



Anatomical Variations of Major Peripheral Nerves and Their Clinical Significance in Surgical Practice

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Abstract

Peripheral nerves exhibit considerable anatomical variability in their origin, course, branching pattern, relationships with adjacent structures, and terminal distribution. Although many of these variations are asymptomatic, they are highly relevant to surgical practice because an unexpected nerve position or branching pattern can increase the risk of iatrogenic nerve injury, incomplete regional anesthesia, inappropriate surgical exposure, and postoperative neurological deficits. Variations involving the median, ulnar, radial, musculocutaneous, sciatic, tibial, common fibular, femoral, and other major peripheral nerves have been documented through cadaveric dissection, imaging, electrophysiological studies, and clinical observations. Common examples include the Martin-Gruber anastomosis, Riche-Cannieu anastomosis, variations in the relationship between the median nerve and brachial artery, high division of the sciatic nerve, variable passage of the common fibular nerve around the fibular head, and accessory or communicating branches of the upper and lower limb nerves. These anatomical differences may significantly influence procedures such as carpal tunnel release, cubital tunnel surgery, vascular reconstruction, tendon transfer, nerve repair, orthopedic fixation, regional nerve blocks, and minimally invasive surgery. Knowledge of peripheral nerve variation is therefore essential for accurate anatomical interpretation, appropriate preoperative planning, safe surgical dissection, and effective postoperative assessment. This review summarizes important anatomical variations of major peripheral nerves and discusses their implications for contemporary surgical practice.

Keywords: Peripheral nerves, anatomical variation, median nerve, ulnar nerve, radial nerve, sciatic nerve, surgical anatomy, nerve injury.

1. Introduction

Peripheral nerves constitute an essential component of the peripheral nervous system, providing motor, sensory, and autonomic communication between the central nervous system and the tissues of the body. Although their general anatomical organization is relatively consistent, substantial individual variation can occur in the origin, course, branching pattern, relationships with adjacent muscles and blood vessels, and terminal distribution of major peripheral nerves [1,2]. These variations are generally considered normal anatomical differences; however, they may become clinically significant when a nerve is encountered during surgical procedures in an unexpected location or when its branching pattern differs from the conventional anatomical description [3]. Knowledge of peripheral nerve anatomy and its variations is particularly important in modern surgical practice because major nerves frequently lie close to bones, joints, blood vessels, muscles, and other structures that are routinely exposed during operative procedures [4].

Variations in nerve anatomy may increase the risk of inadvertent nerve transection, traction injury, compression, or incomplete surgical decompression. Such complications can result in postoperative sensory disturbances, muscle weakness, neuropathic pain, or permanent functional impairment [5]. Therefore, an accurate understanding of both typical and variant nerve anatomy is fundamental to safe surgical dissection and effective management of peripheral nerve injuries.

Several clinically important variations have been described in the upper limb. The median nerve may demonstrate variations in its formation, course, and recurrent motor branch, while communications between the median and ulnar nerves, including the Martin-Gruber and Riche-Cannieu anastomoses, can produce atypical patterns of motor and sensory innervation [6,7]. These variations are particularly relevant during carpal tunnel release, nerve decompression, tendon transfer, reconstructive surgery, and electrodiagnostic assessment. Similarly, variations in the course of the radial and musculocutaneous nerves are important during

surgical approaches to the humerus, elbow, shoulder, and proximal forearm because these nerves may be vulnerable to injury during fracture fixation and soft-tissue procedures [8,9]. In the lower limb, variations of the sciatic nerve have received considerable attention because of their importance in hip surgery, regional anesthesia, intramuscular injections, and the diagnosis of sciatic nerve entrapment syndromes. The sciatic nerve may divide at different levels and may demonstrate variable relationships with the piriformis muscle [10,11]. Variations are also reported in the tibial, common fibular, femoral, obturator, saphenous, and sural nerves, particularly with respect to their branching patterns and relationships with surrounding anatomical structures [12–15]. Such differences may influence the outcome of orthopedic, vascular, reconstructive, and peripheral nerve procedures. The clinical importance of anatomical nerve variation has increased with the widespread adoption of minimally invasive surgery, ultrasound-guided regional anesthesia, and image-assisted interventions. High-resolution ultrasonography and magnetic resonance neurography can provide valuable information regarding nerve morphology, course, branching, and relationships with adjacent structures before or during selected procedures [16,17]. Recognition of anatomical variants may therefore improve preoperative planning, facilitate accurate nerve identification, and reduce the possibility of iatrogenic injury.

2. Anatomical Basis of Peripheral Nerve Variations

The anatomy of peripheral nerves is established through a complex developmental process involving the migration and differentiation of neural tissues, growth of axons, formation of connective tissue sheaths, and interaction with surrounding muscles, blood vessels, and skeletal structures [18]. Although the general arrangement of peripheral nerves follows recognizable anatomical patterns, developmental differences can result in variations in their origin, course, branching, communication, and terminal distribution [19]. Such variations may occur at any level of the peripheral nervous system and can involve both major mixed nerves and smaller motor or sensory branches. Understanding these variations is particularly important because the anatomical position of a nerve may be altered by its relationship with adjacent muscles, fascia, vessels, bones, or other nerves [20].

Peripheral nerve variations can be broadly described according to differences in nerve origin, pathway, branching pattern, communicating branches, and terminal distribution [21]. Variations in origin may involve differences in the roots or fascicles contributing to a nerve, whereas variations in course refer to deviations from the commonly described anatomical pathway. Branching variations may involve early division, delayed division, additional branches, or absence of normally described branches. Communicating branches between nerves may allow motor or sensory fibers to travel through an alternative anatomical route and can therefore produce functional patterns that differ from standard

anatomical descriptions [22]. These variations may remain clinically silent throughout life but can become important following trauma, nerve compression, surgical intervention, or electrodiagnostic examination.

The relationship between nerves and surrounding vascular structures is another important component of anatomical variability. Peripheral nerves may cross arteries, pass between vascular branches, or occupy different positions relative to major vessels than normally expected [23]. Such relationships are particularly important during vascular surgery, orthopedic procedures, catheterization, and surgical exposure of anatomical compartments. Similarly, variations in the relationship between nerves and muscles can influence the risk of injury during muscle release, tendon transfer, decompression, and reconstructive procedures [24]. Consequently, a comprehensive understanding of peripheral nerve anatomy should include both the conventional anatomical pattern and the range of documented variations. From a clinical perspective, anatomical variation should not necessarily be regarded as an abnormality. Many variants represent normal developmental differences and do not produce neurological symptoms [25]. However, their recognition becomes essential when a nerve is exposed during surgery or when neurological findings do not correspond to the expected anatomical distribution. A thorough knowledge of these variations enables clinicians to interpret unusual findings correctly and allows surgeons to adapt their operative techniques according to the anatomy encountered in individual patients.

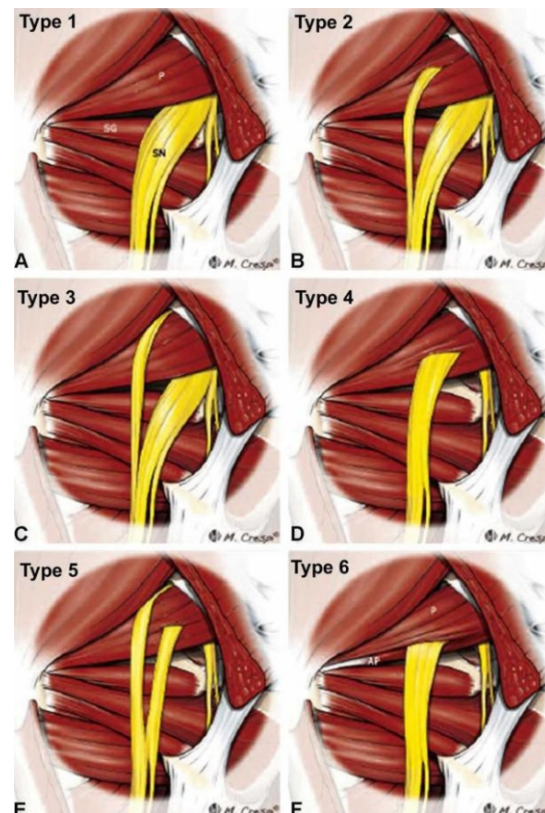


Figure 1: Anatomical overview of major peripheral nerves
[Source adopted from <https://healthjade.net/sciatica/>]

3. Variations of Major Upper-Limb Peripheral Nerves

The peripheral nerves of the upper limb demonstrate considerable anatomical variability, particularly in their formation, course, branching, and communications. The median, ulnar, radial, musculocutaneous, and axillary nerves are frequently involved in surgical procedures and therefore require particular attention. Variations of these nerves may influence the clinical presentation of nerve injuries and have direct implications for procedures involving the shoulder, arm, elbow, forearm, wrist, and hand [26]. Detailed anatomical knowledge is therefore essential for avoiding inadvertent nerve damage and for accurately interpreting postoperative neurological deficits.

The median nerve is normally formed by the union of medial and lateral roots derived from the brachial plexus. However, variations may occur in the level and manner of its formation, its relationship with the brachial artery, and the origin and course of its muscular and cutaneous branches [27]. The recurrent motor branch of the median nerve is particularly variable in its relationship to the transverse carpal ligament. It may pass around the distal margin of the ligament, through the ligament, or follow an atypical course toward the thenar muscles [28]. This variation has substantial clinical significance during carpal tunnel release because accidental injury to the recurrent motor branch can result in weakness of thumb opposition and impaired thenar function. Additional branches of the median nerve may also be encountered during forearm and wrist surgery and should be carefully identified before tissue division.

The median and ulnar nerves may communicate through several anatomically recognized patterns. The Martin-Gruber anastomosis represents a communication between the median nerve or one of its branches and the ulnar nerve in the forearm [29]. Motor fibers crossing through this communication may contribute to muscles that would conventionally be considered predominantly ulnar-innervated. Another important communication is the Riche-Cannieu anastomosis, which occurs in the hand between branches of the median and ulnar nerves and may contribute to variable innervation of the intrinsic muscles of the hand [30]. These communications are clinically important because they can produce unexpected patterns of muscle weakness or preservation following nerve injury and may complicate interpretation of nerve conduction studies. The ulnar nerve is another nerve with considerable anatomical variation. It normally passes posterior to the medial epicondyle and then enters the forearm between the heads of the flexor carpi ulnaris muscle. Variations may occur in its relationship with the medial epicondyle, its muscular branches, and its course through the cubital tunnel [31]. These differences are especially important during surgical treatment of cubital tunnel syndrome and anterior transposition of the ulnar nerve. Failure to recognize anomalous branches or an unusual course may result in incomplete decompression or direct injury to the nerve.

The ulnar nerve also demonstrates variable sensory and motor branching in the hand, which may influence the clinical manifestations of distal ulnar nerve lesions.

The radial nerve travels through the posterior compartment of the arm and is closely associated with the humerus and profunda brachii vessels. Variations in the level of radial nerve division, muscular branches, and the relationship between the nerve and surrounding vascular structures have been documented [32]. These variations are important during surgical procedures involving humeral shaft fractures because the radial nerve may be exposed or manipulated during fracture reduction and fixation. Distally, the deep branch of the radial nerve becomes the posterior interosseous nerve after passing through the supinator, where its anatomical relationship with the proximal radius may vary [33]. Such differences are relevant during radial head surgery, proximal forearm procedures, and decompression of the posterior interosseous nerve. The musculocutaneous nerve normally arises from the lateral cord of the brachial plexus and passes through the coracobrachialis before supplying the anterior compartment muscles of the arm. Variations include communication with the median nerve, unusual entry into the coracobrachialis, and differences in muscular and cutaneous branching [34]. Communication between the musculocutaneous and median nerves may alter the expected distribution of motor fibers and can complicate clinical localization following nerve injury. These variations are particularly relevant during brachial plexus surgery, shoulder procedures, coracoid operations, and approaches to the proximal humerus.

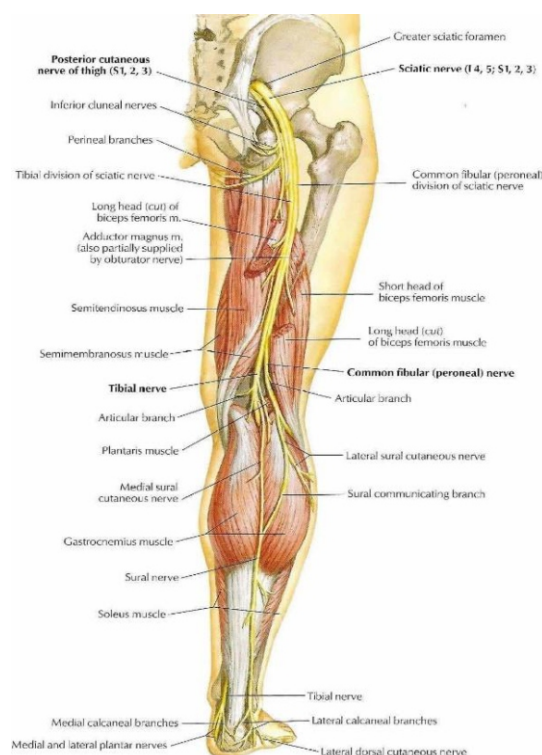


Figure 2: Variations of the median and ulnar nerves Source adopted from <https://www.pinterest.com/pin/375346950174874363/>

4. Median-Ulnar and Other Upper-Limb Nerve Communications

Communications between peripheral nerves represent an important category of anatomical variation because they can create alternative pathways for motor and sensory axons. In the upper limb, communications between the median and ulnar nerves are among the best-documented examples [35]. These connections may occur at different anatomical levels and may involve varying numbers of nerve fibers. Their presence can modify the expected distribution of motor innervation and may explain discrepancies between anatomical examination, clinical findings, and electrodiagnostic studies. The Martin-Gruber anastomosis is one of the most recognized median-ulnar nerve communications. It occurs in the forearm and involves the passage of fibers from the median nerve or its branches toward the ulnar nerve [29]. The communicating branch may arise from the anterior interosseous nerve, median nerve, or other median-derived branches, with considerable variation in its course and destination [36]. Depending on the fibers involved, muscles normally supplied by the ulnar nerve may receive a contribution from median-derived fibers. Consequently, an injury to the median nerve proximal to the communication may produce unexpected weakness of selected ulnar-innervated muscles, whereas an ulnar nerve lesion may show relative preservation of certain motor functions.

The Riche-Cannieu anastomosis represents a distal communication between the median and ulnar nerves within the hand. It commonly occurs in the region of the thenar muscles and deep palm and can provide additional motor innervation to intrinsic hand muscles [30]. The anatomical pattern of this communication varies considerably among individuals. Its presence is clinically relevant because it may influence the severity and distribution of motor deficits following median or ulnar nerve injury. It can also produce unusual findings during electromyography and nerve conduction studies, particularly when clinicians assume that all intrinsic hand muscles have the conventional pattern of innervation [37]. Another recognized communication is the Marinacci communication, which represents a reverse pattern of communication in which fibers pass from the ulnar nerve toward the median nerve in the forearm [38]. Although less frequently discussed than the Martin-Gruber anastomosis, it demonstrates the diversity of peripheral nerve organization and reinforces the importance of considering alternative neural pathways when clinical findings do not conform to expected anatomical patterns. These communications may also influence outcomes following nerve repair, decompression, or reconstructive procedures. From a surgical perspective, identification of nerve communications is important because a communicating branch may be mistaken for a small independent nerve or vascular structure. During nerve decompression or reconstruction, inadvertent division of a communicating branch may alter motor or sensory function.

5. Variations of Major Lower-Limb Peripheral Nerves

The peripheral nerves of the lower limb demonstrate substantial anatomical variation, particularly in their relationships with muscles, bones, and blood vessels. These variations are clinically important because the lower limb is frequently subjected to orthopedic, vascular, reconstructive, and regional anesthetic procedures [39]. The sciatic, tibial, common fibular, femoral, obturator, saphenous, and sural nerves may demonstrate variations in their origin, division, course, and terminal branching. Recognition of these differences is essential for reducing iatrogenic nerve injury and improving the accuracy of regional anesthesia and surgical interventions.

The sciatic nerve is the largest peripheral nerve in the human body and normally exits the pelvis through the greater sciatic foramen below the piriformis muscle. One of the most important anatomical variations concerns the relationship between the sciatic nerve and piriformis [40]. The nerve may pass completely below the piriformis, pass through the muscle, or demonstrate separate relationships involving its tibial and common fibular components [41]. Such variations have been associated with differences in the potential sites of nerve compression and are particularly important during posterior hip surgery, intramuscular injections, and procedures performed in the gluteal region. Variations in the level of division of the sciatic nerve may also result in the tibial and common fibular components separating higher than expected [42]. Recognition of these patterns is important during surgical approaches to the pelvis, hip, and posterior thigh. The tibial nerve generally travels through the posterior compartment of the leg and passes behind the medial malleolus before dividing into the medial and lateral plantar nerves. Variations may occur in the level of terminal division and in the origin and course of muscular, calcaneal, and plantar branches [43]. These differences are particularly relevant during tarsal tunnel decompression and surgery around the medial ankle. An unusually proximal division or an additional branch may increase the possibility of incomplete decompression if the surgeon assumes a conventional branching pattern.

The common fibular nerve passes around the neck of the fibula, where its relatively superficial position makes it vulnerable to trauma and surgical injury. Variations in the level at which it divides into superficial and deep fibular nerves have been reported, together with differences in its muscular and cutaneous branches [44]. These variations are relevant during procedures around the knee and proximal fibula, including total knee arthroplasty, fracture fixation, fibular surgery, and peripheral nerve decompression. Careful identification of the nerve and its branches is particularly important in minimally invasive procedures where the field of direct visualization is limited.

The femoral nerve also exhibits variations in its terminal branching and relationship with the femoral vessels. After passing beneath the inguinal ligament, it divides into branches that supply the anterior thigh and provides the saphenous nerve as its major distal sensory branch [45].

Variations in the level of division and the course of individual branches may influence the effectiveness of femoral nerve blocks and may be relevant during vascular, orthopedic, and reconstructive surgery. The obturator nerve may similarly demonstrate variations in its branching pattern, and an accessory obturator nerve can occasionally contribute to innervation of the medial thigh and hip region [46]. Cutaneous nerves of the lower limb are particularly variable. The lateral femoral cutaneous nerve, for example, may follow different pathways in relation to the inguinal ligament and anterior superior iliac spine [47]. This anatomical variability is clinically important during anterior approaches to the hip and pelvis because injury or compression of the nerve can produce sensory disturbances characteristic of meralgia paresthetica. The sural nerve also demonstrates considerable variation in its formation because it may receive contributions from both tibial and common fibular nerve components [48]. Since the sural nerve is frequently used as a donor nerve for peripheral nerve grafting, knowledge of its variable anatomy is essential for safe harvesting and preservation of adjacent structures.

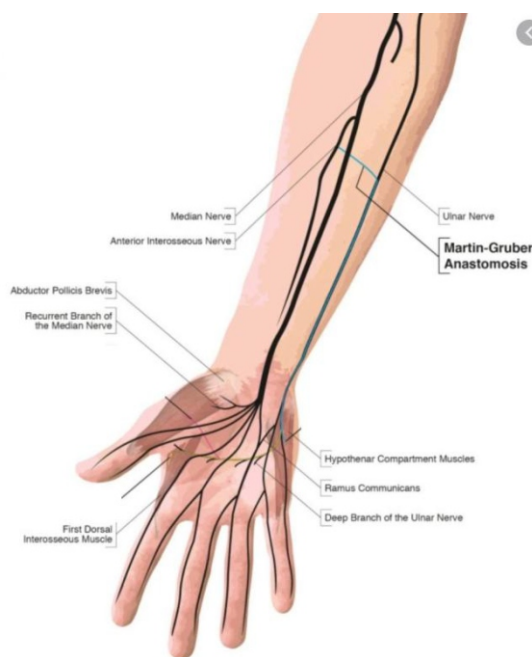


Figure 3: Sciatic nerve and piriformis anatomical variations
Source adopted from
<https://www.orthobullets.com/hand/6019/ain-compressive-neuropathy>

6. Clinical Significance of Peripheral Nerve Variations in Surgical Practice

Anatomical variations of peripheral nerves have considerable clinical significance because surgical procedures are generally planned according to standard anatomical descriptions, whereas individual patients may present with different nerve pathways or branching patterns. An anomalous nerve may be encountered in an unexpected position, increasing the possibility of accidental transection, traction, compression, or thermal injury during surgery [49].

The consequences of peripheral nerve damage can include sensory loss, motor weakness, neuropathic pain, muscle atrophy, and impaired functional recovery. Therefore, recognition of common anatomical variants is an important component of preoperative assessment and intraoperative decision-making, particularly in procedures performed near major nerve pathways [50]. The risk of iatrogenic nerve injury is especially relevant during orthopedic procedures because major peripheral nerves frequently lie close to bones and joints. The radial nerve may be endangered during fixation of humeral shaft fractures, while the common fibular nerve is vulnerable during procedures around the fibular head and knee [51]. Similarly, the sciatic nerve may be exposed to injury during posterior approaches to the hip, and the median and ulnar nerves require careful identification during procedures involving the wrist and elbow. An unusual course or accessory branch may not be apparent from conventional anatomical landmarks, making meticulous surgical dissection essential.

Peripheral nerve variations are also highly relevant to nerve decompression procedures. Carpal tunnel release is a representative example in which variations in the course of the recurrent motor branch of the median nerve may increase the risk of neurological complications [52]. Similarly, variations in the position and branching of the ulnar nerve around the elbow may influence the surgical approach to cubital tunnel syndrome. Incomplete identification of anomalous branches may result in inadequate decompression and persistence of symptoms. Surgeons should therefore consider possible anatomical variations whenever the expected nerve configuration is not encountered. Regional anesthesia represents another important clinical setting in which peripheral nerve variations can influence treatment outcomes. The effectiveness of a nerve block depends on the location of the nerve, its fascicular organization, and the presence of communicating or accessory branches [53]. Anatomical variations may therefore contribute to incomplete anesthesia despite technically appropriate injection. Ultrasound-guided regional anesthesia has improved the ability to visualize peripheral nerves and their surrounding structures and can help clinicians identify unusual nerve locations before injection [54]. This is particularly useful for procedures involving the brachial plexus, sciatic nerve, femoral nerve, and distal peripheral nerves. Anatomical communications between nerves can also influence the clinical manifestations of peripheral nerve injury. For example, the presence of a Martin-Gruber or Riche-Cannieu anastomosis may allow some motor fibers to reach their target muscles through an alternative pathway [55]. Consequently, a patient may retain muscle function despite an injury to the nerve that normally supplies the muscle. Conversely, the presence of a communicating branch may produce neurological findings that appear inconsistent with the anatomical level of injury. Awareness of these variations is therefore essential for accurate neurological examination and interpretation of electrodiagnostic studies.

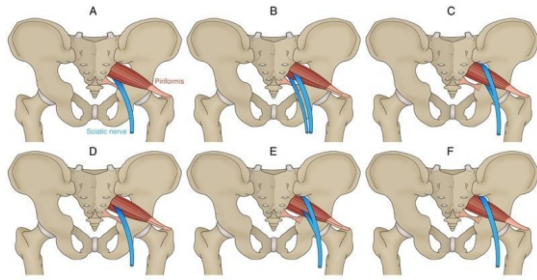


Figure 4: Clinical implications of peripheral nerve variations
Source adopted from
<https://www.sportsinjurybulletin.com/diagnose--treat/piriformis-a-contentious-syndrome>

7. Importance of Peripheral Nerve Variations in Orthopedic and Reconstructive Surgery

Orthopedic surgery frequently involves anatomical regions where major peripheral nerves are closely associated with bones, joints, and soft tissues. Anatomical variations may alter the position of these nerves and consequently affect the safety of surgical approaches [56]. During fracture fixation, joint replacement, arthroscopy, and reconstructive procedures, unexpected nerve branches can be damaged by retractors, drilling, screws, plates, or surgical instruments. Detailed knowledge of normal and variant anatomy can help surgeons select safer approaches and minimize postoperative neurological complications. The radial nerve represents an important example in upper-limb orthopedic surgery. Its close relationship with the humeral shaft makes it vulnerable during fracture fixation and surgical exposure. Variations in its branching pattern may further complicate identification of the nerve and its motor branches [57]. Similarly, the posterior interosseous nerve is at risk during procedures involving the proximal radius because its course through the supinator and its relationship with the radial neck may vary. Careful identification of these structures is therefore essential during radial head surgery and proximal forearm procedures.

In the lower limb, the sciatic and common fibular nerves are particularly important. The sciatic nerve may demonstrate an unusual relationship with the piriformis muscle or divide at a higher level than expected [58]. These variations can influence the risk of nerve injury during hip surgery and may complicate posterior surgical approaches. The common fibular nerve, because of its superficial position around the fibular neck, is vulnerable during knee surgery and procedures involving the proximal fibula. Variations in its branching pattern may increase the risk of damage to motor and sensory branches [59]. Peripheral nerve variations are also relevant to reconstructive surgery and nerve grafting. The sural nerve is commonly used as a donor nerve for autologous nerve grafts, but its formation and course can vary considerably [60]. Accurate identification of the nerve and its communicating branches is necessary to obtain an appropriate graft while minimizing sensory morbidity. Similarly, anatomical variations in the upper-limb nerves should be considered during nerve transfers, tendon transfers, and microsurgical reconstruction.

8. Role of Imaging and Diagnostic Techniques

Advances in imaging have substantially improved the identification and evaluation of peripheral nerves in living patients. High-resolution ultrasonography can visualize superficial nerves, their fascicular architecture, branching patterns, and relationships with adjacent vessels and muscles [61]. This technique is particularly useful for peripheral nerve blocks, nerve decompression procedures, and evaluation of focal neuropathies. Dynamic ultrasound examination can also demonstrate changes in nerve position during limb movement and may reveal anatomical relationships that are difficult to appreciate using static imaging.

Magnetic resonance imaging and magnetic resonance neurography provide additional information regarding nerve morphology, signal characteristics, continuity, and surrounding soft tissues [62]. These techniques are valuable when a peripheral nerve is suspected to be compressed, injured, displaced, or involved in a tumor. Magnetic resonance neurography may also help identify unusual nerve pathways before complex surgical procedures. The combination of anatomical imaging and clinical findings can improve preoperative planning and facilitate individualized surgical approaches. Electrodiagnostic techniques, including nerve conduction studies and electromyography, remain important for assessing peripheral nerve function. However, anatomical communications between nerves may complicate interpretation of electrophysiological findings [63]. For example, the presence of a median-ulnar communication may produce conduction patterns that do not correspond to the conventional anatomical distribution of the median and ulnar nerves. Clinicians should therefore consider anatomical variation when electrophysiological results appear inconsistent with clinical findings.

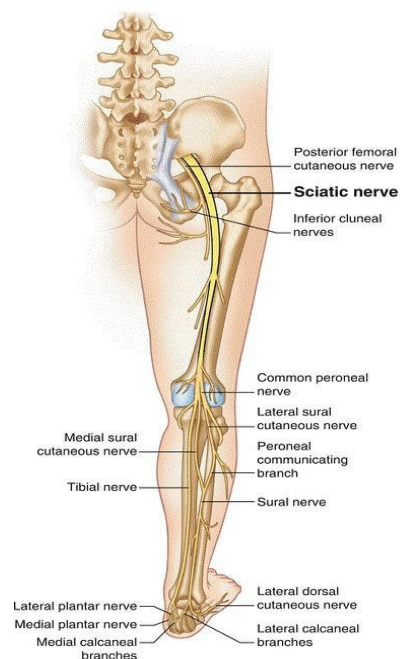


Figure 5: Role of ultrasound and MR neurography in identifying nerve variations
Source: <https://doppleronline.ca/huntsville/another-pain-in-the-butt-sciatica-surge-physio/>

9. Implications for Peripheral Nerve Surgery and Microsurgical Procedures

Peripheral nerve surgery requires precise identification of individual nerve fascicles and branches. Anatomical variations may complicate this process, particularly when a nerve divides earlier than expected or when communicating branches are present [64]. During nerve repair, failure to recognize an anomalous branch may result in incomplete reconstruction or inappropriate alignment of nerve components. Microsurgical techniques can improve visualization, but their success still depends on accurate anatomical identification. Nerve transfer procedures are similarly influenced by anatomical variability. Successful nerve transfer requires identification of an appropriate donor nerve with adequate motor axon supply and a suitable recipient nerve pathway [65]. Variations in the origin and course of motor branches may therefore influence donor selection and surgical exposure. Preoperative imaging, electrodiagnostic assessment, and detailed anatomical knowledge can assist in selecting an appropriate surgical strategy. Peripheral nerve decompression also requires careful recognition of anatomical relationships. Entrapment may occur at predictable anatomical sites, but variations can create additional points of compression or alter the relationship between the nerve and surrounding structures [66]. Identification of these unusual relationships is important to ensure complete decompression and reduce the likelihood of recurrent symptoms.

10. Surgical Prevention of Iatrogenic Peripheral Nerve Injury

Prevention of iatrogenic nerve injury begins with adequate knowledge of regional anatomy and awareness of possible anatomical variations. Surgeons should not assume that a nerve will always occupy its textbook position. Instead, careful tissue dissection and direct identification of neural structures should be performed when operating in anatomically sensitive regions [67]. Excessive traction, electrocautery near nerves, prolonged retraction, and blind instrument placement should be avoided whenever possible. Preoperative imaging can be particularly useful when a surgical procedure involves a region known to contain substantial anatomical variation. Ultrasound, MRI, or magnetic resonance neurography may provide additional information in selected patients [68]. During surgery, nerve stimulation and intraoperative neurophysiological monitoring can also assist in identifying and protecting functional neural structures in complex procedures. Surgeons should additionally document significant anatomical variations encountered during an operation. Such documentation can be valuable for future procedures and may help explain postoperative neurological findings. A multidisciplinary approach involving surgeons, radiologists, anesthesiologists, neurologists, and peripheral nerve specialists may further improve the management of complex cases.

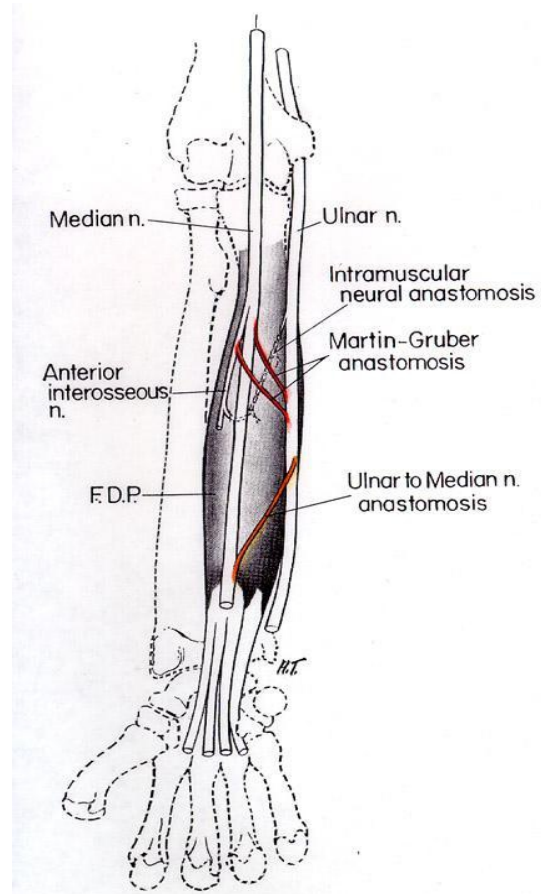


Figure 6 – Surgical considerations and prevention of iatrogenic nerve injury [Source adopted from: <https://www.anatomyatlases.org/AnatomicVariants/NervousSystem/Images/49.shtml>]

11. Anatomical Variations and Regional Anesthesia

The increasing use of ultrasound-guided regional anesthesia has highlighted the importance of understanding peripheral nerve variability. Conventional landmark-based techniques rely on predictable anatomical relationships; however, variations in nerve position and branching can reduce the reliability of these approaches [69]. An accessory nerve branch may escape the anesthetic field, resulting in incomplete sensory or motor blockade. The sciatic nerve provides an important example because its division may occur at different levels, and the tibial and common fibular components may follow separate pathways before reaching the popliteal region [70]. These differences can influence the distribution of anesthetic during sciatic nerve blocks. Similarly, variations in the femoral, saphenous, and obturator nerves may influence the effectiveness of regional anesthesia during lower-limb surgery. Ultrasound allows real-time identification of nerve structures and can facilitate targeted deposition of local anesthetic around the nerve while reducing the risk of vascular puncture and direct nerve trauma [71]. Nevertheless, ultrasound does not eliminate the importance of anatomical knowledge. Accurate interpretation of sonographic images requires familiarity with both normal and variant anatomy.

12. Implications for Clinical Diagnosis

Anatomical nerve variations can influence the clinical presentation of neuropathies and nerve injuries. A patient may exhibit sensory or motor findings that do not correspond precisely to the conventional distribution of a particular nerve because of communicating branches or alternative pathways [72]. This can complicate clinical localization and may result in an incorrect diagnosis if anatomical variation is not considered. Median-ulnar communications are particularly important in this regard. Patients with such communications may show preservation of specific muscle functions after proximal median or ulnar nerve injury [73]. Similarly, variations in cutaneous nerve distribution may result in sensory symptoms that extend beyond or differ from standard dermatomal or peripheral nerve territories. Recognizing these possibilities is particularly important when evaluating patients after trauma or surgery. A discrepancy between the location of an injury and the observed neurological deficit should prompt consideration of anatomical variation, nerve communication, or accessory innervation.

13. Discussion

Anatomical variations of peripheral nerves represent an important consideration in contemporary surgical practice. Although standard anatomical descriptions provide the foundation for surgical training, they cannot encompass the full range of anatomical patterns encountered in clinical practice [74]. Variations may involve the origin, course, division, branching, or communication of nerves and may occur in both the upper and lower limbs. Their clinical importance depends largely on the anatomical region involved and the type of intervention being performed.

The upper limb contains several well-recognized variations with direct surgical implications. Variations of the recurrent motor branch of the median nerve are particularly important during carpal tunnel surgery, while median-ulnar communications may influence motor function and electrodiagnostic findings [75]. Variations involving the radial and musculocutaneous nerves are similarly relevant to procedures involving the humerus, shoulder, elbow, and proximal forearm. In the lower limb, sciatic nerve variations have received considerable attention because of their importance in hip surgery, regional anesthesia, and sciatic nerve entrapment [76]. The relationship between the sciatic nerve and piriformis can vary, and early division of the sciatic nerve may result in separate courses of its major components. Variations in the tibial, common fibular, femoral, obturator, saphenous, and sural nerves further demonstrate the extensive diversity of peripheral nerve anatomy. The clinical significance of these variations extends beyond surgery. Anatomical differences can affect the interpretation of neurological examinations, nerve conduction studies, electromyography, and imaging findings. Consequently, clinicians should avoid interpreting neurological deficits solely according to conventional anatomical maps.

A comprehensive assessment should incorporate the possibility of variant nerve pathways when clinical findings are atypical [77].

Modern imaging has provided important opportunities to identify anatomical variation before intervention. Ultrasound is particularly valuable for superficial peripheral nerves, while MRI and magnetic resonance neurography can provide more extensive anatomical and pathological information [78]. The integration of imaging with clinical examination and electrodiagnostic testing can improve diagnostic accuracy and facilitate individualized treatment planning. Despite technological advances, direct anatomical knowledge remains fundamental to safe surgical practice. Surgeons should be familiar with common nerve variants in the regions they operate upon and should maintain a systematic approach to identifying nerves and their branches. Greater emphasis on anatomical variation during medical and surgical education may help reduce iatrogenic nerve injuries and improve surgical outcomes.

15. Conclusion

Anatomical variations of major peripheral nerves are an important aspect of clinical anatomy and surgical practice. Variations in nerve origin, course, branching, terminal distribution, and inter-nervous communications may be clinically silent under normal circumstances but can become highly significant during surgery, trauma management, regional anesthesia, and diagnostic evaluation. The median, ulnar, radial, musculocutaneous, sciatic, tibial, common fibular, femoral, obturator, saphenous, and sural nerves all demonstrate clinically relevant variations that should be recognized by surgeons and other healthcare professionals. A detailed understanding of these variations is particularly important for preventing iatrogenic nerve injury. Knowledge of the recurrent motor branch of the median nerve, median-ulnar communications, variations of the radial and musculocutaneous nerves, sciatic nerve division patterns, and variations around the fibular head and ankle can directly influence operative planning and technique. Anatomical variation should also be considered when interpreting neurological deficits and electrodiagnostic findings that do not conform to conventional patterns. Modern imaging techniques, particularly high-resolution ultrasonography and magnetic resonance neurography, provide valuable tools for identifying peripheral nerves and their anatomical relationships before and during selected interventions. However, these technologies complement rather than replace fundamental anatomical knowledge. A combination of detailed anatomical understanding, careful surgical dissection, appropriate imaging, and individualized preoperative planning provides the best strategy for minimizing nerve-related complications. Ultimately, recognition of peripheral nerve variability should be regarded as an essential component of safe and effective surgical practice.

Greater integration of anatomical variation into surgical education, imaging interpretation, regional anesthesia, and peripheral nerve reconstruction may contribute to improved diagnostic accuracy, better operative outcomes, and reduced incidence of iatrogenic neurological injury.

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