Pain Medicine, 0(0), 2019, 1–17
doi: 10.1093/pm/pnz189
Review Article

Review of Knee Joint Innervation: Implications for Diagnostic Blocks and Radiofrequency Ablation

Shannon L. Roberts, PhD,* Alison Stout, DO,† and Paul Dreyfuss, MD†

*Toronto, Ontario, Canada; †EvergreenHealth, Kirkland, Washington, USA

Correspondence to: Shannon L. Roberts, PhD, PO Box 68508, Walmer, Toronto, ON M5S 3C9, Canada. Email: shannon.roberts@mail.utoronto.ca.

Funding sources: None.

Conflicts of interest: The authors declare no conflicts of interest.

Prior presentation: Presented at the Spine Intervention Society Annual Meeting; August 15–18, 2018; Chicago, IL.

Abstract

Objective. To determine if commonly used knee radiofrequency ablation (RFA) techniques would be able to completely denervate the knee joint. **Methods.** A comprehensive search of the literature on knee joint innervation was conducted using the databases Medline, Embase, and PubMed from inception through February 1, 2019. Google Scholar was also searched. Data on the origin, number of articular branches, course, distribution, and frequency of each nerve innervating the knee joint were extracted from the included studies and compared in order to identify variations. **Results.** Twelve studies of anterior knee joint innervation and six studies of posterior knee joint innervation were included. The anterior knee joint was innervated by 10 nerves and further subdivided into two parts (anteromedial and anterolateral) or four quadrants (superomedial, inferomedial, superolateral, and inferolateral) based on innervation patterns; the posterior knee joint was innervated by two or three nerves, most commonly via the popliteal plexus. There is a lack of precise, validated anatomic targets identifiable with fluoroscopy and ultrasound for knee diagnostic blocks and RFA. Only three of the 12 or potentially 13 nerves innervating the knee joint are targeted by commonly used knee RFA techniques. **Conclusions.** Commonly used knee RFA techniques would not be able to completely denervate the knee joint. It may not be necessary to capture all of the nerves, but only the nerves mediating a patient's pain. Further clinical studies are required to validate specific diagnostic blocks and evaluate clinical outcomes using rigorous diagnostic blocks and anatomically specific knee RFA techniques.

Key Words: Knee Joint; Innervation; Diagnostic Blocks; Radiofrequency; Ablation

Introduction

Radiofrequency neurotomy of synovial joints is an accepted treatment of recalcitrant pain in the spinal axis. Evolution of these techniques and improved clinical outcomes have occurred in the cervical, lumbar, and sacroiliac regions of the spine, when precise fluoroscopic techniques evolved from a more detailed anatomical understanding of the joints' innervation relative to osseous landmarks [1]. Relative to denervation of the facet and sacroiliac joints in the spine, knee radiofrequency denervation is a relatively new treatment option for persistent knee pain.

The most commonly used knee radiofrequency ablation (RFA) targets were proposed by Choi et al. [2] in 2011 based upon their understanding of knee joint innervation that could be more readily targeted with conventional monopolar RFA. This technique targets three of the genicular nerves innervating the anterior knee joint: the superior lateral, superior medial, and inferior medial genicular nerves (Table 1). Choi et al. [2] described their chosen targets as being "three main articular branches… with relatively precise anatomic aspects" that "can be easily approached percutaneously under fluoroscopic guidance" based upon an anatomy textbook [3] and superficial dissections of two cadaveric specimens [4,5].

Table 1. Most common targets for knee radiofrequency ablation, proposed by Choi et al. [2] in 2011*

Target Nerves	Target RFA Needle Placement Locations (on Periosteum)	
	Anterior–Posterior FL View	Lateral FL View
Superior lateral genicular nerve	Junction of shaft of femur with lateral epicondyle	Midpoint of femur
Superior medial genicular nerve	Junction of shaft of femur with medial epicondyle	Midpoint of femur
Inferior medial genicular nerve	Junction of shaft of tibia with medial condyle	Midpoint of tibia

FL = fluoroscopic; RFA = radiofrequency ablation.

*A single monopolar RF lesion was created at each target needle placement location using a 22-gauge conventional RF cannula with a 10-mm active tip at 70°C for 90 seconds [2].

A number of subsequent clinical studies have used these proposed targets with either conventional [6–12] or cooled [13–18] monopolar RFA for the treatment of chronic knee osteoarthritis (OA) pain [7,8,10–13,15–18] or persistent pain after total knee arthroplasty (TKA) [6,8,9,13,14] with questionable results. Similar historical origins of RFA techniques occurred in regions of the spine until anatomy knowledge was advanced and fluoroscopic targets were more idealized [19]. The anatomical basis and evolution of RFA techniques that occurred in the spine should logically occur in the knee as well.

Ideal patient selection with diagnostic blocks and improved clinical outcomes with knee RFA require optimization of nerve capture rates. A strong anatomical foundation is required to achieve this goal, as has been the case with cervical, lumbar, and sacroiliac joint RFA. Studies to date have largely assumed that adequate denervation of the knee has been achieved using the anatomic targets proposed by Choi et al. [2]. The purpose of this review is to determine if commonly used knee RFA techniques would be able to completely denervate the knee joint.

Methods

A comprehensive search of the literature on knee joint innervation was conducted using the databases Medline (Ovid platform), Embase (Ovid platform), and PubMed from inception through February 1, 2019. Google Scholar was also searched (first 200 hits). The following search terms were used for all databases: “knee,” “knee joint,” “knee joint capsule,” “innervation,” “genicular nerve,” and “genicular nerves.” No language restrictions were applied. The searches were limited to humans. Both subject heading and text word searching were conducted in Medline and Embase. Inclusion criteria were 1) cadaveric studies, 2) primary publications (studies that produced original data), and 3) English language. Exclusion criteria were 1) conference abstracts and 2) secondary publications (did not produce original data, e.g., reviews). The reference list of each included article was reviewed to identify additional articles that had not been identified in the database searches. Study titles, abstracts, and full texts were assessed based on the inclusion and exclusion criteria. Data extracted from the included studies were the study sample size and origin, number of articular branches, course, distribution, and frequency of each nerve innervating the knee joint. The data were compared among the included studies to identify variations of each nerve.

Results

Twelve studies of anterior knee joint innervation [20–31] and six studies of posterior knee joint innervation [20–22,28,32,33] were included. In the literature, the anterior and posterior aspects of the knee joint have been reported to receive innervation from different sources [20–33]. The anterior aspect of the knee joint was further subdivided into two parts (anteromedial and anterolateral) in some studies or four quadrants (superomedial, inferomedial, superolateral, and inferolateral) in other studies based on innervation patterns (Table 2). This was a result of anatomical variations and methodological differences among studies. Eleven studies traced the nerves to their points of entry into the knee joint in adult specimens [21–31], whereas only one study traced the nerves to their terminal branches in adult specimens and serial sections of fetal specimens, which enabled determination of nerve distribution patterns within the knee joint capsule [20]. Thus, the parts and quadrants of the anterior knee joint were based on nerve entry points in 11 studies [21–31] and terminal branches in one study [20]. This resulted in some studies reporting that each nerve innervated one quadrant only based on nerve entry points into the knee joint capsule [24,31], whereas tracing terminal branches within the fibrous layer of the knee joint capsule in adult specimens and serial fetal sections demonstrated that some nerves innervate two quadrants (superior and inferior), forming the anteromedial or anterolateral part of the knee joint [20]. A nerve innervates two quadrants by either 1) penetrating one quadrant (superior) of the knee joint capsule and then coursing inferiorly within the fibrous layer of the capsule to innervate two quadrants (superior and inferior), forming the anteromedial or anterolateral part; or 2) penetrating and innervating two quadrants (superior and inferior), forming the anteromedial or anterolateral part [20]. The posterior innervation can also cross to the anterior knee joint [20], complicating the discussion of the anterior quadrants.

Anterior Knee Joint Innervation

Anteromedial Part: Superomedial Quadrant

The superomedial quadrant of the knee joint has been reported to be innervated by three nerves: 1) the nerve to

Table 2. Summary of knee joint innervation

Knee Joint			
Aspect	Part	Quadrant	Innervation*
Anterior	Anteromedial	Superomedial	Nerve to vastus medialis
			Nerve to vastus intermedius: medial branch†
			Superior medial genicular nerve
		Inferomedial	Infrapatellar branch of saphenous nerve
			Inferior medial genicular nerve
	Anterolateral	Superolateral	Nerve to vastus lateralis
			Nerve to vastus intermedius: lateral branch†
			Superior lateral genicular nerve
			Articular branch of common fibular nerve
		Inferolateral	Inferior lateral genicular nerve
			Recurrent fibular nerve
Aspect	**Part**	**Region**	**Innervation**
Posterior‡	Both	All	Popliteal plexus:§
	Both	All	Articular branch(es) of tibial nerve
	Posteromedial	Superomedial	Posterior branch of obturator nerve
	Posterolateral	Superolateral	Posterior branch of common fibular nerve or sciatic nerve¶

— = not applicable; fibular = peroneal.

*Superomedial and superolateral quadrants of anterior knee joint: nerves ordered from anterior to posterior [31]. Inferomedial and inferolateral quadrants of anterior knee joint: nerves ordered from superior to inferior [31].

†Nerve to vastus intermedius had two variations: 1) one or more articular branches innervate suprapatellar pouch [20–22,24,30]; and 2) nerve to vastus intermedius divides into a medial branch innervating the superomedial quadrant and a lateral branch innervating the superolateral quadrant [20,31].

‡Gardner [20] reported that the posterior knee joint innervation penetrates as far anterior as the infrapatellar fat pad and supplies intra-articular structures.

§Tran et al. [33] reported that articular branches of the tibial nerve (inferior branch only in N = 8/15 [53.3%]; both superior and inferior branches in N = 7/15 [46.7%]), the articular branch of the posterior branch of the obturator nerve, and the posterior branch of the common fibular nerve (N = 8/15 [53.3%]) or sciatic nerve (N = 3/15 [20.0%]) "interdigitated to form a fine plexus," but did not refer to it as the popliteal plexus and did not report an anastomosis of articular branches, as reported by Gardner [20].

¶One study [33] reported that the posterior branch of the common fibular nerve or sciatic nerve innervated the posterior knee joint capsule in N = 11/15 (73.3%).

vastus medialis; 2) the nerve to vastus intermedius; and 3) the superior medial genicular nerve (ordered from anterior to posterior [31]). The origin, number of articular branches, course, distribution, and frequency of each nerve are summarized in Table 3. The nerve to vastus medialis has been found to give off one to five articular branches, most intramuscular, some extramuscular (Table 4). Four studies found that the nerve to vastus medialis innervated the superomedial quadrant [22–24,31], whereas five studies found that it innervated the anteromedial part of the knee joint (Figures 1 and 2 ant.) [20,21,27,28,30] as far inferiorly within the knee joint capsule as the tibial tuberosity in one study of five fetal specimens [20]. The nerve to vastus intermedius has been reported to have two variations: 1) most commonly, one articular branch innervating the suprapatellar pouch (Figures 1, 2D and F ant.) [20–22,24,30]; and 2) two articular branches, medial and lateral, innervating the superomedial and superolateral quadrants, respectively (Figure 2E ant.) [20,31]. The superior medial genicular nerve has been reported to have four variations in origin: 1) tibial nerve or its articular branch [20,26]; 2) posterior branch of the obturator nerve [20]; 3) femoral nerve [31]; and 4) a deep nerve plexus formed by the nerve to vastus medialis and the saphenous nerve [27]. One study found that the superior medial genicular nerve innervated the superomedial quadrant [31], whereas three studies found that it innervated the anteromedial part of the knee joint (Figures 1, 2D and F ant. and post.) [20,26,27] .

Anteromedial Part: Inferomedial Quadrant

The inferomedial quadrant of the knee joint has been reported to receive innervation from two nerves: 1) the infrapatellar branch of the saphenous nerve and 2) the inferior medial genicular nerve (ordered from superior to inferior [31]). Table 5 summarizes the origin, number of articular branches, course, distribution, and frequency of each nerve. Variation was found in the level of origin of the infrapatellar branch of the saphenous nerve (Table 6) and its course relative to sartorius as it emerged from the adductor canal, most commonly anterior to sartorius ([25]: N = 22/32 [68.7%]; [31]: N = 13/15 [86.7%]), followed by posterior to sartorius ([25]: N = 1/32 [3.1%]; [31]: N = 2/15 [13.3%]) and piercing the sartorius ([25]: N = 9/32 [28.1%]; [31]: N = 0/15 [0.0%]). The infrapatellar branch of the saphenous nerve was reported to provide mainly cutaneous innervation (Table 5). Four studies reported that the infrapatellar branch of the saphenous nerve also innervated the inferomedial quadrant [21,22,24,31], whereas three studies reported that it also innervated the anteromedial part (Figure 2F ant.) [20,23,28] of the knee joint capsule; however, this was only in a small number of specimens via one or a few small branches in two of these studies [20,31]. The inferior medial genicular nerve was reported to innervate the inferior part of the inferomedial quadrant in one study [31], and the anteromedial part of the knee joint in the region of the patellar ligament in another study (Figures 1 and 2 ant. and post.) [20].

The obturator nerve did not innervate the anterior knee joint directly in nine studies [20–24,27,28,30,31]. Two variations of low frequency have been reported: 1) the anterior branch of the obturator nerve anastomosed with the saphenous nerve in the adductor canal,

Table 3. Anterior knee joint innervation: Superomedial quadrant

	Nerve to Vastus Medialis	Nerve to Vastus Intermedius		Superior Medial Genicular Nerve			
		Variation 1	Variation 2	Variation 1	Variation 2	Variation 3	Variation 4
Origin	Femoral nerve	Femoral nerve	Femoral nerve	Tibial nerve [26] or its articular branch [20]	Posterior branch of obturator nerve	Femoral nerve	Deep nerve plexus formed by nerve to vastus medialis and saphenous nerve (both from femoral nerve)*
No. of articular branches	1–5, most IM, some EM (Table 4)	≥1 (most commonly 1)	Divides into a medial branch (to superomedial quadrant) and a lateral branch (to superolateral quadrant)	1	1	1	1
Course	Inferiorly, IM through VM, or EM along its medial border†	Inferiorly on anterior surface of femur, deep to VI, and enters suprapatellar pouch	Medial branch: inferiorly on anteromedial surface of femur between VM and VI‡	Anteriorly around shaft of femur at attachment of ADM tendon to adductor tubercle with SMGA&V‡,§	Accompanies SMGA&V	Deep to sartorius, then along ADM tendon with DGA, and then accompanies SMGA&V‡	Inferiorly on surface of femur, deep to VM, in distal third of adductor canal
Distribution¶	• Knee joint capsule: superomedial quadrant [22–24,31] or anteromedial part [20,21,27,28,30]‖ • Medial retinaculum ([22]: N = 45/45 [100.0%]; [27]: N = 7/20 [35.0%] via EM branch; [28]: N = 25/25 [100.0%]) • Medial collateral ligament [22] • Infrapatellar fat pad, patellar periosteum, and BVs supplying medial femoral condyle ([20]: N = 5/5 [100.0%] fetuses)	• Knee joint capsule: suprapatellar pouch • Periosteum of anterior surface of femur to border of articular cartilage [20] • BVs supplying suprapatellar pouch and adjacent femur ([20]: N = 5/5 [100.0%] fetuses)	Medial branch: • Knee joint capsule: superomedial quadrant • Periosteum of anterior surface of femur to border of articular cartilage [20]	• Knee joint capsule: anteromedial part	• Knee joint capsule: anteromedial part‖ • Infrapatellar fat pad and BVs supplying medial femoral condyle ([20]: N = 5/5 [100.0%] fetuses)	• Knee joint capsule: superomedial quadrant	• Knee joint capsule: deep anteromedial aspect

(continued)

Table 3. continued

	Nerve to Vastus Medialis	Nerve to Vastus Intermedius		Superior Medial Genicular Nerve			
		Variation 1	Variation 2	Variation 1	Variation 2	Variation 3	Variation 4
References[|||]	9 studies ([20,21];[22]: N = 45/45 [100.0%]; [23];[24]: N = 8/8 [100.0%]; [27]: N = 20/20 [100.0%]; [28]: N = 25/25 [100.0%];[30]: N = 6/14 [42.9%]; [31]: N = 15/15 [100.0%])	5 studies ([20,21]; [22]: N = 45/45 [100.0%];[24]: N = 8/8 [100.0%]; [30]: N = 11/14 [78.6%]**)	2 studies ([20]; [31]: N = 15/15 [100.0%])	2 studies ([20]: N = 3/11 [27.3%];[26]: N = 10/10 [100.0%]††)	1 study ([20]: N = 4/11 [36.4%])	1 study ([31]: N = 15/15 [100.0%])	1 study ([27]: N = 18/20 [90.0%])
Figures	1 and 2 ant.	1, 2D and 2F ant.	2E ant.	2D ant., post.	1 and 2F post.	—	—

— = not applicable; ADM = adductor magnus; ant. = anterior; BV = blood vessel; DGA = descending genicular artery; EM = extramuscular; IM = intramuscular; NVM = nerve to vastus medialis; post. = posterior; SMGA&V = superior medial genicular artery and vein; SMGN = superior medial genicular nerve; VI = vastus intermedius; VM = vastus medialis.

*Deep nerve plexus gave rise to two deep genicular nerves: anterior and medial genicular nerves [27].

†Mean distance of IM branches from periosteum of femur at level of apex of suprapatellar bursa: 0.71 ± 0.28 cm ([31]: N = 15).

‡Courses at periosteal level before penetrating anterior knee joint capsule [26,31].

§Yasar et al. [26] found in N = 4 that the adductor tubercle was an ultrasound landmark for the SMGN (variation 1) and that the target point for nerve blocks was "the bony cortex one cm anterior to the peak of the adductor tubercle."

¶Superomedial quadrant innervation: nerves ordered from anterior to posterior [31].

‖Gardner [20] reported that some branches of the articular branch of the NVM and the SMGN (variation 2) innervating the anteromedial part of the knee joint capsule coursed as far inferiorly as the tibial tuberosity in N = 5 fetuses. Gardner [20] also reported that some branches of the articular branch of the NVM occasionally coursed to the attachment of the knee joint capsule to the medial tibial condyle in N = 11 adult specimens (Figure 1B ant.). In addition, Gardner [20] found that the articular branch of the NVM anastomosed with the infrapatellar branch of the saphenous nerve and the SMGN (variation 2) in the fibrous layer of the anteromedial part of the knee joint capsule in N = 5 fetuses.

|||Frequency of variations given for studies that reported it; other studies reported the presence of the variations, but not the frequency.

**Orduña Valls et al. [28] reported that the nerve to vastus intermedius "descends along the fascia between the vastus lateralis and vastus intermedialis muscles to the distal portion of the femur, where it branches out to the periosteum of the prepatellar bursa."

††Hirosawa et al. [23] reported that "the tibial nerve projected articular branches at the popliteal fossa…[that] innervate the articular capsule following the superomedial popliteal vessels and the superolateral vessels."

Table 4. Number and course of articular branches of nerve to vastus medialis innervating superomedial quadrant of anterior knee joint

Authors	N	No. of Articular Branches	Course Relative to VM
Gardner [20]	11	1	EM
Kennedy et al. [21]	15	1	NR
Horner and Dellon [22]	45	1	90% IM, 10% EM
Hirosawa et al. [23]	5	NR	IM
Franco et al. [24]	8	1	EM
Burckett-St. Laurant et al. [27]	20	1–3*	IM
		1†	EM
Orduña Valls et al. [28]	25	2–5	Most IM, some EM
Sakamoto et al. [30]	14	NR‡	IM
Tran et al. [31]	15	2–3	IM

EM = extramuscular; IM = intramuscular; NR = not reported; VM = vastus medialis.

*One branch in N = 11/20 (55.0%); two branches in N = 8/20 (40.0%); three branches in N = 1/20 (5.0%) [27].

†N = 7/20 (35.0%) [27].

‡N = 6/14 (42.9%) [30].

contributing to the infrapatellar branch of the saphenous nerve mainly innervating the skin ([27]: N = 2/20 [10.0%]), but also the inferomedial quadrant ([22]: N = 5/45 [11.1%]; [30]: N = 1/14 [7.1%]) or anteromedial part [20] of the knee joint capsule in some specimens in four studies; and 2) the posterior branch of the obturator nerve gave rise to the superior medial genicular nerve innervating the anteromedial part of the knee joint in some specimens in one study ([20]: N = 4/11 [36.4%]).

Anterolateral Part: Superolateral Quadrant

The superolateral quadrant of the knee joint has been reported to be innervated by four nerves: 1) the nerve to vastus lateralis; 2) the nerve to vastus intermedius; 3) the articular branch of the common fibular (peroneal) nerve; and 4) the superior lateral genicular nerve (ordered from anterior to posterior [31]). The origin, number of articular branches, course, distribution, and frequency of each nerve are summarized in Table 7. The nerve to vastus lateralis was reported to penetrate the anterior knee joint capsule at the superolateral aspect of the patella in one study [31]. Four studies reported that the nerve to vastus lateralis innervated the superolateral quadrant [21,23,24,31], whereas three studies reported that it innervated the anterolateral part of the knee joint (Figures 1 and 2 ant.) [20,28,30], coursing within the knee joint capsule almost to the tibial tuberosity in one study of five fetal specimens [20]. The two variations of the nerve to vastus intermedius were previously described for the superomedial quadrant (Table 7). For variation 2, the lateral branch of the nerve to vastus intermedius innervated the superolateral quadrant (Figure 2E ant.) [20,31]. The articular branch of the common fibular nerve has also been reported to have two variations: 1) it innervated the lateral aspect of the knee joint [23,24,28] and 2) it gave rise to the superior lateral genicular nerve and/or inferior lateral genicular nerve and also innervated the superolateral quadrant [31] or anterolateral part [20] of the knee joint directly via its own branches (Figures 1B, 2D and 2F ant. and post.). The superior lateral genicular nerve arose from either 1) the sciatic nerve just superior to its bifurcation or the common fibular nerve and coursed inferiorly [22,29,31] or 2) the articular branch of the common fibular nerve and coursed superiorly [20,31] to join the superior lateral genicular artery just superior to the lateral femoral condyle [31]. Two studies reported that the superior lateral genicular nerve innervated the superolateral quadrant [22,31], whereas another study reported that it innervated the anterolateral part of the knee joint (Figure 2D post.), occasionally coursing within the knee joint capsule as far inferiorly as the border of the lateral tibial condyle and almost to the patellar ligament [20].

Anterolateral Part: Inferolateral Quadrant

The inferolateral quadrant of the knee joint has been reported to receive innervation from two nerves: 1) the inferior lateral genicular nerve and 2) the recurrent fibular nerve (ordered from superior to inferior [31]). Table 8 summarizes the origin, number of articular branches, course, distribution, and frequency of each nerve. The inferior lateral genicular nerve has been found to have two variations: 1) it arose from the common fibular nerve and coursed deep to the biceps femoris tendon to accompany the inferior lateral genicular artery [21,22]; and 2) it arose from the articular branch of the common fibular nerve and coursed deep to the lateral collateral ligament to accompany the inferior lateral genicular artery just inferior to the lateral femoral condyle [20,31]. Three studies found that the inferior lateral genicular nerve innervated the inferolateral quadrant [21,22,31], specifically the superior part of the inferolateral quadrant of the knee joint capsule in one of these studies [31], whereas another study found that it innervated the anterolateral part of the knee joint (Figure 2D ant. and post.) as far inferiorly within the knee joint capsule as the lateral tibial condyle in five fetal specimens [20]. The recurrent fibular nerve has been reported to divide into one to three branches [22,31]. Five studies found that the recurrent fibular nerve innervated the inferolateral quadrant [21,22,24,28,31], specifically the inferior part of the inferolateral quadrant of the knee joint capsule in one of these studies [31], whereas another study found that it coursed anteriorly around the neck of the fibula and then superiorly to innervate the anterolateral part of the knee joint (Figures 1 and 2 ant. and post.) in five fetal specimens [20].

Posterior Knee Joint Innervation

The posterior innervation of the knee joint was reported in most studies to be from the popliteal plexus, formed

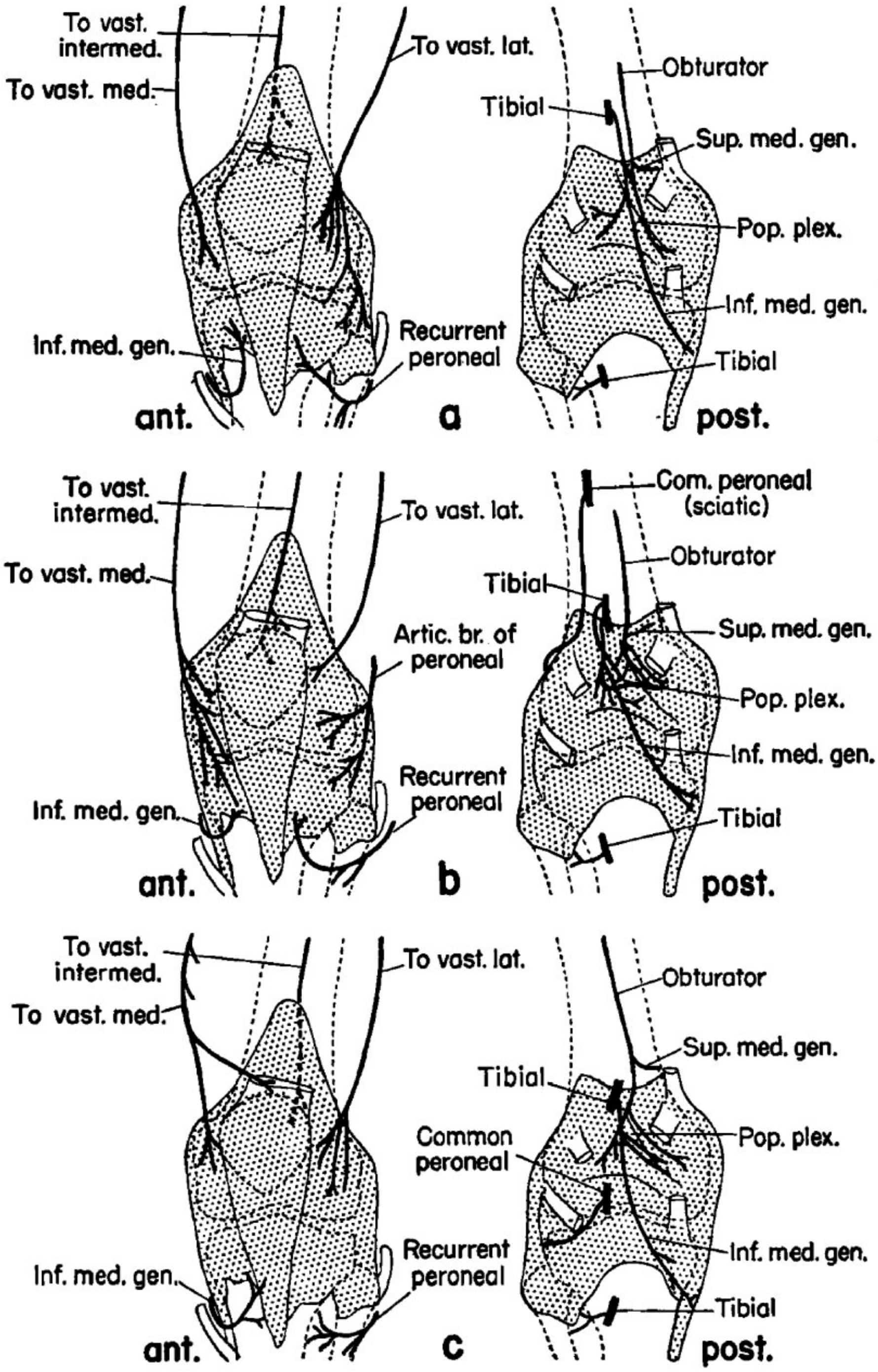

Figure 1. Innervation of knee joint, anterior and posterior views. A–C) Variations in innervation pattern. Peroneal = fibular; stippling = knee joint capsule. Reproduced with permission from Gardner [20]. Copyright John Wiley and Sons.

by 1) articular branch(es) of the tibial nerve and 2) the posterior branch of the obturator nerve (Figure 2F post.) [20–22,32]. One to five articular branches of the tibial nerve were found to contribute to the popliteal plexus, most commonly one large branch (Table 9). These branches were reported to originate either in the thigh (10–25 cm superior to the joint line in one study [22]: N = 45]) or within the popliteal fossa (Table 9). The posterior branch of the obturator nerve contributed to the popliteal plexus in most specimens ([20]: N = 9/11 [81.8%]; [21,22];[32]: N = 10/10 [100.0%]). Only one study found in one of 11 (9.1%) specimens that the anterior branch of the obturator nerve anastomosed with an articular branch of the saphenous nerve in the adductor canal to form a branch that accompanied the femoral artery into the popliteal fossa and contributed to the popliteal plexus [20]. In contrast, Tran et al. [33] found that the posterior knee joint capsule was innervated by

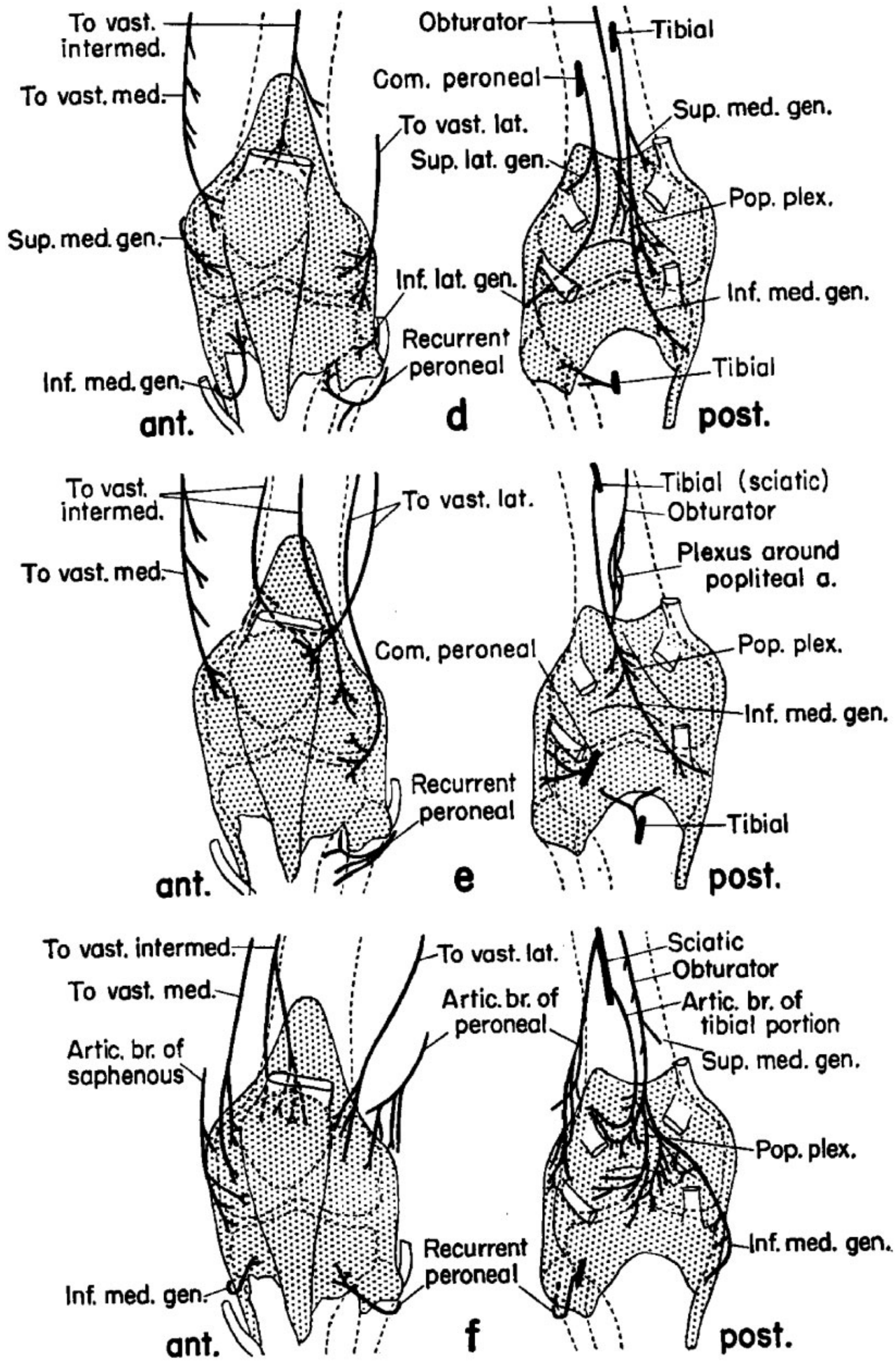

Figure 2. Innervation of knee joint, anterior and posterior views. D–F) Variations in innervation pattern. Peroneal = fibular; stippling = knee joint capsule. Reproduced with permission from Gardner [20]. Copyright John Wiley and Sons.

1) articular branch(es) of the tibial nerve (inferior branch only in N = 8/15 [53.3%]; both superior and inferior branches in N = 7/15 [46.7%]) (Table 9); 2) the articular branch of the posterior branch of the obturator nerve (N = 15/15 [100.0%]); and 3) the posterior branch of the common fibular nerve (N = 8/15 [53.3%]) or sciatic nerve (N = 3/15 [20.0%]). Tran et al. [33] reported that these articular branches "interdigitated to form a fine plexus" but did not refer to it as the popliteal plexus and did not report an anastomosis of articular branches, as reported by Gardner [20].

The popliteal plexus surrounds and supplies the popliteal artery and vein [20]. In a study of 11 adult and five fetal specimens, Gardner [20] reported that the popliteal plexus innervated the oblique popliteal ligament and the fibrous layer of the posterior part of the knee joint capsule, with fibers from the posterior branch of the obturator nerve mainly innervating the superior region of the

Table 5. Anterior knee joint innervation: Inferomedial quadrant

	Infrapatellar Branch of Saphenous Nerve	Inferior Medial Genicular Nerve
Origin	Saphenous nerve (a branch of femoral nerve)* (level of origin: variable within thigh from femoral triangle to medial aspect of knee) (Table 6)	Tibial nerve [26,31] or direct continuation of articular branch of tibial nerve arising from popliteal plexus [20]
No. of articular branches	1	1
Course	Most commonly emerges from adductor canal anterior to sartorius [25,31], pierces deep fascia to become subcutaneous, then courses anteroinferiorly and divides into 1–3 branches that course between patella and tibial tuberosity†,‡	Anteriorly, inferior to medial tibial condyle, deep to medial collateral ligament with IMGA&V†,§
Distribution¶	• Mainly cutaneous (skin overlying anteromedial aspect of knee and inferior to patella) • Knee joint capsule: inferomedial quadrant [21,22,24,31]‖ or anteromedial part [20,23,28]‖‖ (only in a small number of specimens via 1 [20] or a few [31] small branches in 2 studies) • Infrapatellar fat pad ([20]: N = 5/5 [100.0%] fetuses)	• Knee joint capsule: inferomedial quadrant [31] ‖ or anteromedial part [20]** • Tibial periosteum [20] • BVs supplying medial tibial condyle ([20]: N = 5/5 [100.0%] fetuses)
References††	9 studies ([20]: N = 5/15 [33.3%]; [21];[22]: N = 45/45 [100.0%]; [23];[24]: N = 8/8 [100.0%]; [25]: N = 32/32 [100.0%]‡‡; [27]: N = 11/20 [55.0%]‡‡; [28]: N = 25/25 [100.0%]; [31]: N = 3/15 [20.0%]§§)	3 studies ([20];[26]: N = 10/10 [100.0%]; [31]: N = 15/15 [100.0%])
Figures	2F ant.	1 and 2 ant., post.

Ant. = anterior; BV = blood vessel; IMGA&V = inferior medial genicular artery and vein; IMGN = inferior medial genicular nerve; IPBSN = infrapatellar branch of the saphenous nerve; post. = posterior.

*The anterior branch of the obturator nerve anastomosed with the saphenous nerve in the adductor canal, contributing to the IPBSN in some specimens in four studies ([20];[22]: N = 5/45 [11.1%]; [27]: N = 2/20 [10.0%]; [30]: N = 1/14 [7.1%]).

†Courses at periosteal level before penetrating anterior knee joint capsule [26,31].

‡One branch in N = 13/32 (40.6%); two branches in N = 11/32 (34.3%); three branches in N = 8/32 (25.0%) [25].

§Yasar et al. [26] found in N = 4 that the medial collateral ligament was an ultrasound landmark for the IMGN and that the target point for nerve blocks was "the bony cortex at the midpoint between the peak of the tibial medial epicondyle and the initial fibers inserting on the tibia of the medial collateral ligament."

¶Inferomedial quadrant innervation: nerves ordered from superior to inferior [31].

‖Tran et al. [31] reported that the IPBSN innervated the superior part of the inferomedial quadrant and the IMGN innervated the inferior part of the inferomedial quadrant.

‖‖Gardner [20] reported that some branches of the IPBSN innervating the anteromedial part of the knee joint capsule coursed almost to the patellar ligament in N = 5 adult specimens. Gardner [20] also found that the IPBSN anastomosed with the articular branch of the nerve to vastus medialis and the superior medial genicular nerve (variation 2) in the fibrous layer of the anteromedial part of the knee joint capsule in N = 5 fetuses.

**Gardner [20] reported that the IMGN innervated the anteromedial part of the knee joint capsule in the region of the patellar ligament in N = 11 adult specimens and that some branches coursed almost to the inferior part of the patellar ligament in N = 5 fetuses.

††Frequency of variations given for studies that reported it; other studies reported the presence of the variations, but not the frequency.

‡‡Only innervated the skin.

§§Sakamoto et al. [30] reported that "articular branches [from the femoral nerve; N = 4/14 {28.6%}] ran down the adductor canal separately from the saphenous nerve, perhaps similar to the articular branch originating from the saphenous nerve reported in previous studies." These "articular branches entered the knee joint capsule at the medial region of the patella ligament" [30].

Table 6. Level of origin of infrapatellar branch of saphenous nerve

Authors	N	Level of Origin
Gardner [20]	15	FT or just proximal to ADH
Kennedy et al. [21]	15	Between tendons of SR and GR
Horner and Dellon [22]	45	TH:proximal third (17.6%), middle third (58.8%), distal third (23.5%)
Franco et al. [24]	8	Medial aspect of knee
Burckett-St. Laurant et al. [27]	11	ADC: proximal third (9.1%); medial aspect of knee (90.9%)
Orduña Valls et al. [28]	25	Distally in fascia between SR and VM (92.0%) or more proximally (8.0%)

ADC = adductor canal; ADH = adductor hiatus; FT = femoral triangle; GR = gracilis; NR = not reported; SR = sartorius; TH = thigh; VM = vastus medialis.

posteromedial part. Consistent with the findings of Gardner [20], Tran et al. [33] found that the articular branches of the tibial nerve innervated the entire posterior knee joint capsule and the articular branch of the posterior branch of the obturator nerve innervated the superomedial aspect of the posterior knee joint capsule in all 15 specimens. The tibial nerve innervated the entire posterior knee joint capsule either via its inferior branch only (N = 8/15 [53.3%]) or via its superior branch to the superior one-third and inferior branch to the inferior two-thirds (N = 7/15 [46.7%]) [33]. In contrast to the findings of Gardner [20], Tran et al. [33] found that the posterior branch of the common fibular nerve or sciatic nerve innervated the superolateral aspect of the posterior knee joint capsule in 11 of 15 (73.3%) specimens. Tran et al. [33] localized 1) articular branch(es) of the tibial

Table 7. Anterior knee joint innervation: Superolateral quadrant

	Nerve to Vastus Lateralis	Nerve to Vastus Intermedius		Articular Branch of Common Fibular Nerve		Superior Lateral Genicular Nerve	
		Variation 1	Variation 2	Variation 1	Variation 2	Variation 1	Variation 2
Origin	Femoral nerve	Femoral nerve	Femoral nerve	Common fibular nerve (level of origin: variable, popliteal fossa [28], or lateral aspect of joint [24])	Common fibular nerve (level of origin: variable, frequently midthigh (from common fibular portion of sciatic nerve) or popliteal fossa ([20]: N = 11) or just inferior to bifurcation of sciatic nerve ([31]: N = 15/15 [100.0%])	Sciatic nerve (level of origin: just superior to bifurcation [29]: N = 16/20 [80.0%]; [31]: N = 5/15 [33.3%]; or 8–10 cm superior to joint line [22]: N = 45]) or common fibular nerve ([29]: N = 4/20 [20.0%]; level of origin: close to superior border of popliteal fossa)	Articular branch of common fibular nerve
No. of articular branches	1	≥1 (most commonly 1)	Divides into a medial branch (to superomedial quadrant) and a lateral branch (to superolateral quadrant)	1	1	1	1
Course	Inferiorly along anteromedial border of VL, between VL and VI*	Inferiorly on anterior surface of femur, deep to VI, and enters suprapatellar pouch	Lateral branch: inferiorly, IM through VI, then distally on anterolateral surface of femur†	Laterally from popliteal fossa, deep to biceps femoris	• Anteroinferiorly at level of superior border of lateral femoral condyle† • Gives rise to superior lateral genicular nerve ([20];[31: N = 10/15 [66.7%]) and/or inferior lateral genicular nerve ([20];[31]: N = 15/15 [100.0%]) • Also innervates directly via its own branches ([20];[31]: N = 15/15 [100.0%])	Inferiorly on posterolateral surface of femur, deep to biceps femoris, then just superior to lateral femoral condyle, courses anteriorly to accompany SLGA&V†	Arises just superior to lateral femoral condyle and courses superiorly to accompany SLGA&V†

(continued)

Table 7. continued

	Nerve to Vastus Lateralis	Nerve to Vastus Intermedius		Articular Branch of Common Fibular Nerve		Superior Lateral Genicular Nerve	
		Variation 1	Variation 2	Variation 1	Variation 2	Variation 1	Variation 2
Distribution‡	• Knee joint capsule: superolateral quadrant [21,23,24,31] or anterolateral part [20,28,30]§ • Infrapatellar fat pad, patellar periosteum, and BVs supplying lateral femoral condyle ([20]: N = 5/5 [100.0%] fetuses)	• Knee joint capsule: suprapatellar pouch • Periosteum of anterior surface of femur to border of articular cartilage [20] • BVs supplying suprapatellar pouch and adjacent femur ([20]: N = 5/5 [100.0%] fetuses)	Lateral branch: • Knee joint capsule: superolateral quadrant • Periosteum of anterior surface of femur to border of articular cartilage [20]	• Knee joint capsule: lateral aspect	• Knee joint capsule: superolateral quadrant [31] or anterolateral part [20]§ • Infrapatellar fat pad, tibial periosteum, and BVs supplying lateral femoral condyle ([20]: N = 5/5 [100.0%] fetuses)	• Knee joint capsule: superolateral quadrant [22,31] • Lateral retinaculum (via lateral retinacular nerve branch [22]: N = 5/45 [11.1%]; [29]: N = 20/20 [100.0%¶]) • Synovial surface of lateral epicondyle of femur [29]	• Knee joint capsule: superolateral quadrant [31] or anterolateral part [20]§ • Infrapatellar fat pad, tibial periosteum, and BVs supplying lateral femoral condyle ([20]: N = 5/5 [100.0%] fetuses)
References‖	7 studies ([20,21,23];[24]: N = 8/8 [100.0%]; [28]: N = 25/25 [100.0%]; [30]: N = 1/14 [7.1%]; [31]: N = 15/15 [100.0%])	5 studies ([20,21];[22]: N = 45/45 [100.0%];[24]: N = 8/8 [100.0%]; [30]: N = 11/14 [78.6%]‖‖)	2 studies ([20];[31]: N = 15/15 [100.0%])	3 studies ([23];[24]: N = 8/8 [100.0%]; [28]: N = 25/25 [100.0%]**)	2 studies ([20: N = 10/11 [90.9%]; 31: N = 15/15 [100.0%])	3 studies ([22];[29]: N = 20/20 [100.0%]; [31]: N = 5/15 [33.3%]††)	2 studies ([20];[31]: N = 10/15 [66.7%])
Figures	1 and 2 ant.	1 and 2D, F ant.	2E ant.	—	1B and 2D, F ant., post.	—	2D post.

— = not applicable; ant. = anterior; BV = blood vessel; CFN = common fibular nerve; fibular = peroneal; IM = intramuscular; NVL = nerve to vastus lateralis; post. = posterior; SLGA&V = superior lateral genicular artery and vein; SLGN = superior lateral genicular nerve; VI = vastus intermedius; VL = vastus lateralis.

*Mean distance of nerve from periosteum of femur at level of apex of suprapatellar bursa: 0.97 ± 0.27 cm; penetrated knee joint capsule at superolateral aspect of patella ([31]: N = 15).

†Courses at periosteal level before penetrating anterior knee joint capsule [31].

‡Superolateral quadrant innervation: nerves ordered from anterior to posterior [31].

§Gardner [20] reported for the articular branch of the NVL that "the level to which the twigs descend and the extent to which they branch varies inversely according to the distribution of the articular branch of the common peroneal [fibular] nerve." In N = 1/11 (9.1%) adult specimens, no articular branch of the CFN was found; however, the articular branch of the NVL "had an extensive distribution to the anterolateral portion of the joint capsule" (Figure 1A ant.) [20]. Gardner [20] also reported that some branches of the articular branches of the NVL and CFN innervating the anterolateral part of the knee joint capsule coursed almost to the tibial tuberosity in N = 5 fetuses. In addition, some branches of the SLGN (variation 2) innervating the anterolateral part of the knee joint capsule occasionally coursed as far inferiorly as the border of the lateral tibial condyle and almost to the patellar ligament in N = 11 adult specimens [20].

¶Sutaria et al. [29] found in N = 20 that "the branch point of the lateral retinacular nerve from the superior lateral genicular nerve was, on average, 5.5 ± 0.66 cm (with a range of 4.5–7.0 cm) proximal to the lateral tibiofemoral joint line in line with the head of the fibula and 2.6 ± 0.62 cm (2.0–4.5 cm) proximal to the tip of the lateral femoral epicondyle."

‖Frequency of variations given for studies that reported it; other studies reported the presence of the variations but not the frequency.

‖‖Orduña Valls et al. [28] reported that the nerve to vastus intermedius "descends along the fascia between the vastus lateralis and vastus intermedialis muscles to the distal portion of the femur, where it branches out to the periosteum of the prepatellar bursa."

**Lateral retinacular nerve [24,28].

††Hirosawa et al. [23] reported that "the tibial nerve projected articular branches at the popliteal fossa. . .[that] innervate the articular capsule following the superomedial popliteal vessels and the superolateral vessels."

Table 8. Anterior knee joint innervation: Inferolateral quadrant

	Inferior Lateral Genicular Nerve		
	Variation 1	Variation 2	Recurrent Fibular Nerve
Origin	Common fibular nerve	Articular branch of common fibular nerve	Common fibular nerve
No. of articular branches	1	1	1
Course	Arises posterosuperior to head of fibula and courses anteriorly, deep to biceps femoris tendon, to accompany ILGA&V	Inferiorly, deep to lateral collateral ligament, then anteriorly with ILGA&V, just inferior to lateral femoral condyle*	Arises inferior to head of fibula and courses anteriorly around neck of fibula, then anterosuperiorly IM through tibialis anterior; divides into 1–3 branches ([22]: N =45; [31]: N =15);* when 2 branches are present, they course [22]: 1. Between head of fibula and Gerdy's tubercle 2. Between Gerdy's tubercle and tibial tuberosity
Distribution†	• Knee joint capsule: inferolateral quadrant • Lateral collateral ligament [21]	• Knee joint capsule: inferolateral quadrant [31]‡ or anterolateral part [20]§ • BVs supplying lateral tibial condyle [20]	• Knee joint capsule: inferolateral quadrant [21,22,24,28,31]‡ or anterolateral part [20]¶ • Periosteum of anterolateral surface of tibia [20] • Tibial tuberosity [20] • Infrapatellar fat pad ([20]: N =5/5 [100.0%] fetuses) • Superior tibiofibular joint [20,22]
References‖	2 studies [21,22]‖‖,**	2 studies ([20];[31]: N =15/15 [100.0%])	6 studies ([20–22];[24]: N = 8/8 [100.0%]; [28]: N =8/25 [32.0%]; [31]: N = 15/15 [100.0%])
Figures	—	2D ant., post.	1 and 2 ant., post.

— = not applicable; ant. = anterior; BV = blood vessel; fibular = peroneal; ILGA&V = inferior lateral genicular artery and vein; ILGN = inferior lateral genicular nerve; IM = intramuscular; post. = posterior; RFN = recurrent fibular nerve.

*Courses at periosteal level before penetrating anterior knee joint capsule [31].

†Inferolateral quadrant innervation: nerves ordered from superior to inferior [31].

‡Tran et al. [31] reported that the ILGN innervated the superior part of the inferolateral quadrant and the RFN innervated the inferior part of the inferolateral quadrant.

§Gardner [20] reported that branches of the ILGN (variation 2) innervating the anterolateral part of the knee joint capsule coursed as far inferiorly as the lateral tibial condyle in N = 5 fetuses.

¶Gardner [20] reported that the RFN "fibers accompany blood vessels which supply the anterolateral portion of the tibia and some continue superiorly, pierce the capsule of the knee joint and enter the infrapatellar fat pad" in N = 5 fetuses.

‖Frequency of variations given for studies that reported it; other studies reported the presence of the variations but not the frequency.

‖‖Lateral articular nerve [21,22].

**Hirosawa et al. [23] reported that "the common peroneal [fibular] nerve also projected an articular branch...[that] ran with the inferolateral popliteal vessels and innervated the anterolateral side of the articular capsule."

nerve at the level of the superior border of the medial femoral condyle and intercondylar fossa (Table 9); 2) the articular branch of the posterior branch of the obturator nerve "in close proximity to the popliteal artery at the level of the medial femoral condyle"; and 3) the posterior branch of the common fibular nerve or sciatic nerve "by the popliteal vein at the level of the lateral femoral condyle."

Only two studies traced the nerves within the knee joint [20,23]. Gardner [20] found that the popliteal plexus also innervated intra-articular structures. In five fetal specimens, branches of the popliteal plexus coursed anteriorly with blood vessels 1) along the attachment of the knee joint capsule to the menisci almost as far as the infrapatellar fat pad and innervated the external part of the menisci and 2) within the synovial membrane that lines the cruciate ligaments as far anteriorly as the infrapatellar fat pad and with the blood vessels supplying the cruciate ligaments and adjacent tibia and femur [20]. In contrast, Hirosawa et al. [23] found in five adult specimens that the anterior cruciate ligament was innervated by nerves supplying the anterior part of the knee joint

Table 9. Number and level of origin of articular branches of tibial nerve innervating posterior knee joint

Authors	N	No. of Articular Branches	Level of Origin
Gardner [20]	11	≥1*	TH > PF
Kennedy et al. [21]	15	1	TH or PF
Horner and Dellon [22]	45	1–5*	TH†
Orduña Valls et al. [28]	25	2–4	PF
Tran et al. [33]	15	1–2‡	PF‡

PF = popliteal fossa; TH = thigh.
*Most commonly one large branch.
†10–25 cm superior to joint line [22].
‡One branch in N = 8/15 (53.3%); two branches in N = 7/15 (46.7%) [33]. Superior branch originated proximal and inferior branch originated distal to the superior border of the medial femoral condyle [33].

capsule (articular branches of the femoral, common fibular, and saphenous nerves), the posterior cruciate ligament by nerves supplying the posterior part of the capsule (articular branch of the tibial nerve and posterior branch of the obturator nerve), and the peripheral border of the menisci by both. Gardner [20] reported that the tibial nerve also gave off a few branches inferior to the popliteal fossa that innervated the fibular periosteum, and occasionally the superior tibiofibular joint and "the most inferior portion of the capsule of the knee joint."

Bony Landmarks

Precise bony landmarks identifiable with fluoroscopy and ultrasound have been determined for three nerves innervating the anterior knee joint: 1) the superior medial genicular nerve just anterior to the adductor tubercle [26,31], "the bony cortex one cm anterior to the peak of the adductor tubercle" in one study of four specimens [26]; 2) the inferior medial genicular nerve inferior to the medial tibial condyle, deep to the medial collateral ligament [20,26,31], "the bony cortex at the midpoint between the peak of the tibial medial epicondyle and the initial fibers inserting on the tibia of the medial collateral ligament" in one study of four specimens [26]; and 3) the recurrent fibular nerve divided into two branches, one that coursed between the head of the fibula and Gerdy's tubercle and the other between Gerdy's tubercle and the tibial tuberosity in one study of 45 specimens [22]. No precise bony landmarks identifiable with fluoroscopy and ultrasound were found in the literature for the remaining nine or 10 nerves innervating the knee joint.

Discussion

The findings of this review show that commonly used RFA techniques would not be able to completely denervate the knee joint based upon the complexity and wide variability of its innervation, which is far more elaborate than what is currently targeted. Recent anatomical studies have shown a wide variability of innervation to the anterior and posterior knee joint capsule [31,33]. In addition, the posterior knee joint innervation penetrates as far anterior as the infrapatellar fat pad [20] and has not been addressed with current knee RFA techniques.

Commonly used knee RFA techniques [2,18] only target three of 12 or 13 nerves innervating the knee joint: the superior lateral, superior medial, and inferior medial genicular nerves (Figure 3). A recent study by Cushman et al. [34] investigated which nerves would be captured using common targets by mapping the following on anterior–posterior and lateral fluoroscopic images of the knee: 1) the estimated course of the nerves based on the anterior knee joint capsule innervation frequency map in the anatomical study by Tran et al. ([31]: N = 15) and 2) the estimated cooled monopolar RFA lesion at each target site (Table 1), assuming a lesion diameter of 8–10 mm based on lesion size data from ex vivo bovine liver using an 18-gauge cooled RF electrode with a 4-mm active tip at 60°C for 2.5 minutes [35]. Cushman et al. [34] found that the superior lateral genicular nerve (variations 1 and 2) and inferior medial genicular nerve may be captured, but the superior medial genicular nerve (variation 3) may not be captured in some individuals using common targets. In addition, one or more articular branches of the nerve to vastus medialis and the articular branch of the common fibular nerve (variation 2) may be captured in some individuals using cooled RF with the current targets for the superior medial and superior lateral genicular nerves, respectively [34]. According to their study, seven or eight nerves would remain untreated with current cooled RF targets [34]. The findings of this review suggest that the current target for the inferior medial genicular nerve may be adequate [20,26,31] but that the adductor tubercle is a more precise anatomic target for the superior medial genicular nerve than the current target [26,31]. More medially located bony landmarks were identified by Horner and Dellon [22] for the recurrent fibular nerve. These potential anatomic targets need to be validated and shown to be safe. No other precise bony landmarks identifiable with fluoroscopy and ultrasound have been determined that could be currently used to target the remaining nerves innervating the knee joint.

It is important to consider intracapsular nerve distribution patterns when developing new diagnostic blocks to determine the source of pain and RFA techniques to denervate it. Intracapsular nerve distribution patterns showed that some nerves innervate two quadrants (superior and inferior), forming the anteromedial or anterolateral part of the anterior knee joint [20]. Gardner [20] demonstrated that the articular branch of the nerve to vastus medialis and the superior medial genicular nerve (variation 2) most commonly penetrated the superomedial quadrant to innervate both the superomedial and inferomedial quadrants (anteromedial part) intracapsularly. Similarly, the articular branch of the nerve to vastus lateralis, the articular branch of the common fibular nerve, and the superior lateral genicular nerve most frequently penetrated the superolateral quadrant to

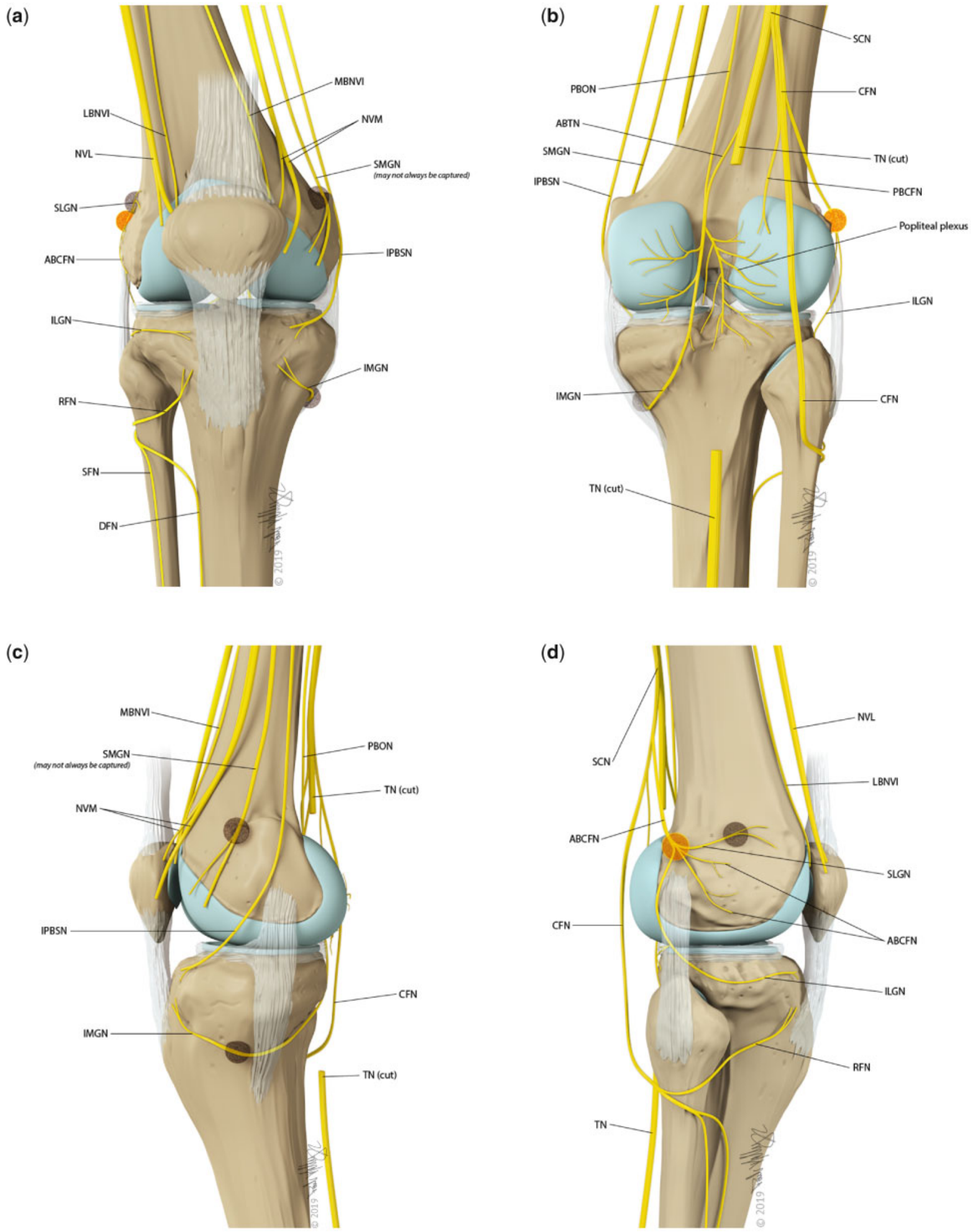

Figure 3. Innervation of the knee joint vs current and proposed cooled radiofrequency ablation targets, 3D model. A) Anterior view. B) Posterior view. C) Medial view. D) Lateral view. Current targets (black circles) for the SLGN (A and D), SMGN and IMGN (A and C). Proposed target (orange circle) may capture three nerves (ABCFN, SLGN, and/or ILGN) with a single lesion (A, B, and D). Black/orange circles indicate cooled monopolar radiofrequency lesions [33]. ABCFN = articular branch of common fibular nerve; ABTN = articular branch of tibial nerve; CFN = common fibular nerve; DFN = deep fibular nerve; ILGN = inferior lateral genicular nerve; IMGN = inferior medial genicular nerve; IPBSN = infrapatellar branch of saphenous nerve; LBNVI = lateral branch of nerve to vastus intermedius; MBNVI = medial branch of nerve to vastus intermedius; NVL = nerve to vastus lateralis; NVM = nerve to vastus medialis; PBCFN/SCN = posterior branch of common fibular nerve or sciatic nerve; PBON = posterior branch of obturator nerve; RFN = recurrent fibular nerve; SCN = sciatic nerve; SFN = superficial fibular nerve; SLGN = superior lateral genicular nerve; SMGN = superior medial genicular nerve; TN = tibial nerve. Images printed with permission from *PKVisualization*.

innervate both the superolateral and inferolateral quadrants (anterolateral part) intracapsularly [20]. Alternatively, in some specimens, the articular branch of the nerve to vastus medialis and the infrapatellar branch of the saphenous nerve penetrated and innervated both the superomedial and inferomedial quadrants (anteromedial part) intracapsularly, while the articular branch of the nerve to vastus lateralis and the articular branch of the common fibular nerve penetrated and innervated both the superolateral and inferolateral quadrants (anterolateral part) intracapsularly [20]. These findings demonstrate that the inferomedial and inferolateral quadrants of the knee joint capsule are more highly innervated than is suggested by nerve entry points. Therefore, capturing these nerves with RFA may partially denervate the inferomedial and inferolateral quadrants.

Some knee RFA techniques have targeted the infrapatellar branch of the saphenous nerve in patients with chronic knee OA pain [36] or persistent pain following TKA [37]. The findings of this review suggest that the infrapatellar branch of the saphenous nerve provides mainly cutaneous innervation; it may only innervate the superior part of the inferomedial quadrant ([31]: N = 3/15 [20.0%]) or anteromedial part ([20]: N = 5/15 [33.3%]) of the knee joint capsule in a minority of individuals via a few small branches. Therefore, the infrapatellar branch of the saphenous nerve may not need to be captured in patients with chronic knee OA pain. In contrast, it may need to be captured in patients with persistent pain following TKA if some of the patient's pain is due to injury of the infrapatellar branch of the saphenous nerve [37]. In either case, rigorous diagnostic blocks can be used to determine if the infrapatellar branch of the saphenous nerve mediates some of the patient's pain and, thus, if it needs to be treated with RFA.

Clinically, the inferior lateral genicular nerve and the recurrent fibular nerve innervating the inferolateral quadrant [21,22,24,28,31] or anterolateral part [20] of the knee joint are not targeted with RFA due to the risk of injury to the common fibular nerve [38]. However, the articular branch of the common fibular nerve gave rise to the superior lateral genicular nerve ([20];[31]: N = 10/15 [66.7%]) and/or inferior lateral genicular nerve ([20];[31]: N = 15/15 [100.0%]) in two studies. Therefore, potentially capturing the articular branch of the common fibular nerve may also capture the superior lateral and/or inferior lateral genicular nerves, and thus three nerves may be captured by a single block or RFA lesion. The block/RFA needle would theoretically be placed just proximal to the branching point of the articular branch of the common fibular nerve into the superior lateral and/or inferior lateral genicular nerves and direct articular branches to capture all three nerves with a single block or RFA lesion (Figure 3A, B, and D). Further anatomical research is required to determine a precise, safe, and quantitative bony landmark identifiable with fluoroscopy and ultrasound to guide needle placement for this target. This would reduce the total number of lesions required, and thus decrease damage to other surrounding structures. This technique may help to provide partial denervation of the inferolateral quadrant.

The posterior knee joint innervation is not targeted with RFA due to the risk of injury to vital neurovascular structures. The posterior knee joint was reported to be innervated by two or three nerves (most commonly via the popliteal plexus) vs 10 nerves supplying the anterior knee joint [20–33]. However, the popliteal plexus makes an important contribution to the innervation of the knee joint by supplying both the posterior knee joint capsule and intra-articular structures [20]. Further research is required to better understand the contribution of the posterior innervation to different types of knee pain and then develop safe, rigorous methods for diagnosis and treatment.

It may not be necessary to capture all of the nerves innervating the knee joint to effectively treat pain. Additionally, lesioning more sites than is necessary may potentially be harmful [39,40]. Only the nerves mediating a patient's pain need to be captured. Development and validation of specific diagnostic blocks targeting the presumed nerves mediating each patient's pain would be appropriate. This would allow for optimization of patient selection and tailored knee RFA techniques, which should improve clinical outcomes.

The limitations of this review include the small sample size of each anatomical study, which does not account for all anatomical variations. In addition, most studies focused on the innervation of the knee joint capsule, most commonly the anterior aspect, and traced the nerves to their entry points in adult specimens [21–31]. Only one study traced the nerves to their terminal branches in the knee joint in adult specimens and serial fetal sections [20]. Data on intra-articular innervation are limited [20,23]. Furthermore, not all studies reported the frequency of nerve variations. Additionally, the ability of common RFA targets [2,18] to capture the nerves innervating the anterior knee joint capsule was evaluated in one study [34] based on the estimated course of the nerves mapped on fluoroscopic images ([31]: N = 15) and lesion size assumptions derived from findings in ex vivo bovine liver [35]. Anatomical variations exist [20–31]. In vivo lesion sizes in humans may be different in clinical practice [35]. If these assumptions are not valid, then nerve capture rates would be different.

There is a lack of precise, quantitative, and validated bony landmarks identifiable with fluoroscopy and ultrasound for knee diagnostic blocks and RFA in the literature. Such data are necessary to optimize nerve capture rates. Precise, validated anatomic targets are required for the development of new diagnostic blocks and RFA techniques that would be able to completely denervate the knee joint, and thus optimize clinical outcomes.

To address these knowledge gaps, future anatomical studies are required 1) to further investigate the distribution of terminal nerve branches in the knee joint, including intracapsular nerve distribution patterns and intra-articular structures; 2) to visualize and quantify in 3D the course and distribution of each nerve innervating the knee joint and surrounding blood vessels relative to bony and soft tissue landmarks identifiable with fluoroscopy and/or ultrasound as in situ; 3) fluoroscopic imaging with radiopaque wires sutured directly over the nerves to determine precise, validated anatomic targets, such that any combination of targets could be used to develop new diagnostic blocks and patient-specific RFA techniques only targeting the nerves mediating each patient's pain; and 4) to evaluate the accuracy, consistency, effectiveness (nerve capture rates), and safety of these new targets using fluoroscopic and/or ultrasound guidance in cadaveric specimens. Future clinical studies are needed 1) to investigate the use of Doppler ultrasound in combination with fluoroscopy to localize the target nerves via their accompanying blood vessels [6,38,39,41]; 2) to develop and validate new diagnostic blocks; and 3) to evaluate clinical outcomes using rigorous diagnostic blocks and patient-specific knee RFA techniques with fluoroscopic and/or ultrasound guidance.

From the literature, it appears that the biggest diversity in neuroanatomy of the knee exists in the superomedial and superolateral quadrants. Further clinical studies may determine if alternate or additional targets in these regions would be beneficial in knee RFA.

There are a number of studies that support significant and lasting pain relief with knee RFA (at the traditionally targeted points) [42]. Though, as pointed out in critiques, at least one of these studies has some significant flaws [4]. Further clinical study of outcomes with alternate techniques is warranted, as is ensuring proper patient selection. It is important to define block criteria for prognostic blocks. It has been shown that a single block with 1 mL of local anesthetic and a criterion of ≥50% pain relief does not improve treatment success [43]. From corollary literature and guidelines set forth by the Spine Intervention Society, a higher degree of relief (≥80% pain relief) and dual comparative blocks [19] would likely improve the specificity of prognostic blocks for knee RFA.

Conclusions

Commonly used knee RFA techniques would not be able to completely denervate the knee joint, as it is innervated by a greater number of nerves than are currently targeted. Further anatomical research is required to determine precise, validated anatomic targets, which would then be used to develop new diagnostic blocks and RFA techniques. Future clinical studies are required to validate these diagnostic blocks and evaluate the impact of patient-specific knee RFA techniques on clinically meaningful outcomes.

Acknowledgments

The authors would like to thank Paul F. Kelly, MScBMC, CMI, PKVisualization, Toronto, Ontario, Canada, for his valuable professional artistic expertise in creating Figure 3. The authors would also like to thank the individuals who donate their bodies and tissue for the advancement of education and research.

References

1. Lord SM, McDonald GJ, Bogduk N. Percutaneous radiofrequency neurotomy of the cervical medial branches: A validated treatment for cervical zygapophysial joint pain. Neurosurg Q 1998;8(4):288–308.
2. Choi WJ, Hwang SJ, Song JG, et al. Radiofrequency treatment relieves chronic knee osteoarthritis pain: A double-blind randomized controlled trial. Pain 2011; 152(3):481–7.
3. Clemente CD. Anatomy of the Human Body by Henry Gray. Philadelphia: Lea & Febiger; 1985. p. 1239–41.
4. Gofeld M. Letter to the editor. Pain 2014;155 (4):836–7.
5. Choi WJ, Shin JW. Response to letter to the editor. Pain 2014;155(4):837.
6. Protzman NM, Gyi J, Malhotra AD, et al. Examining the feasibility of radiofrequency treatment for chronic knee pain after total knee arthroplasty. PM R 2014;6 (4):373–6.
7. Sarı S, Aydın ON, Turan Y, et al. Which one is more effective for the clinical treatment of chronic pain in knee osteoarthritis: Radiofrequency neurotomy of the genicular nerves or intra-articular injection? Int J Rheum Dis 2018;21(10):1772–8.
8. Iannaccone F, Dixon S, Kaufman A. A review of long-term pain relief after genicular nerve radiofrequency ablation in chronic knee osteoarthritis. Pain Physician 2017;20:E437–44.
9. Qudsi-Sinclair S, Borrás-Rubio E, Abellan-Guillén JF, et al. A comparison of genicular nerve treatment using either radiofrequency or analgesic block with corticosteroid for pain after a total knee arthroplasty: A double-blind, randomized clinical study. Pain Pract 2017;17(5):578–88.
10. Santana Pineda MM, Vanlinthout LE, Moreno Martín A, et al. Analgesic effect and functional improvement caused by radiofrequency treatment of genicular nerves in patients with advanced osteoarthritis of the knee until 1 year following treatment. Reg Anesth Pain Med 2017;42(1):62–8.
11. Sarı S, Aydın ON, Turan Y, et al. Which imaging method should be used for genicular nerve radio frequency thermocoagulation in chronic knee osteoarthritis? J Clin Monit Comput 2017;31(4):797–803.
12. El-Hakeim EH, Elawamy A, Kamel EZ, et al. Fluoroscopic guided radiofrequency of genicular nerves for pain alleviation in chronic knee osteoarthritis: A single-blind randomized controlled trial. Pain Physician 2018;21:169–77.
13. Bellini M, Barbieri M. Cooled radiofrequency system relieves chronic knee osteoarthritis pain: The first case-series. Anaesthesiol Intensive Ther 2015;47 (1):30–3.
14. Menzies RD, Hawkins JK. Analgesia and improved performance in a patient treated by cooled

radiofrequency for pain and dysfunction postbilateral total knee replacement. Pain Pract 2015;15(6):E54–8.
15. Farrell ME, Gutierrez G, Desai MJ. Demonstration of lesions produced by cooled radiofrequency neurotomy for chronic osteoarthritic knee pain: A case presentation. PM R 2017;9(3):314–7.
16. McCormick ZL, Korn M, Reddy R, et al. Cooled radiofrequency ablation of the genicular nerves for chronic pain due to knee osteoarthritis: Six-month outcomes. Pain Med 2017;18(9):1631–41.
17. Rojhani S, Qureshi Z, Chhatre A. Water-cooled radiofrequency provides pain relief, decreases disability, and improves quality of life in chronic knee osteoarthritis. Am J Phys Med Rehabil 2017;96(1):e5–8.
18. Davis T, Loudermilk E, DePalma M, et al. Prospective, multicenter, randomized, crossover clinical trial comparing the safety and effectiveness of cooled radiofrequency ablation with corticosteroid injection in the management of knee pain from osteoarthritis. Reg Anesth Pain Med 2018;43(1):84–91.
19. Bogduk N, ed. Practice Guidelines for Spinal Diagnostic and Treatment Procedures. 2nd ed. San Francisco: International Spine Intervention Society; 2013.
20. Gardner E. The innervation of the knee joint. Anat Rec 1948;101(1):109–30.
21. Kennedy JC, Alexander IJ, Hayes KC. Nerve supply of the human knee and its functional importance. Am J Sports Med 1982;10(6):329–35.
22. Horner G, Dellon AL. Innervation of the human knee joint and implications for surgery. Clin Orthop Relat Res 1994;(301):221–6.
23. Hirasawa Y, Okajima S, Ohta M, et al. Nerve distribution to the human knee joint: Anatomical and immunohistochemical study. Int Orthop 2000;24(1):1–4.
24. Franco CD, Buvanendran A, Petersohn JD, et al. Innervation of the anterior capsule of the human knee: Implications for radiofrequency ablation. Reg Anesth Pain Med 2015;40(4):363–8.
25. Kalthur SG, Sumalatha S, Nair N, et al. Anatomic study of infrapatellar branch of saphenous nerve in male cadavers. Ir J Med Sci 2015;184(1):201–6.
26. Yasar E, Kesikburun S, Kılıç C, et al. Accuracy of ultrasound-guided genicular nerve block: A cadaveric study. Pain Physician 2015;18:E899–E904.
27. Burckett-St. Laurant D, Peng P, Girón Arango L, et al. The nerves of the adductor canal and the innervation of the knee: An anatomic study. Reg Anesth Pain Med 2016;41(3):321–7.
28. Orduña Valls JM, Vallejo R, López Pais P, et al. Anatomic and ultrasonographic evaluation of the knee sensory innervation: A cadaveric study to determine anatomic targets in the treatment of chronic knee pain. Reg Anesth Pain Med 2017;42(1):90–8.
29. Sutaria RG, Lee SW, Kim SY, et al. Localization of the lateral retinacular nerve for diagnostic and therapeutic nerve block for lateral knee pain: A cadaveric study. PM R 2017;9(2):149–53.
30. Sakamoto J, Manabe Y, Oyamada J, et al. Anatomical study of the articular branches innervated the hip and knee joint with reference to mechanism of referral pain in hip joint disease patients. Clin Anat 2018;31(5):705–9.
31. Tran J, Peng PWH, Lam K, et al. Anatomical study of the innervation of anterior knee joint capsule: Implication for image-guided intervention. Reg Anesth Pain Med 2018;43(4):407–14.
32. Runge C, Moriggl B, Børglum J, et al. The spread of ultrasound-guided injectate from the adductor canal to the genicular branch of the posterior obturator nerve and the popliteal plexus: A cadaveric study. Reg Anesth Pain Med 2017;42(6):725–30.
33. Tran J, Peng PWH, Gofeld M, et al. Anatomical study of the innervation of posterior knee joint capsule: Implication for image-guided intervention. Reg Anesth Pain Med 2019;44(2):234–8.
34. Cushman DM, Monson N, Conger A, et al. Use of 0.5 mL and 1.0 mL of local anesthetic for genicular nerve blocks. Pain Med 2019;20(5):1049–52.
35. Cosman ER Jr, Dolensky JR, Hoffman RA. Factors that affect radiofrequency heat lesion size. Pain Med 2014;15(12):2020–36.
36. Ikeuchi M, Ushida T, Izumi M, et al. Percutaneous radiofrequency treatment for refractory anteromedial pain of osteoarthritic knees. Pain Med 2011;12 (4):546–51.
37. Clendenen S, Greengrass R, Whalen J, et al. Infrapatellar saphenous neuralgia after TKA can be improved with ultrasound-guided local treatments. Clin Orthop Relat Res 2015;473(1):119–25.
38. Bhatia A, Peng P, Cohen SP. Radiofrequency procedures to relieve chronic knee pain: An evidence-based narrative review. Reg Anesth Pain Med 2016;41 (4):501–10.
39. Kim SY, Le PU, Kosharskyy B, et al. Is genicular nerve radiofrequency ablation safe? A literature review and anatomical study. Pain Physician 2016;19 :E697–E705.
40. Kapural L. Bigger is better, or is it? Reg Anesth Pain Med 2018;43(4):339–40.
41. Bhatia A, Hoydonckx Y, Peng P, et al. Radiofrequency procedures to relieve chronic hip pain: An evidence-based narrative review. Reg Anesth Pain Med 2018;43(1):72–83.
42. Jamison DE, Cohen SP. Radiofrequency techniques to treat chronic knee pain: A comprehensive review of anatomy, effectiveness, treatment parameters, and patient selection. J Pain Res 2018;11:1879–88.
43. McCormick ZL, Reddy R, Korn M, et al. A prospective randomized trial of prognostic genicular nerve blocks to determine the predictive value for the outcome of cooled radiofrequency ablation for chronic knee pain due to osteoarthritis. Pain Med 2018;19 (8):1628–38.