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ORIGINAL COMMUNICATION

Intramuscular Innervation of the Human Soleus Muscle:
A 3D Model

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The purpose of this study was to document the neural distribution patterns within the human soleus muscle using 3D computer modelling. Through serial dissection, pinning, and digitization, nerve distribution and muscle volume of a human cadaveric soleus muscle were documented and a detailed 3D computer model of neural distribution within the muscle volume was generated. Branching patterns demonstrated divisions that parallel architectural partitions within the soleus; that is, into anterior, posterior, and marginal soleus. Additionally, branching patterns demonstrated further partitioning of the posterior soleus into five distinct regions and the anterior soleus into two regions. Communication between nerve branches of the five regions of posterior soleus and between the anterior and posterior soleus were recorded. Knowledge of these anatomical partitions and their interaction is important as it will aid in the development of functional muscle models and in the understanding of normal and pathological muscle function. Clin. Anat. 16:378–382, 2003. © 2003 Wiley-Liss, Inc.

Key words: nerves; soleus; muscle; modelling; anatomical partitioning

INTRODUCTION

The human soleus is a complex muscle that has three distinct portions: the posterior, anterior, and the marginal soleus (Agur, 2001). Various authors (Brash, 1955; Schultz et al., 1973; Sekiya, 1991) have documented the nerve supply to soleus, as well as the distribution of nerves within the muscle. Two distinct branches that arise from the tibial nerve enter soleus (Brash, 1955; Sekiya, 1991); one branch, the posterior branch, enters the posterior surface of the muscle, whereas the second branch, the anterior branch, enters the anterior surface of the muscle. In these studies, the method used to document the intramuscular distribution of nerves involves dissection, two-dimensional drawings/photographs and written documentation (Brash 1955; Schultz et al., 1973; Sekiya, 1991; Kumar et al., 1998; Segal et al., 1991). Two-dimensional renderings make the interpretation of the results difficult because these descriptions are based on the accuracy of the drawing (Nakajima et al., 1998). Furthermore, two-dimensional models make depth of the nerve branch within the muscle belly difficult to determine. Human muscle is three-dimensional and cannot be fully visualized in two dimensions.

Due to the problems associated with the two-dimensional studies, Nakajima et al. (1998) used a method involving silicone permeation to preserve the intramuscular innervation of the masseter muscle. Using this method the neural branches were preserved, but not the muscle fiber bundles. Therefore, although the extent of the nerves could be seen, their relation to the muscle volume could not be described.

The purpose of this study was two-fold: first, to develop a method that generates 3D models of neural distribution within the volume of soleus; second, to use the model to describe branching patterns within soleus in relation to muscle volume and architecture.

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MATERIALS AND METHODS

For this study, a formalin-fixed cadaveric soleus muscle from the right leg was serially dissected. Pins were inserted along the external surface of the muscle at regular intervals, and the location of each pinhead digitized using a Microscribe 3D-X Digitizer. This generated a contour of the muscle surface. Non-neural tissue was then removed by fine tweezers to expose short segments of nerve, and pins were inserted along the exposed nerve and their locations digitized. Dissection and digitization continued using a dissecting microscope until the nerve could no longer be followed within the specimen. Nerves arising from the posterior branch were digitized separately from those in the anterior branch.

The computer modelling software assigned a number to each individual branch as it was digitized, and a record of communicating branches was kept. A 3D, fully manipulable model of the nerve, in situ, was generated from the digitized data using DANCE software.

Throughout the serial dissection the surface of the soleus muscle was re-digitized. The digitized data from the external surface and the deeper surfaces were combined, and the computer modelling program generated a solid model of the external volume of the muscle from the digitized template by interpolating between the digitized points. Finally, the model of muscle volume was combined with the digitized nerve branches.

RESULTS

3D Model

A 3D model of neural distribution throughout the entire volume of the muscle was generated. This model was manipulable; it could be rotated (Fig. 1) as well as magnified. Branches could be studied individually or in groups. Color coding of the individual branches and their intramuscular distribution aided in clarifying innervation patterns.

Nerve Distribution in Soleus

Nerve entry into soleus. Two independent branches from the tibial nerve entered soleus. The posterior branch proximally entered the posterior soleus in a central position. The anterior branch entered the anterior soleus at its proximal third. For the most part, the branches of the posterior branch remained within the posterior soleus, whereas the branches of the anterior branch remained within the anterior soleus; therefore, the nerves of the posterior soleus could be examined separately from the anterior soleus.

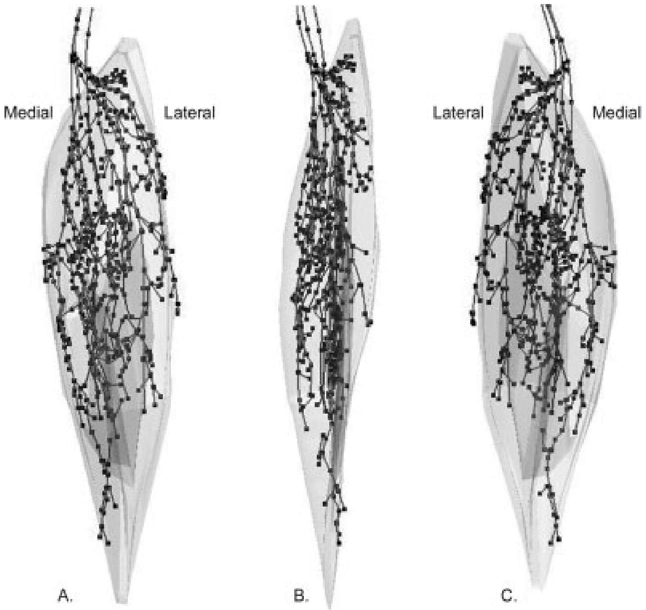

Fig. 1. Views of soleus generated by rotation of the model. **A:** Posterior. **B:** Lateral. **C:** Anterior.

Intramuscular nerve distribution within the posterior soleus. After entering the posterior soleus, the posterior branch divided into five main branches, P-1, P-2, P-3, P-4, and P-5 (Fig. 2). The group of nerves on the lateral side that curved proximally comprised P-1. The P-2 nerve divided into two branches, the more lateral branch distributed its twigs toward the medial side of the muscle, whereas the medial branch distributed its nerves toward both the lateral and medial sides of the muscle. P-3 did not descend as far distally and the nerve ended in the middle third of the muscle. Proximally, its twigs extended toward the lateral part of the muscle, whereas distally, its twigs extended toward the medial side of the muscle. The twigs of P-4 and P-5 supplied the medial and lateral sides of the muscle. The P-5 nerve differed from P-4, however, because twigs of P-5 distributed more anteriorly and posteriorly.

There was not much overlap between the branches (P1–P5), but if overlap did occur it tended to be in the periphery of two neighboring regions. Therefore, when the regions occupied by P1–P5 were shaded, it was found that each of the main branches and its twigs occupied a discrete portion of the muscle volume (Figs. 2,3).

Each of the regions within the posterior soleus was labeled according to the name assigned to the main branch within that region; for example, branch P-1 and its twigs occupied the P-1 region of the muscle. The P-4 and P-5 regions occupied the medial portion of the muscle, whereas the P-1, P-2, and P-3 regions occupied a lateral to central position within the mus-

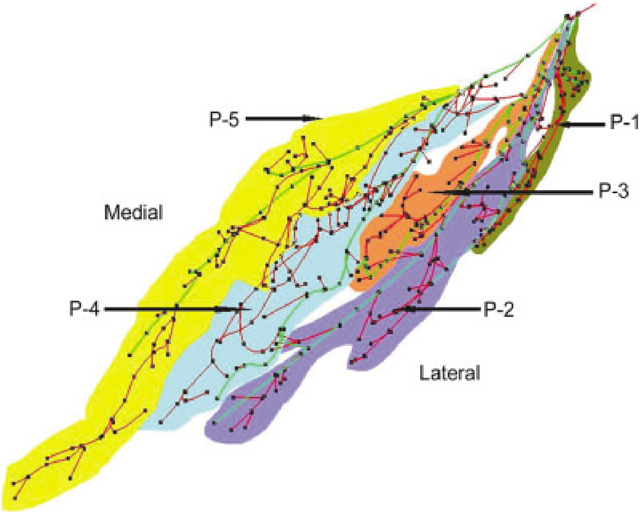

Fig. 2. Innervation of posterior soleus, posterolateral view. Note the innervation by five branches (P1–P5) of the posterior branch of tibial nerve.

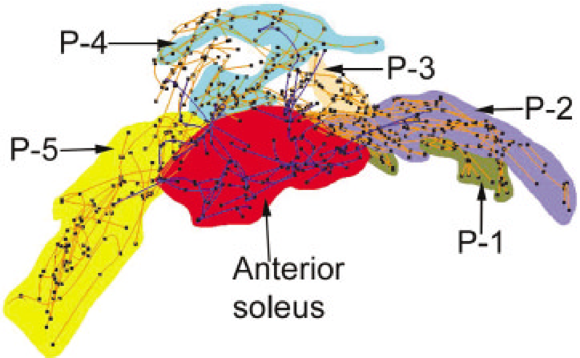

Fig. 3. Subdivisions of anterior (red) and posterior (P1–P5) soleus, superior view.

cle. The P-1 and P-3 regions were located proximally, whereas the P-2 region extended throughout the length of the muscle. P-2 was more prominent distally (Fig. 2).

The regions within posterior soleus were arranged like a jigsaw puzzle; that is, if one of the main branches had twigs extending exclusively in one direction, the side that had no twigs from that branch would be occupied by twigs from a neighboring main branch. For example, proximally, the twigs of P-3 extend laterally; the proximo-medial side of P-3, therefore, was occupied by twigs from the neighboring branch on the medial side (the branch that divides into P-4 and P-5).

Intramuscular nerve distribution within the anterior soleus. The anterior branch divided into two main branches after entering the anterior soleus; one branch supplied the lateral portion of the anterior soleus (i.e., on the lateral side of the median septum), whereas the other branch supplied the medial portion of the anterior soleus (i.e., on the medial side of the median septum). These two branches were named the lateral and medial branches of the anterior soleus, respectively (Fig. 4).

The lateral branch of anterior soleus divided into two further branches; one of the additional branches coursed to an anterior position within the anterior soleus (anterolateral branch), whereas the other coursed to a posterior position (posterolateral branch). The medial branch divided into two additional branches in a similar way (anteromedial and posteromedial branches) (Fig. 4).

In summary, the anterior branch divided into the lateral and medial branches of the anterior soleus, and the lateral and medial branches further divided into the anterolateral, posterolateral, anteromedial and posteromedial branches of the anterior soleus.

Intramuscular nerve distribution within the marginal soleus. There were discrete portions of nerves on both the lateral and medial sides of soleus that branched into the marginal soleus. On the medial side, twigs from P-5 branched into the marginal soleus (Figs. 2,3). On the lateral side, twigs from P-2 gave off branches to the distal part of marginal soleus and a branch from the P-1 region innervated the proximal part.

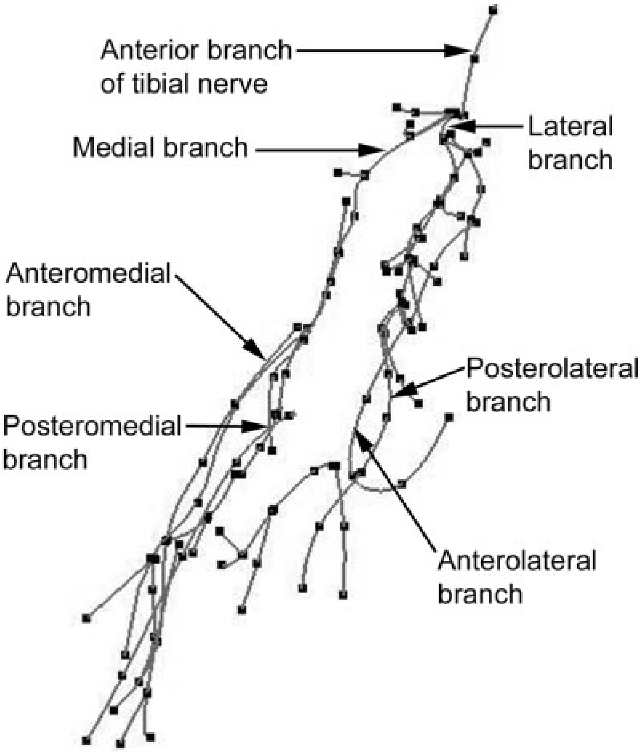

Fig. 4. Innervation of anterior soleus, posterolateral view.

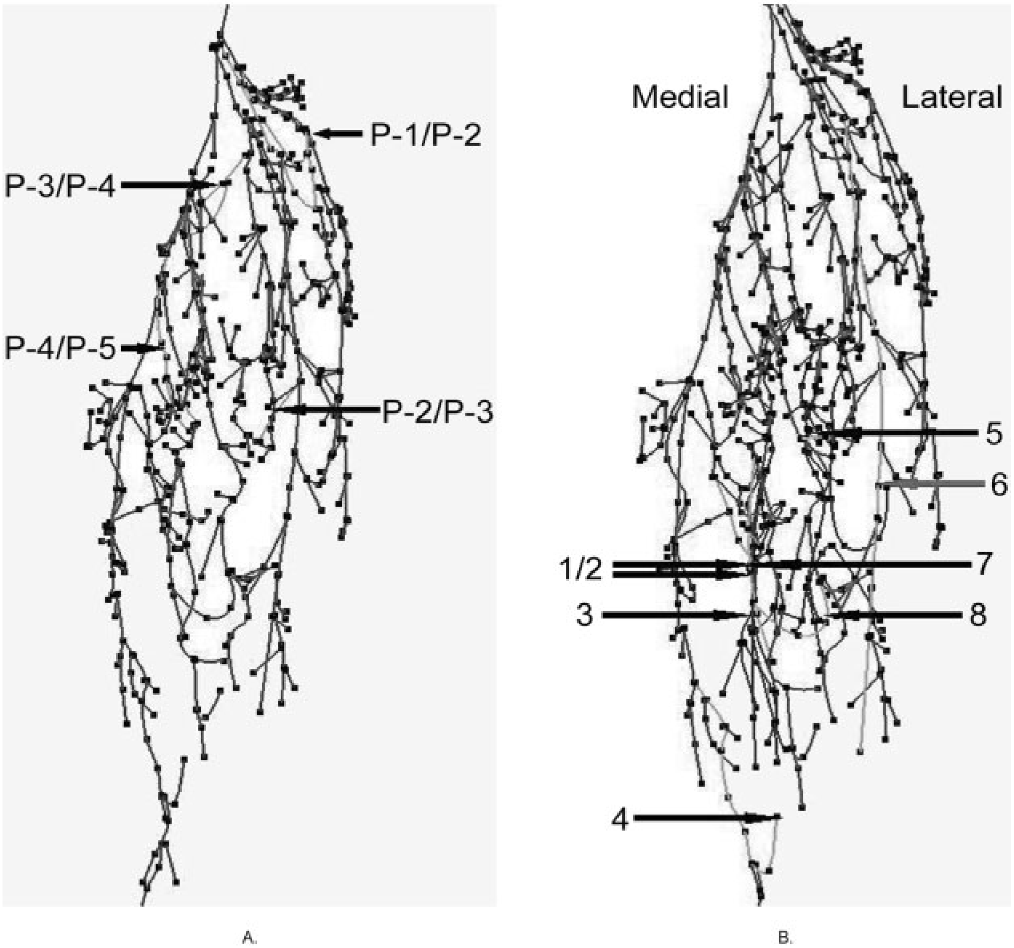

Fig. 5. Communicating branches, posterior views. **A:** Between parts of posterior soleus. **B:** Between anterior and posterior soleus.

Communicating Nerves

Communicating nerves were found between the five regions of the posterior soleus and between the posterior and anterior soleus. In the posterior soleus, communicating nerves occurred between neighboring regions (Fig. 5a). The communicating nerves between the P-1 and P-2 regions and the P-3 and P-4 regions were more proximal than those between the P-4 and P-5 regions and the P-2 and P-3 regions. A double-looped communication was found between P-1 and P-2 (Fig. 5a).

Figure 5b illustrates the locations of communications between the nerves of the posterior and anterior soleus. Seven locations of communication were found between the anterior and posterior nerves. An eighth posterior nerve entered the anterior soleus and appeared to communicate with a nerve in the anterior soleus, but the nerve within the anterior was not found.

With one exception, nerves of the anterior soleus that communicated with a posterior nerve arose from the posteromedial or posterolateral branches. In the exceptional case, a nerve arising from the anterolateral branch communicated with a nerve from posterior soleus. The P-4 nerve had five communications with the nerves of anterior soleus, P-5 two communicating branches, and P-2 one communicating branch. No communicating nerves were found between the two halves of the anterior soleus, which are separated by the median septum.

DISCUSSION

3D Model

The model of neural anatomy generated in this study was advantageous in a number of ways. First, the model was manipulable, and was thus viewable from a variety of perspectives, and the depth of individual nerves within the muscle could be determined. Second, because the nerves could be color-coded, any number of nerves could be viewed simultaneously, and their relative areas of muscle belly innervation visualized. Because individual nerves could be highlighted, location of a nerve within the muscle in relation to other nerves could be determined. Furthermore, any nerve and all of its sub-branches could be followed. Thus, the location within the muscle of an entire group of nerves having a common origin could be observed. Communicating branches could be localized with this technique.

Nerve Distribution in Soleus

Neuromuscular partitions within muscle are determined by architecture, histochemical composition, and nerve branching patterns of a muscle (Segal et al., 1991). Three distinct partitions are evident in soleus by its muscle architecture: the posterior, anterior, and marginal soleus (Agur, 2001). Because there were two distinct points of nerve entry into soleus, and because nerves arising from the posterior branch tended to remain in the posterior soleus and nerves of the anterior branch in anterior soleus, there was congruency of muscle architecture and neural branching patterns. That is, muscle architecture and neural branching patterns demonstrated the same partitions (posterior and anterior soleus) within the muscle.

Nerve branching patterns demonstrated further partitioning of the posterior soleus into five regions. A further partition was found to exist between the lateral and medial halves of anterior soleus. The five regions of posterior soleus were not separated by aponeuroses or septa, whereas the anterior soleus was divided by the median septum.

The subdivisions in posterior and anterior soleus may explain how the soleus functions to maintain balance. The activation of different regions of the muscle at different times may change the direction of the force generated by the muscle depending on the situation. The different partitions within soleus may also explain how the muscle is torn or strained during physical activity; if one or more regions contract at an inappropriate time or with an inappropriate force, the muscle fibers in those regions or neighboring regions may become injured.

Explanations of how the soleus functions, however, are complicated by the existence of communicating nerves between each of the regions. There must not only be an explanation of how each region may function independently, but how it may interact with neighboring regions could also be important.

Communication between the P-1 and P-2 regions was "double-looped" in this study. Sketches by Sekiya (1991) showed a similar looped communication between these regions. Other communicating branches of posterior soleus were linear, not looped. The eight communicating nerves between the posterior and anterior soleus correlates with the number found by Sekiya (1991). Sekiya (1991) found that P-3 and P-5 were chiefly involved in communication with the anterior soleus, whereas P-4, P-5, and P-2 were involved in communication with the anterior soleus in this study. It may be the case, however, that no matter which posterior soleus nerves communicate with the anterior soleus, the posterolateral and posteromedial branches of the anterior soleus are usually involved, rather than the anterolateral and anteromedial branches.

Although this single specimen showed a lack of communication between the two halves of anterior soleus, Sekiya (1991) found that one specimen with two bipennate anterior soleus muscles had communications between the medial and lateral halves unilaterally. He did not report this in the normal bipennate anterior soleus. Hence it is clear that inter-specimen variability is an important consideration. Although various types of anomalous anterior soleus muscles have been reported (Loetzke and Trzenschik, 1969), it has not been possible previously to fully document their 3D innervation patterns throughout the volume of the muscle. Three-dimensional recording techniques could be used to further investigate inter-specimen variability.

A detailed knowledge of the neuromuscular partitions will aid in the development of more realistic muscle models and further understanding of normal and pathological muscle function.

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