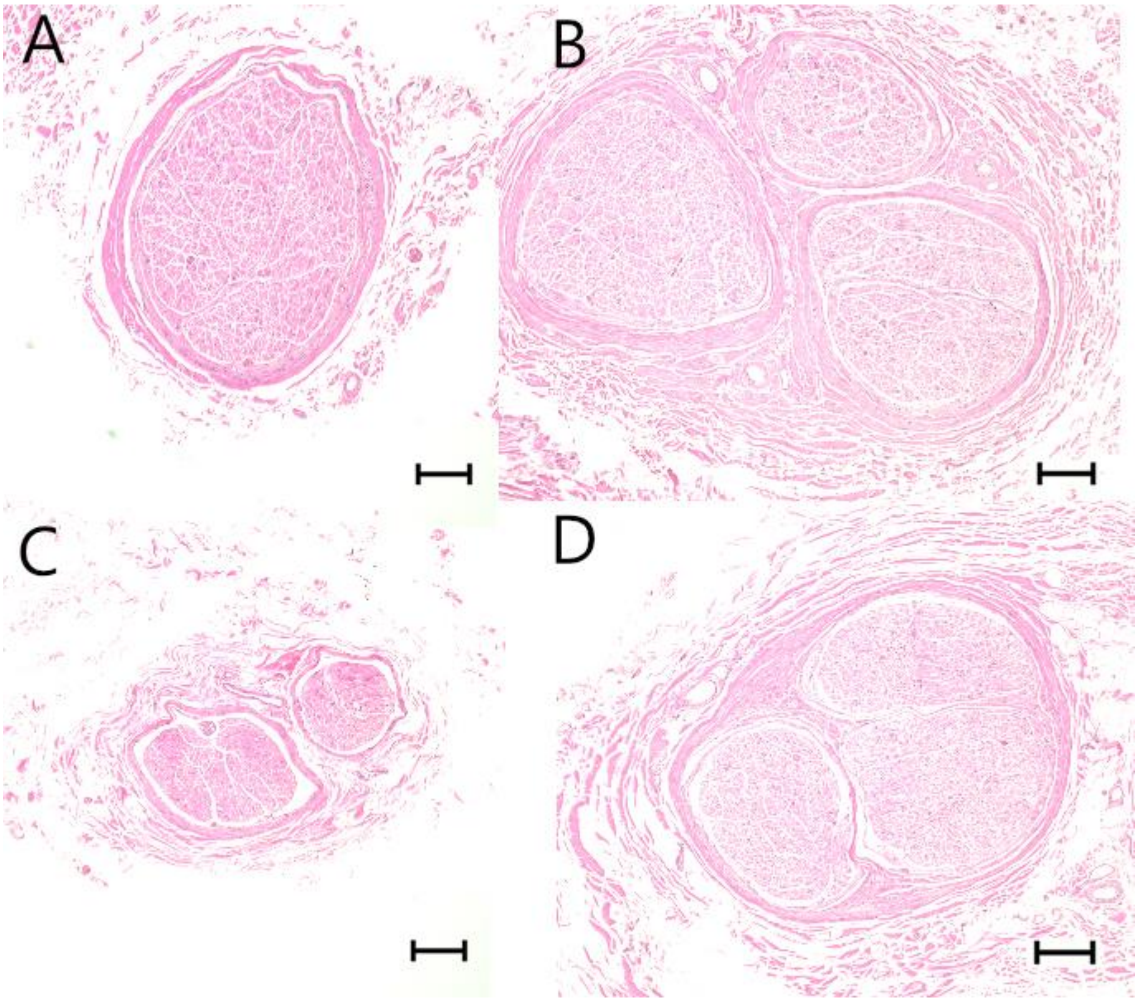

Fig. 4. Cross-section of the posterior muscular branches of the TN. (A) Cross-section of the branch to the MH, (B) Cross-section of the common trunk of the LH and So, (C) Cross-section of the branch to the lateral head of the gastrocnemius muscle (LH), and (D) Cross-section of the branch to the soleus muscle (So). The common trunk of the LH and So is larger than the branch to the MH, and the So branch is larger than the LH branch. The LH and So branches bifurcate from the common trunk of the LH and So. Scale bar = 200 ㎛.

Table. 1. Data of the cross-sectional area of each sample.

	Case 1 M	2 M	3 F	4 F	5 F	6 M	7 M	8 M	Mean ± Standard deviation	p value
The branch to the MH	0.5	0.5	0.7	0.2	0.3	0.2	0.2	0.2	0.4 ± 0.2	* $p = 0.0011$
The common trunk of the LH and So	1.0	0.9	1.2	0.5	0.8	0.9	0.8	0.5	0.8 ± 0.2	
The branch to the lateral head of the gastrocnemius muscle (LH)	0.7	0.3	0.3	0.2	0.2	0.5	0.2	0.2	0.3 ± 0.2	* $p = 0.0051$
The branch to the soleus muscle (So)	1.0	0.7	1.2	0.6	0.4	0.7	0.7	0.4	0.7 ± 0.3	

(Unit: mm^2, *: $p < 0.05$, M: Male, F: Female)

Table. 2. Data of the number of axons in each sample.

	Case 1 M	2 M	3 F	4 F	5 F	6 M	7 M	8 M	Mean ± Standard deviation	p value
The branch to the MH	882	907	4050	976	1312	1561	562	838	1386.0 ± 118. 9	* $p = 0.0037$
The common trunk of the LH and So	2503	1980	3967	1813	3813	2364	4261	1833	2817.5 ± 1026.0	
The branch to the lateral head of the gastrocnemius muscle (LH)	460	538	811	765	765	1339	936	528	767.8 ± 283.2	* $p = 0.0012$
The branch to the soleus muscle (So)	2514	1590	3171	1931	1706	2507	1072	1435	1990.8 ± 689.9	

(*: $p < 0.05$, M: Male, F: Female)

3.3. Branching patterns of the Pl and Po branches

The Pl and Po branches arose anteriorly from the TN (arrows and asterisks in Fig. 2B). The branch to the Po extended anteriorly and laterally from the TN and passed under the Pl on its anterior side. There is also a sensory articular branch within the popliteal fossa (the inferomedial genicular nerve) that branches anteriorly from the TN, at the most proximal part of the popliteal fossa, and descends along the superior border of the Po towards the articular capsule.

The total number of examined branches to the Pl and Po was reduced to 47 lower limbs because we were unable to identify the Pl branch in 15 lower limbs; the Pl was absent in 11 lower limbs (17.7%) and the branch to the Pl was destroyed during dissection in 4 limbs (6.5%). The limbs with destroyed Pl were excluded because we could not confirm the muscle innervation even though we could observe a stump of the branches to the Pl in the TN. In these lower limbs, the branches to the Po were located more anteriorly and distally than the branches to the MH and the common trunk of the LH and So. The total number of limbs containing the Pl and Po branching patterns was therefore reduced to 47 lower limbs.

The mean Pl and Po branching levels were -19.5 ± 15.2 mm and -35.7 ± 25.1 mm, respectively in the 47 lower limbs. The Pl and Po branching patterns were classified into two types (Fig. 5). In the 39 out of 47 lower limbs (83.0 %), the branches to the Pl and Po arose individually. The level of Pl branch in this type was located more proximally than the branch to the Po, and the mean branching level of the Pl and Po branches were –17.6 ± 14.1 mm and –39.5 ± 25.3 mm, respectively. In 8 out of 47 lower limbs (17.0 %), the branches to the Pl and Po arose from the same level. The mean length of the branching levels in this type was –29.1 ± 16.8 mm. There were no lower limbs in our study where the branching level of the Po branch was located more proximally than that of the Pl branch.

From the mean lengths of the branching levels and the actual branching patterns in all the lower limbs, the most proximal muscular branches of the TN within the popliteal fossa were invariably the branch to the MH and the common trunk of the LH and So, meanwhile the branches to the Pl and Po arose more distally in this order. The branching directions of the branch to the MH and the common trunk of the LH and So were posterior to the TN, and the branches to the Pl and Po arose anteriorly to the TN. The branching directions of the muscular branches of the TN within the popliteal fossa were related to the relative locations of each muscle belly and the TN (except for the branch to the Pl since the belly of the Pl runs parallel to the lateral side of the TN, and its tendon passes posterior to the TN).

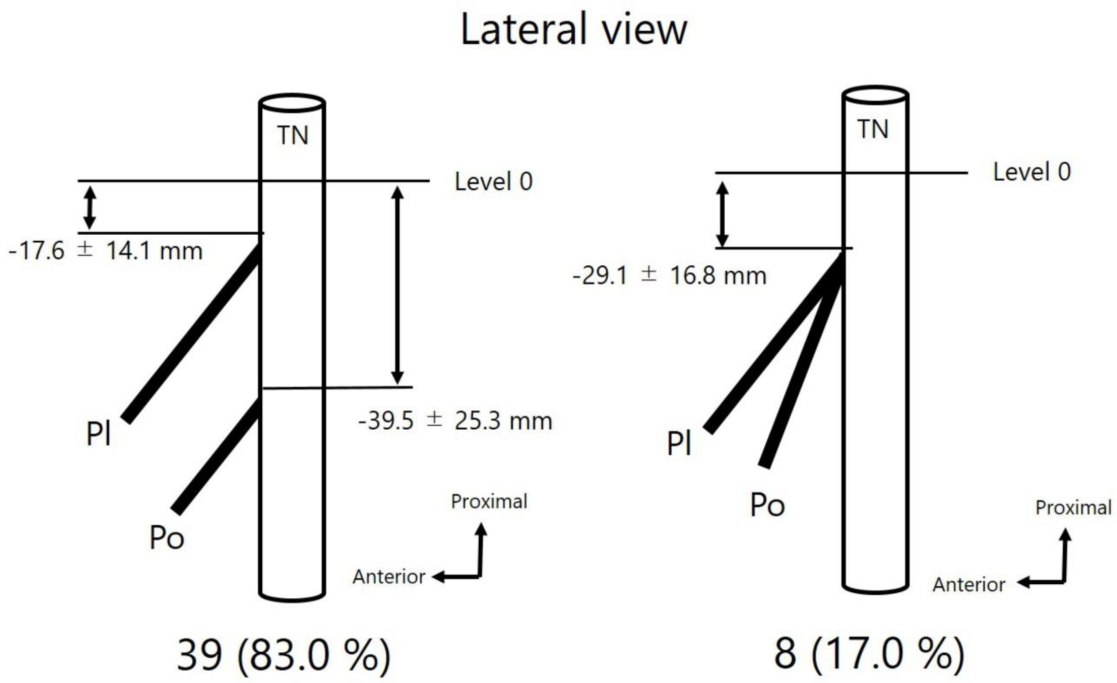

Fig. 5. Branching patterns of the anterior branches. The branching patterns of the anterior branches are classified into two types: the first type where the branches to the plantaris muscle (Pl) and to the popliteus muscle (Po) arise individually in the proximal-distal order (39/47 lower limbs, 83.0 %) and the second type where the Pl and Po branches arise at the same level (8/47 lower limbs, 17.0 %). The branching levels, equivalent to length (mm), are indicated as mean ± standard deviation.

4. Discussion

4.1. A novel categorization of the branches of the TN within the popliteal fossa

In this study, we attempted to re-categorize the branching pattern of the TN within the popliteal fossa. First, we suggest the categorizations of these branches into a posterior group and an anterior group with respect to the branching directions. The branches to both heads of the gastrocnemius muscle (MH and LH) and to the So are included in the posterior group, and the branches to the Pl and Po are included in the anterior group. This classification is reasonable because the nerve branching directions are consistent with the directions of the innervated structures. Similarly in the upper limbs the anterior interosseous nerve arises from the posterior aspect of the median nerve, between the two heads of pronator teres muscle (Standring, 2021). This fact is a reasonable assumption describing our re-categorization.

Second, we attempted to name the posterior group branches; for example, the common trunk of the LH and So. In general, the muscular branches are named after the muscles that they innervate. In fact, in textbooks, the muscular branch to the lateral side within the popliteal fossa is described as the LH branch, and it is said to further give rise to a subbranch that innervates the So. This description has also been applied in earlier studies (Benjamin et al., 2020; Hwang et al., 2003; Hwang et al., 2008; Prathapamchandra et al., 2019). However, from our microscopic observations, the cross-sectional area of the branch to the So was 1.4–4.0 times larger than the branch to the LH (Fig. 4, Table. 1). Therefore, we can conclude that the branch to the So is consistently larger than the branch to the LH. This suggests that the main part of the common trunk of the LH and So is not the branch to the LH but rather the branch to the So. We hereby suggest the "common trunk of the LH and So" as the appropriate term to name this branch. As such, we can say without creating confusion that the common trunk of the LH and So arose from the TN and bifurcated into the branches to the LH and So.

Earlier studies reported that the branch to the So arose from the branch to the common trunk of the LH and So in 10–81% of cases, and the rest of the cases showed a direct branching of the So branch from the TN at more distal level than the LH branch, sometimes more distally than the base line in each study (Benjamin et al., 2020; Hwang et al., 2003; Prathapamchandra et al., 2019). A possible explanation for the difference with our results is the fact that we used different dissection and research methods. The earlier studies were conducted to reveal anatomical structure to guide surgery; the nerve branch to the gastrocnemius muscle was incised since those studies aimed at preserving the branches of the TN almost intact with the perineurium (Benjamin et al., 2020; Hwang et al., 2003; Prathapamchandra et al., 2019). In contrast, our main purpose was to trace the branches more proximally by dissecting the perineurium to reveal the ontogeny of the muscles and their innervations. Our results are consistent with the findings of an earlier study which also reported that the LH and So branches arise from the bifurcation of a common trunk (Okamoto et al., 2013). Another report suggested that the Pl branch was more proximally located than the Po branch (Benjamin et al., 2020);

this agrees with our results since we found that the branching pattern where the Pl branch was proximal to the Po branch was most common (Fig. 5).

4.2. Ontogeny of the Pl

The branching directions in our study can be described using the location of the muscle bellies, except for the branch to the Pl (the Pl belly runs parallel to the lateral side of the TN, and its tendon passes posterior to the TN). This contradiction may be the key to understanding the ontogeny of the Pl, whose origin and development in the human legs are still unclear. In general, there is a consensus that the gastrocnemius and So develop independently from the deeper muscles (the tibialis posterior and flexor digitorum longus muscles) during the developmental stages of the human leg (Jager and Moll, 1951). However, there is still a controversy regarding the origin of the Pl; whether it develops from the deep muscle anlage of the leg (Okamoto et al., 2013) or arises proximal to the So and the tibial side of the LH (Bardeen, 1906; Jin et al., 2017). Numerous variations in the LH, So, and Pl have been reported in cadaver studies (Ishii et al., 2021; Olewnik et al., 2020; Tubbs et al., 2016). The nerve innervation and origin of variations in muscles have been discussed from the perspective of the ontogeny (Ogawa et al., 2005). Variations in muscles are suggested to be caused by the process of the muscle segregation. These variations of the nerve innervation could be used to understand the detailed developmental processes. We have previously reported a third head of the gastrocnemius muscle which resembled to the Pl since it is innervated by the branch to the MH in one of these variations (Ishii et al., 2021). These findings and the present study bring us to hypothesize that the Pl stands near the borderline between the posterior and anterior groups. When the Pl mismigrates posteriorly, it may receive its innervations from the branch to the MH and thus be identified as a third head of the gastrocnemius muscle.

The prevalence of the absence of the Pl has been reported to be 0-19.2% in an earlier study (Yammine et al., 2019). In this study, the Pl was absent in lower limbs that did not have the TN branch to the Pl. The prevalence of absent Pl was 17.7% (11 out of 62 lower limbs), which was not outlier when compared to the earlier study.

4.3. Clinical relevance

Information about the branching pattern and direction of the TN revealed in this study will be useful for the clinical diagnosis and treatment of medical conditions involving the popliteal fossa. For example, the TN and its branches within the popliteal fossa are often injured during knee dislocations secondary to trauma (O'Malley et al., 2016). We can estimate the injury level of the TN using our findings when a paralysis develops in the leg. Also, selective motor blocks and neurotomy of the TN are sometimes attempted to enhance the gait in the spastic foot condition (Buffenoir et al., 2008). Selective neurotomy of the TN has been useful strategy to reduce the size of the calf (Hwang et al., 2003). The branch to the MH has been often transected and effective in this surgery. However, there was a case of iatrogenic complication, which the branch to the So was transected by mistake (Lee et al., 2006). Therefore, a detailed mastery of the topography of the muscular branches, especially the presence of the common trunk of the LH and So, will be essential to prevent iatrogenic neurotomy.

5. Conclusions

In this study, we have suggested a novel categorization of the muscular branches of the TN within the popliteal fossa; that is, to classify these branches into a posterior group and an anterior group based on the branching directions. The posterior group branches innervate the MH, LH and So, meanwhile the anterior group branches innervate the Pl and Po. The anterior and posterior groups are completely segregated. We revealed that the main component of the common trunk to the LH and So is the So branch. To date, this common trunk has been named as "the branch to the LH" (from which a subbranch to the So arises). We propose a new term, "the common trunk of the LH and So".

6. Acknowledgment

The authors wish to sincerely thank those who donated their bodies to science so that anatomical research could be performed. Such research can potentially improve patient care and increase the overall knowledge of humanity. Therefore, these donors and their families deserve the highest gratitude. The authors also thank Ms. Arai for her excellent technical assistance and encouragement.

7. References

Bardeen, C.R., 1906. Development and variation of the nerves and the musculature of the inferior extremity and of the neighboring regions of the trunk in man. Am J Anat 6, 259-390.

Benjamin, W., Pisale, R.V., Premchand, S.A., Indla, E., Ennazhiyil, S.V., Akshara, V.R., L.S, L., 2020. A study of tibial nerve in the popliteal fossa along with its variations in its branching pattern. Acad Anat Int 6, 29-34.

Buffenoir, K., Rigoard, P., Lefaucheur, J.P., Filipetti, P., Decq, P., 2008. Lidocaine hyperselective motor blocks of the triceps surae nerves: role of the soleus versus gastrocnemius on triceps spasticity and predictive value of the soleus motor block on the result of selective tibial neurotomy. Am J Phys Med Rehabil 87, 292-304.

David H, S., Peter C, N., 2017. Plastic Surgery: Volume 4: Trunck and Lower Extremity, 4 ed. Elsevier, London, New York, Oxford, Philadelphia, St Louis, Sydney, pp. 1-52.e51.

Drake, R.L., Vogl, A.W., Mitchell, A.W.M., 2015. Gray's Anatomy for Students, 3 ed. Churchill Livingstone/Elsevier, Philadelphia, pp. 525-670.e528.

Hwang, K., Jin, S., Hwang, J.H., Han, S.H., 2008. Proximity of the common peroneal nerve to the tibial nerve entering the gastrocnemius muscle: the implications for calf reduction. Aesthetic Plast Surg 32, 116-119.

Hwang, K., Kim, Y.J., Chung, I.H., Won, H.S., Tanaka, S., Lee, S.I., 2003. Innervation of calf muscles in relation to calf reduction. Ann Plast Surg 50, 517-522.

Ishii, T., Kawagishi, K., Hayashi, S., Yamada, S., Yoshioka, H., Matsuno, Y., Mori, Y., Kosaka, J., 2021. A bilateral third head of the gastrocnemius which is morphologically similar to the plantaris. Surg Radiol Anat 43, 1095-1098.

Jager, K.W., Moll, J., 1951. The development of the human triceps surae; observations on the ontogenetic formation of muscle architecture and skeletal attachments. J Anat 85, 338-349.

Jin, Z.W., Shibata, S., Abe, H., Jin, Y., Li, X.W., Murakami, G., 2017. A new insight into the fabella at knee: the foetal development and evolution. Folia Morphol (Warsz) 76, 87-93.

Kudoh, H., Sakai, T., 2007. Fascicular analysis at perineurial level of the branching pattern of the human common peroneal nerve. Anat Sci Int 82, 218-226.

Lee, C.J., Park, J.H., Park, S.W., 2006. Compensatory Hypertrophy of Calf Muscles After Selective Neurectomy. Aesthetic Plast Surg 30, 108-112.

Magee, D.J., 2013. Orthopedic physical assessment, 6 ed. Sunders, St. Louis, Missouri, pp. 888-980.

Netter, F.H., 2018. Atlas of Human Anatomy with latin terminology, 7 ed. Elsevier, Philadelphia, pp. 521-593.e511.

Ogawa, K., Yatsunami, M., Irie, Y., Tai, T., Tsujita, N., Tachibana, K., Miyauchi, R., 2005. A morphological study of the human gastrocnemius tertius muscle. Med Bull of Fukuoka Uni 32, 81-88.

O'Malley, M.P., Pareek, A., Reardon, P., Krych, A., Stuart, M.J., Levy, B.A., 2016. Treatment of Peroneal Nerve Injuries in the Multiligament Injured/Dislocated Knee. J Knee Surg 29, 287-292.

Okamoto, K., Wakebe, T., Saiki, K., Tsurumoto, T., 2013. The nerves to the plantaris muscle and a bipennate part of the soleus muscle. Anat Sci Int 88, 17-24.

Olewnik, Ł., Zielinska, N., Paulsen, F., Podgórski, M., Haładaj, R., Karauda, P., Polguj, M., 2020. A proposal for a new classification of soleus muscle morphology. Ann Anat 232, 151584.

Pailsen, F., Waschke, J., Klonisch, T., Hombach-Klonisch, S., 2011. Sobotta Atlas of Human Anatomy, 15 ed. Urban & Fischer, Churchill Livingstone, pp. 243-374.

Prathapamchandra, V., Prabhu, L.V., Pai, M.M., Murlimanju, B.V., Vadgaonkar, R., 2019. Morphological variants of nerve to gastrocnemius muscle, an anatomical guide to perform surgical dissection. Muscles Ligaments Tendons J 09, 119-123.

Standring, S., 2021. Gray's Anatomy: the anatomical basis of clinical practice, 42 ed. Elsevier, Amsterdam, Netherlands, pp. 858-861, 1400-1417.

Tubbs, R.S., Shoja, M.M., Loukas, M., 2016. Bergman's comprehensive encyclopedia of human anatomic variation. John Wiley & Sons, Hoboken, New Jersey.

Yammine, K., Saghie, S., Assi, C., 2019. A Meta-Analysis of the Surgical Availability and Morphology of the Plantaris Tendon. J Hand Surg Asian Pac 24, 208-218.