NOYES' KNEE DISORDERS

Surgery, Rehabilitation, Clinical Outcomes

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Second Edition

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To JoAnne, my loving and precious wife, and to all our families.

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PREFACE

I am grateful to all of the contributors to this textbook, *Noyes' Knee Disorders*, which is appropriately subtitled *Surgery, Rehabilitation, Clinical Outcomes*. The chapters reflect the writings and teachings of the scientific and clinical disciplines required for the modern treatment of clinical afflictions of the knee joint. Our goal is to present rational, evidence-based treatment programs based on published basic science and clinical data to achieve the most optimal outcomes for our patients.

The key to understanding the different disorders of the knee joint encountered in clinical practice truly rests on a multidisciplinary approach that includes a comprehensive understanding of knee anatomy, biomechanics, kinematics, and biology of soft tissue healing. Restoration of knee function then requires an accurate diagnosis of the functional abnormality of the involved knee structures, a surgical technique that is precise and successful, and a rehabilitation program directed by skilled professionals to restore function and avoid complications. Each chapter follows a concise outline of indications, contraindications, physical examination and diagnosis, step-by-step open and arthroscopic surgical procedures, clinical outcomes, and analysis of relevant published studies.

The second edition of *Knee Disorders* is the result of complete editing of each chapter, the addition of new chapters on partial knee replacements, updates on anterior cruciate ligament (ACL) and posterior cruciate ligament arthroscopic reconstructions as well as posterolateral reconstructions, the addition of clinical studies on meniscus transplants and meniscus repairs, and the addition of newer concepts on neuromuscular testing and conditioning. Importantly, each rehabilitation postoperative protocol for every surgical procedure has been updated because this textbook serves a readership of surgeons, physical therapists, athletic trainers, and exercise specialists. As a result, this textbook has 45 chapters, 30 authors, 1000 figures, 285 tables, and more than 4500 references, including 1500 new references (1050 clinical studies and 450 articles on biomechanics, anatomy, or basic science).

A special feature of second edition is the video library referenced in the chapters, allowing the reader to both read and see the content being presented. There are 45 videos totaling more than 11 hours of content: 11 surgical videos, 19 patient rounds focusing on surgical procedures and postoperative rehabilitation, and 15 presentations of knee content pertaining to certain selected book chapters.

The first two chapters comprise an anatomic description of the structures of the knee joint. The images and illustrations represent the result of many cadaveric dissections to document knee anatomic structures. It was a pleasure to have four of our fellows (class of 2008-2009) involved in these dissections, which resulted in two superb, award-winning instructional anatomic videos included with this book. Numerous anatomy textbooks and publications were consulted during the course of these dissections to provide, to the best of our ability, accurate anatomic descriptions, with the realization there is still ambiguity in the nomenclature used for certain knee structures.

Special thanks go to Joe Chovan, a wonderful and highly talented professional medical illustrator. Joe attended anatomic dissections and worked hand in hand with us to produce the final anatomic illustrations. Joe and I held weekly to bimonthly long working sessions for more than 2 years, resulting in the unique, highly detailed, and accurate anatomic and medical illustrations throughout this book.

All surgeons appreciate that operative procedures come and go as they are proved inadequate by long-term clinical outcome studies and replaced by newer techniques that are more successful. I am reminded that the basic knowledge of anatomy, biomechanics, kinematics, biology, statistics, and validated clinical outcome instruments always remain our lightposts for patient treatment decisions. For this reason, there is ample space devoted in the text to these scientific disciplines. Equally important are the descriptions of surgical techniques, presented in a step-by-step approach with precise details by experienced surgeons on the critical points for each technique to achieve successful patient outcomes. It is hoped that surgeons in training will appreciate the necessity for the basic science and anatomic approach that, combined with surgical and rehabilitation principles, are required to become a true master of knee surgery and rehabilitation.

There is a special emphasis placed in each of the 13 sections on rehabilitation principles and techniques, including preoperative assessment, postoperative protocols, and functional progression programs to restore lower limb function. The comprehensive rehabilitation protocols in this book have been used and continually modified over many years. My coauthor on these sections, Timothy Heckman, is a superb physical therapist. We have worked together treating patients in a wonderful harmonious relationship for more than 30 years. In addition, there are special programs for the female athlete to reduce the risk of ACL injury. Sportsmetrics, a nonprofit neuromuscular training and conditioning program developed at our Foundation, is one of the largest women's knee injury prevention programs in the world and has been in existence for more than 15 years. A number of scientists, therapists, athletic trainers, and physicians at our Foundation have been involved in the research efforts and publications of this program. All centers treating knee injuries in athletes are reminded of the importance of preventive neuromuscular and conditioning programs, whose need has been well established by many published studies. Recent studies show a high rate of repeat injury to the ACL-reconstructed knee or the opposite knee, approaching 12% to 30% with return to athletics. Our goals are not only to prevent or decrease the incidence of ACL injuries, but (of equal importance) also incorporate Sportsmetrics neuromuscular programs after ACL surgery before return to sports activities.

The entire staff at Cincinnati SportsMedicine and Orthopaedic Center and the Foundation functions as a team, working together in various clinical, research, and rehabilitation programs. The concept of a team approach is given a lot of attention; those who have visited our center have seen the actual programs in place. This team effort is appreciated by all, including patients, staff, surgeons, physical therapists, athletic trainers, administrative staff, and clinical research staff. Our administrative staff has been directed by a superb and highly effective clinical operations manager, Linda Raterman, whom I thank and express my gratitude for her dedication and time. As the President and CEO, I have been freed of many of the operational administrative duties because of this excellent staff, allowing time required for clinical and research responsibilities. I have been blessed to be associated with a highly dedicated group of orthopaedic partners who provide excellent patient care and are a vehicle for lively discussions and debate at our academic meetings and journal clubs.

Nearly all of the patients treated at the Noyes Knee Institute are entered into prospective clinical studies by a dedicated clinical research group directed by Sue Barber-Westin and Cassie Fleckenstein. The staff meticulously tracks patients over many years to obtain a 90% to 100% follow-up rate; I thank Jenny Riccobene for diligently keeping track of all our patients. I invite you to read the Preface by Sue Barber-Westin, who has performed such an admirable and dedicated job in bringing our clinical outcome studies to publication. It is only through her efforts of more than 30 years that we have been successful in conducting large prospective clinical outcome studies. In each chapter, the results of these outcome studies are rigorously compared with other authors' publications. The research and educational staff work with fellows and students from many different disciplines, including physicians, therapists, trainers, and biomedical students. There have been 147 Orthopaedic and SportsMedicine Fellows who have received training and awarded their certification at our center. The scientific contributions of fellowship research projects working hand-in-hand with our teaching staff are acknowledged numerous times in this text. Our staff enjoys the mentoring process; from a personal perspective, this has been one of my greatest professional joys.

In regard to mentoring, one might ask where the specialty of orthopaedics (or any medical specialty) would be today without the professional mentoring system that trains new surgeons and advances our specialty, providing a continuum of patient treatment approaches and advances. The informal dedication of the teacher to the student, often providing wisdom and guidance over many years, is actually contrary to capitalistic principles because the hours of dedication are rarely (if ever) compensated; it is the gift from one generation to another. I mention this specifically, as I hope that I have been able to repay in part the mentors who provided this instruction and added time and interest for my career. I graduated from the University of Utah with a Philosophy degree, which provided an understanding of the writings and wisdom of the great scientists and thinkers of all time, taught by superb educators in premedical courses and philosophy. I received my medical degree from George Washington University and am thankful to the dedicated teachers who laid a solid medical foundation for their students and taught the serious dedication and obligation that physicians have in treating patients. I was fortunate to be accepted for internship and orthopaedic residency at the University of Michigan and remember the opportunity to be associated with truly outstanding clinicians and surgeons. Under the mentorship of the chairman, William S. Smith, MD, my fellow residents and I received training from one of the finest orthopaedic surgeons and dedicated teachers. Many graduates of this program have continued as orthopaedic educators and researchers, which is a great tribute to Bill Smith and his mentorship. My fellow residents know one of his many favorite sayings that reminded residents of the need for humility: After a particularly enthusiastic lecture or presentation by a prominent visiting surgeon who received glowing statements of admiration, Bill Smith would say with a wink and smile, “He puts his pants on one leg at a time, just like you do.”

After orthopaedic residency, I accepted a 4-year combined clinical and research biomechanics position at the Aerospace Medical Research Laboratories with the United States Air Force in Dayton, Ohio. The facilities and veterinary support for biomechanical knee studies were unheralded. It was here that some of the first high-strain-rate experiments on the mechanical properties of knee ligaments were performed. I am indebted to Victor Frankel and Albert Burstein, the true fathers of biomechanics in the United States, who guided me in these formative years of my career. I was particularly fortunate to have a close association with Al Burstein, who mentored me in the discipline of orthopaedic biomechanics. This research effort also included professors and students at the Air Force Institute of Technology. I am grateful to all of them for instructing me in the early years of my research training. As biomechanics was just in its infancy, it was obvious that substantive research was only possible with a combined MD-PhD team approach.

One of the most fortunate blessings in my professional life is the relationship I have had with Edward S. Grood, PhD. I established a close working relationship with Ed, and we currently have the longest active MD-PhD (or PhD-MD) team that I know of, and we are currently conducting the next round of knee ligament function studies using sophisticated three-dimensional robotic methodologies. We worked together to establish one of the first biomechanical and bioengineering programs in the country at the University of Cincinnati College of Engineering, and I greatly appreciated that it was named the Noyes Biomechanics and Tissue Engineering Laboratory. This initial effort expanded with leadership and dedicated faculty and resulted in a separate Bioengineering Department within the College of Engineering, with a complete program for undergraduate and graduate students. Dr. Grood pioneered this effort with other faculty and developed the educational curriculum for the 5-year undergraduate program. Many students of this program have completed important research advances that are referenced in this book. David Butler, PhD, joined this effort in its early years and contributed important and unique research works that are also credited throughout the chapters. This collaborative effort of many scientists and physicians resulted in three Kappa Delta Awards, the Orthopaedic Research and Education Clinical Research Award, American Orthopaedic Society for Sports Medicine Research Awards, and the support of numerous grants from the National Institutes of Health, National Science Foundation, and other organizations. The publications from the clinical and translational research team have been recognized in bibliographic studies as some of the most quoted in the world, as referenced by a recent *Journal of Bone & Joint Surgery* publication of the 100 most quoted knee studies in the past 40 years. Thomas Andriacchi, PhD, collaborated on important clinical studies that provided an understanding of joint kinematics and gait abnormalities. It has been an honor to have Tom associated with our efforts throughout the years.

On a personal note, my finest mentors were my parents, a dedicated and loving father, Marion B. Noyes, MD, who was a true renaissance surgeon entirely comfortable doing thoracic, general surgery, and orthopaedics, and who, as a Chief Surgeon at academic institutions, trained decades of surgical residents. Early in my life, I read through classic Sobotta anatomic textbooks and orthopaedic textbooks that remain in my library with his writings and notations alongside the surgical procedures. Later in my training, I was fortunate to scrub with him on surgical cases. My loving mother, a nurse by training, was truly God's gift to our family. She provided unqualified love and sage and expert advice for generations, with knowledge, wisdom, and our admiration—all the way into her nineties. She expected excellence, performance, and adherence to a rigorous value system. These are also the attributes of the most wonderful gift of all, the opportunity to go through life with a loving and true soulmate, my wife JoAnne Noyes, to whom I remain eternally grateful and devoted. Our family includes a fabulous daughter and two wonderful sons and their families and five wonderful grandchildren. Together with JoAnne and all our brothers and sisters, we enjoy many family events together. As I look back on my career, it is the closeness of family and friends that has provided the greatest enrichment.

In closing, I wish to thank Laura Schmidt, Dolores Meloni, and the other Elsevier staff who are true professionals and were a joy to work with in completing this textbook. Given all the decisions that must be made in bringing a textbook to publication, at the end of the process the Elsevier team made everything work in a harmonious manner, always striving for the highest quality possible.

Frank R. Noyes, MD

PREFACE

Revising and updating *Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes* has been a stimulating experience, and I am extremely grateful to the medical community and Elsevier for providing us with this opportunity. Numerous advances have occurred in the treatment and published outcomes of knee injuries and problems in the 7 years since the first edition. This is reflected in the more than 1000 new references that are included in the chapters Dr. Noyes and I completed. Postoperative rehabilitation has also progressed, with more objective and functional measures used to determine when an athlete may safely resume sports participation. Paramount for a successful outcome is the restoration of normal proprioception, balance, coordination, and neuromuscular control for desired activities. These concepts are discussed in detail in chapters Dr. Noyes, Timothy Heckmann, and I revised, as well as in the two chapters contributed by Kevin Wilk.

My interest in conducting clinical research stemmed from my experience of undergoing open knee surgery as a collegiate athlete many years ago. Although the operation was done in an expert manner, it was followed by inadequate rehabilitation and a poor outcome. Three years later, the experience was repeated except that the patient education process was markedly improved, as was the postoperative therapy program, both of which contributed to a successful result. The tremendous contrast between these experiences prompted a lifelong interest in helping patients who face the difficulty of dealing with knee problems. Having undergone arthroscopic surgery more recently on my knee and shoulders, I can personally attest to the incredible advances sports medicine has achieved in the past 3 decades. However, it is important to acknowledge that there is still much to learn and understand regarding the complex knee joint.

My initial experience with research involved collecting and analyzing data from a prospective randomized study on the effect of immediate knee motion after anterior cruciate ligament allograft reconstruction with Dr. Noyes and our rehabilitation staff. The experience was remarkable for the time Dr. Noyes spent mentoring me on all aspects of clinical studies, including critical analysis of the literature, correct study design, basis statistics, and manuscript writing. The scientific methodology adopted by Drs. Noyes and Grood, along with our center's philosophy of the physician-rehabilitation team approach, provided an extraordinary opportunity to learn and work with those on the forefront of orthopaedics and sports medicine. My second major project, used as the thesis for my undergraduate work, involved the analysis of functional hop testing. Dr. Noyes and our statistical consultant at that time, Jack McCloskey, were invaluable in their assistance and efforts to see the investigations through to completion. I remain grateful for these initial stimulating experiences, which provided the basis and motivation for my research career.

The clinical outcomes sections of the chapters of this textbook represent a compilation of knowledge from studies involving thousands of patients from both our center and other published cohorts. We have attempted to justify the recommendations for treatment based in part on the results of our clinical studies, which consistently use rigorous knee rating systems to determine outcome. The development and validation of the Cincinnati Knee Rating System was a major research focus for Dr. Noyes and I for several years. As a result, we have long advocated that "outcome" must be measured by many factors, including patient perception of the knee condition along with valid functional, subjective, and objective measures such as radiographs, knee arthrometer testing, and magnetic resonance imaging when necessary. Simply collecting data from questionnaires does not, in our opinion, provide a scientific basis for treatment recommendations. Even more compelling is the necessity to conduct long-term clinical studies with at least a 10-year follow-up evaluation. These studies must also include these measures to determine the long-term sequelae of various injuries and disorders. At our center, we will continue to conduct clinical research in this manner in our efforts to advance knowledge of the knee joint and provide the best patient care possible.

Another area of particular research interest of mine over the years has been in the field of rehabilitation. In fact, the first clinical study I participated in was initiated while I worked on the physical therapy staff for 2 years. Having been a patient myself, I had a strong interest in studying the effects of different rehabilitation treatment programs on clinical outcomes. At our center, we have always held the belief that postoperative rehabilitation is just as important as the operative procedure for successful resolution of a problem. I have enjoyed working with Tim Heckmann in these studies for many years, as well as many other therapists, assistants, and athletic trainers vital to the success of our rehabilitation research and clinical programs.

Many individuals have contributed to the success of our clinical research program over 30-plus years, but it is not possible to name them all. However, I want to especially recognize Jennifer Riccobene, who for many years has doggedly tracked down and assisted hundreds of patients from all over the United States and beyond with their clinical research visits. Cassie Fleckenstein manages the studies in Cincinnati, keeping track of a multitude of tasks, including fellowship involvement in research, which has been a cornerstone of this program since the early 1980s. We are also very grateful for the statistical expertise provided by Dr. Marty Levy of the University of Cincinnati.

Finally, I'd like to thank my family—my husband Rick and my children Teri and Alex—for their support during this endeavor. I hope this textbook will be of value to many different types of health professionals for many years to come.

Sue D. Barber-Westin

FOREWORD TO THE FIRST EDITION

It has been my observation over the years that Frank Noyes has three fundamental beliefs, or organizing principles, around which he has dedicated his professional life and that explain the contents of this book. These are:

1. Diagnosis and treatment of patient disorders should be strongly informed by knowledge gained from basic science studies.
2. The outcome of surgical treatment is critically dependent on rehabilitation therapy.
3. Advancement of medical care, both surgical and nonsurgical, requires carefully conducted outcomes studies that account for differences in outcome caused by the type and intensity of a patient's activities and avoid bias due to the loss of patients to follow-up.

These core beliefs help explain the many research studies he and his colleagues have conducted. The results of these studies and their clinical correlations, along with the broader base of knowledge developed by numerous investigators, form the foundation of Dr. Noyes' approach to the diagnosis and treatment of knee disorders.

This book details the approaches Dr. Noyes has developed to the diagnosis and treatment of knee disorders, along with the scientific foundations on which his approaches are based. The result is a valuable reference book for both physicians and physical therapists who care for patients with knee disorders. The inclusion of supporting basic science data also makes this book an excellent reference for any investigator or student who is interested in improving the care provided to patients with knee disorders by further advancing knowledge of the normal and pathologic knee.

Although the title *is Noyes' Knee Disorders,* and the content in large part reflects his clinical approaches and research, it also includes the clinical approaches and research results of other leading surgeons and physical therapists. There is, however, a common thread in that the clinical approaches presented include the scientific foundations on which they are based. Furthermore, the reader will find that the chapters that present the research of Dr. Noyes and his colleagues also include results of other leading scientific investigators. The studies included were selected to fill in gaps and provide a broader perspective in areas where a consensus has not yet been developed.

The quality of the content of this book is complemented by the quality of its production. Each chapter has "Critical Points" boxes that focus the reader's attention on the main takeaway messages. There is extensive use of color to enhance readability, particularly in the presentation of data. Great care has been taken to make the anatomic drawings and medical illustrations accurate and to carefully label all illustrations and images. The care put into the production by Elsevier reflects the high standard of care Dr. Noyes brings to those projects he undertakes, including the care delivered to his patients and his dedication to advancing care through carefully conducted basic science and clinical research studies. Although one result of Elsevier's and Dr. Noyes' efforts is the book's visual appeal, it was not the goal. Rather, the visual appeal is a byproduct of their efforts to provide the reader with a useful text in which the content is easily understood and accessible.

This book presents much of the research conducted by Dr. Noyes and his collaborators, including much of my own research. I would like to take this opportunity to express my appreciation and gratitude to Frank Noyes for the opportunity of collaboration, for the time and energy he has devoted to our collaboration, and to the significant financial support he and his partners have provided our research. I first met Frank in 1973 when he was stationed with the 6570th Aerospace Medical Research Laboratory, located at Wright Patterson Air Force Base just outside Dayton, Ohio. I had recently received my PhD and was working at the University of Dayton Research Institute. It was there we met thanks to the efforts of a mutual friend and colleague, George "Bud" Graves. It was also in Dayton we did the first collaborations that led to our paper on the age-related strength of the anterior cruciate ligament. In 1975 we moved to the University of Cincinnati, thanks to the encouragement of Edward Miller, MD, then Head of the Division of Orthopaedics. This move was made possible by the generosity of Nicholas Giannestras, MD, and many other orthopaedic surgeons in the community who provided support to initiate a Biomechanics Laboratory. It was in Cincinnati where we initiated our first study on whole knee biomechanics and designed and initiated our first studies on primary and secondary ligamentous restraints. We were fortunate to have David Butler join our group in late 1976 and complete the study in progress on ACL and PCL restraints, a study for which he later received the Kappa Delta Award.

In addition to working with excellent colleagues, I have been fortunate to work with many engineering students, orthopaedic residents, postdoctoral students, sports medicine fellows, and visiting professors. Without their combined intellectual contributions and hard work, I would not have been able to complete many of the studies that are included in this text. They all have my sincerest appreciation for their support and contributions.

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FOREWORD

The 1970s saw the beginning of dramatic changes in the diagnosis and treatment of knee injuries. Frank Noyes has remained in the forefront of this revolution. Frank Noyes, MD, and Edward Grood, PhD, together with coworkers at the University of Cincinnati and later Cincinnati SportsMedicine and Orthopaedic Center, were the first to perform sophisticated biomechanical studies that changed the way we think about knee instabilities. They were the first to perform three-dimensional analysis of knee motions. They wrote the software that characterized the three axes of knee motion, about which each axis has a rotation and a translation. This concept is used today in all robotic and computerized programs on knee motion analysis.

Noyes and his coworkers studied normal and abnormal knee kinetics and kinematics, specifically anterior and posterior cruciate ligament graft placement sites and tension, as well as strengths of knee ligaments and replacement grafts; they then introduced the flexion-rotation drawer test. They also developed a logical classification of knee ligament injuries. Noyes has published more than 50 articles that have characterized the scientific basis of knee ligament function. His laboratory received a Kappa Delta Award for this research program.

In particular, Dr. Noyes has demanded evidence to support treatments and published the results of many prospective randomized control outcome studies. Dr. Noyes developed and validated the Cincinnati Knee Rating System, considered the gold standard for outcome studies today. He stressed the importance of postoperative rehabilitation and pioneered innovative rehabilitation techniques. Dr. Noyes developed the first program to show that neuromuscular conditioning could decrease the incidence of ACL injuries. This nonprofit program is the largest ACL injury prevention program in the world; it is active at more than 1500 sites in the United States, Europe, Asia, Australia, and elsewhere.

In 1980 the American Orthopaedic Society for Sports Medicine, acting on Dr. Noyes' proposal, created a Research Committee with Dr. Noyes as its Chairman for 10 years. He was appointed the to the National Institutes of Health (NIH) Arthritis Advisory Panel and paved the way for the NIH awarding its first grants in sports medicine.

In "The 100 Classic Papers of Orthopaedic Surgery," Dr. Noyes is listed twice.[1] Only two other orthopaedic surgeons have more citations, none in sports medicine. Several other studies show Dr. Noyes to have the highest number of citations in the published orthopaedic literature.[2-4] Dr. Frank Noyes can unquestionably be called the "father of scientific sports medicine."

In 2010, Dr. Noyes published the culmination of his 40 years of clinical and research experience: *Noyes' Knee Disorders: Surgery, Rehabilitation, and Clinical Outcomes.* He has now prepared an updated and expanded second edition. This new book contains 45 chapters written by 30 authors. The edition also comes with 45 videos lasting 11 hours and has new chapters on unicompartmental knee arthroplasty.

Recently, questions have been raised regarding when athletes may safely return to sports after major knee surgery. The rehabilitation chapters in this new second edition include a detailed progression of exercises and parameters to be met before patients may be released to unrestricted activities.

This edition also contains some of the most comprehensive and advanced chapters on knee arthrofibrosis, complex regional pain syndrome, tibial and femoral osteotomies, and posterolateral reconstructions available in current published literature.

It would be difficult to imagine how the first edition of *Noyes' Knee Disorders* could be made better. But Dr. Noyes has done just that in this new and enhanced second edition.

Bertram Zarins, MD
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FOREWORD

I am honored to write this forward for *Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes* by Dr. Frank Noyes. I would not have thought that the first edition could have been enhanced, but it certainly was with this edition. My compliments to the editors and authors of this insightful and wonderful textbook. It is truly a wealth of knowledge in one package.

The objective of this book was to produce an all-inclusive text on the knee joint that would include a multidiscipline approach to the evaluation and treatment of knee disorders. The textbook was designed to provide both basic and clinical sciences to enhance the reader's knowledge of the knee joint.

The knee joint continues to be one of the most researched, written about, and talked about subjects in orthopaedics and sports medicine. Even with the extensive literature available, Dr. Noyes and Ms. Barber-Westin have done a masterful job pulling a tremendous amount of information together into over 1200 pages, with over 4600 references and nearly 1000 figures in one comprehensive textbook. There are numerous chapters on the anatomy and biomechanics of various knee structures. There are specific and detailed sections on the evaluation and treatment of specific knee lesions, including the anterior cruciate ligament (ACL), posterior cruciate ligament, articular cartilage, patellofemoral joint, the menisci, and other structures. There are numerous chapters on the rehabilitation for each of the various knee disorders, and even a section on the gender disparity in ACL injuries. Furthermore, there are thorough sections on clinical outcomes—a much-needed area for clinicians to understand and utilize.

I have had the true pleasure of knowing Dr. Noyes for over 25 years, and he has always practiced medicine using several principles. These include a scientific basis (evidence) to support his treatment approach, a team approach to treatment, meticulous surgery, and the attitude to always do what is best for the patient. He has applied these key principles into this outstanding textbook. Dr. Noyes has always been a proponent of a team approach to the evaluation and treatment of patients with knee disorders. This book illustrates this point beautifully, with chapters written by biomechanists, orthopaedic surgeons, and physical therapists. Furthermore, Dr. Noyes has always searched for the best treatments for the patient, seeking clinical evidence to support the treatment.

As they have done more than one hundred times before in published manuscripts and chapters, Dr. Noyes and Ms. Barber-Westin have teamed up to provide us with an outstanding reference book. This text will surely remain on every knee clinician's desk for a very long time. It should be read and studied by physicians, physical therapists, athletic trainers, students, and anyone involved in treating patients with knee disorders. This book will surely be a favorite for all practitioners.

This is a truly great contribution to the literature. Thank you, Dr. Noyes, for the guidance you have given and continue to give us.

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VIDEO CONTENTS

Medial and Anterior Knee Anatomy

Alvin Detterline, John Babb, Frank R. Noyes

OUTLINE

VIDEO CONTENT

Video 1-1 The Key to the Knee: A Layer-by-Layer Demonstration of Medial and Anterior Knee Anatomy
Video 1-2 Arthroscopic Resection of the Infrapatellar Pad Using a Superolateral Portal

MEDIAL ANATOMY OF THE KNEE

The medial anatomy of the knee consists of several layers of structures that work together to provide stability and function.[39,59-61] Authors have used a variety of anatomic terms and descriptions that, unfortunately, have created ambiguity and confusion regarding this area of the knee. Two anatomic classifications or descriptions have been proposed to aid in the understanding of the relationships of the medial knee structures. These include a layered approach,[57] which describes the qualitative relationship of each medial structure, and a more quantitative description,[35] which details the exact attachment site and origin of each structure. In this chapter, both approaches will be presented; however, emphasis is on the precise anatomic relationships that provide a more thorough understanding of the structures compared with the layer approach.

Medial Layers of the Knee

The three-layer description of the medial anatomy of the knee was proposed by Warren and Marshall.[57] In this approach, layer 1 consists of the deep fascia or crural fascia; layer 2 includes the superficial medial collateral ligament (SMCL), medial retinaculum, and the medial patellofemoral ligament (MPFL); and layer 3 is composed of the distal medial collateral ligament (DMCL) and capsule of the knee joint (Fig. 1-1). For this chapter, the term *medial collateral ligament* (MCL) has been used instead of tibial collateral ligament because it represents the term most commonly used in the English language literature. The medial structures identified as important in preventing lateral patellar subluxation are the MPFL[2,19,20] and the medial patellomeniscal ligament, which inserts onto the inferior third of the patella to the anterior portion of the medial meniscus and runs adjacent to the medial fat pad. The medial parapatellar retinaculum and so-called *medial patellotibial ligament* (thickening of the anterior capsule inserting from the inferior aspect of the patella to the anteromedial aspect of the tibia) are retinacular tissues that have been described; however, these structures are not believed important in providing patellar stability.

The layer approach is important because the ligaments and soft tissues on the medial side of the knee are not discrete, individual structures like the SMCL, but rather, fibrous condensations within tissue planes.[57] This qualitative description of anatomy assists in understanding the spatial relationships of these structures and how they function to support the knee.[63] It is equally important to understand the quantitative anatomy from precise measurements of the attachments and origins of each individual structure. The complex medial anatomy of the knee has been illustrated in the past with oversimplification of the soft tissue attachments to bone and other structures, which makes it difficult to compare the origins, insertions, and courses of the many separate structures among studies.[6,7,15,21,37,52,57] LaPrade and coworkers[35] published detailed quantitative measurements that provide a better understanding of the medial knee anatomy (Figs. 1-2 and 1-3).

Layer 1: Deep Fascia

Layer 1 (see Fig. 1-1) consists of the deep fascia that extends proximally to invest the quadriceps, posteriorly to invest the two heads of the gastrocnemius and cover the popliteal fossa, and distally to involve the sartorius muscle and sartorial fascia. Anteriorly, layer 1 blends with the anterior part of layer 2 approximately 2 cm anterior to the SMCL.[57] Inferiorly, the deep fascia continues as the investing fascia of the sartorius and attaches to the periosteum of the tibia. Layers 1 and 2 are always distinct at the level of the SMCL unless extensive scarring has occurred.[57] The gracilis and semitendinosus tendons are discrete structures that lie between layers 1 and 2 and are easily separated from these two layers. However, according to Warren and Marshall,[57] these tendons will occasionally blend with the fibers in layer 1 anteriorly before they insert onto the tibia. As depicted in Figure 1-4, dissections and clinical experience of the authors concur in that there is a blending of layer 1 with a confluence of the semitendinosus and gracilis tendons at their common insertion onto the tibia; however, they are easily

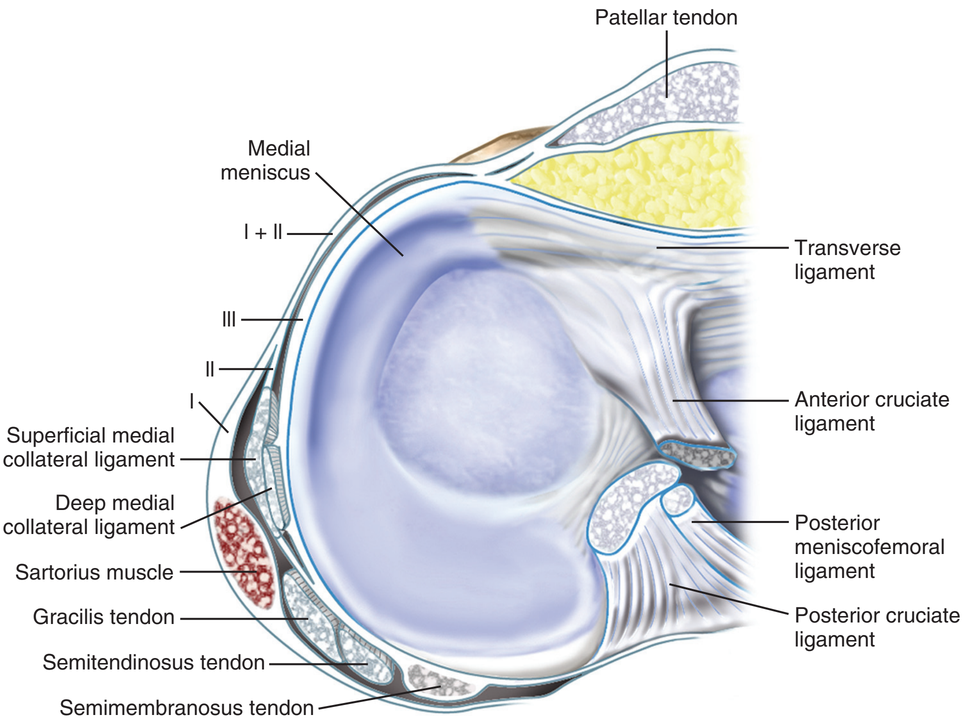

FIG 1-1 Medial layers of the knee. The gracilis and semitendinosus lie between layers 1 and 2.

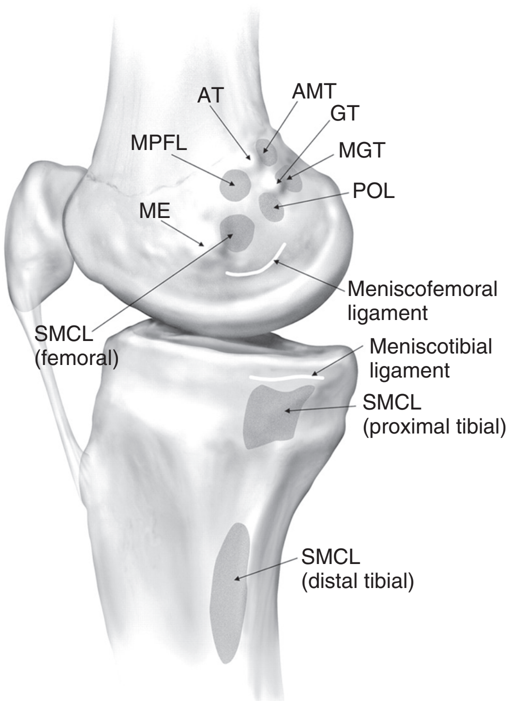

FIG 1-2 The femoral osseous landmarks and attachment sites of the main medial knee structures. *AT,* Adductor tubercle; *AMT*, adductor magnus tendon; *GT*, gastrocnemius tubercle; *ME*, medial epicondyle; *MGT*, medial gastrocnemius tendon; *MPFL*, medial patellofemoral ligament; *POL*, posterior oblique ligament; *SMCL*, superficial medial collateral ligament. (From LaPrade RF, Engebretsen AH, Ly TV, et al. The anatomy of the medial part of the knee. *J Bone Joint Surg.* 2007;89A:2000-2010.)

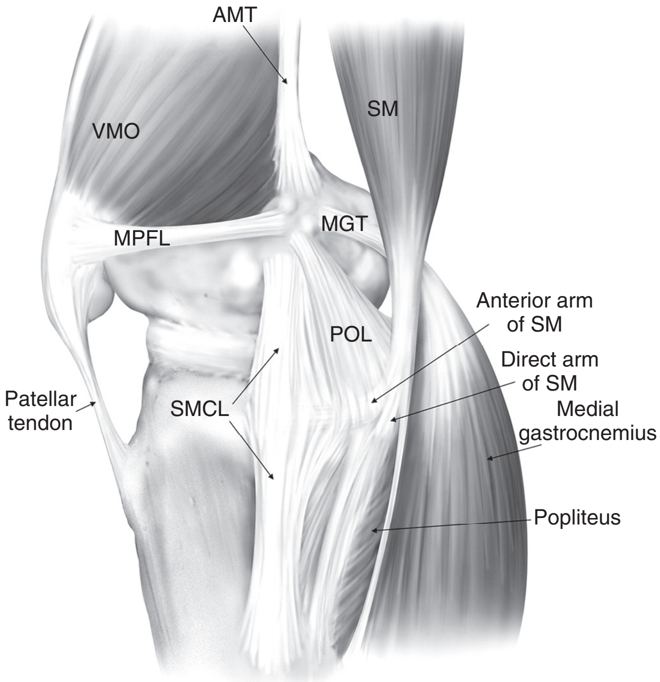

FIG 1-3 The main medial knee structures (right knee). *AMT*, Adductor magnus tendon; *MGT*, medial gastrocnemius tendon; *SM*, semimembranosus muscle; *SMCL*, superficial medial collateral ligament; *MPFL*, medial patellofemoral ligament; *POL*, posterior oblique ligament; *VMO*, vastus medialis obliquus. (From LaPrade RF, Engebretsen AH, Ly TV, et al. The anatomy of the medial part of the knee. *J Bone Joint Surg.* 2007;89A:2000-2010.)

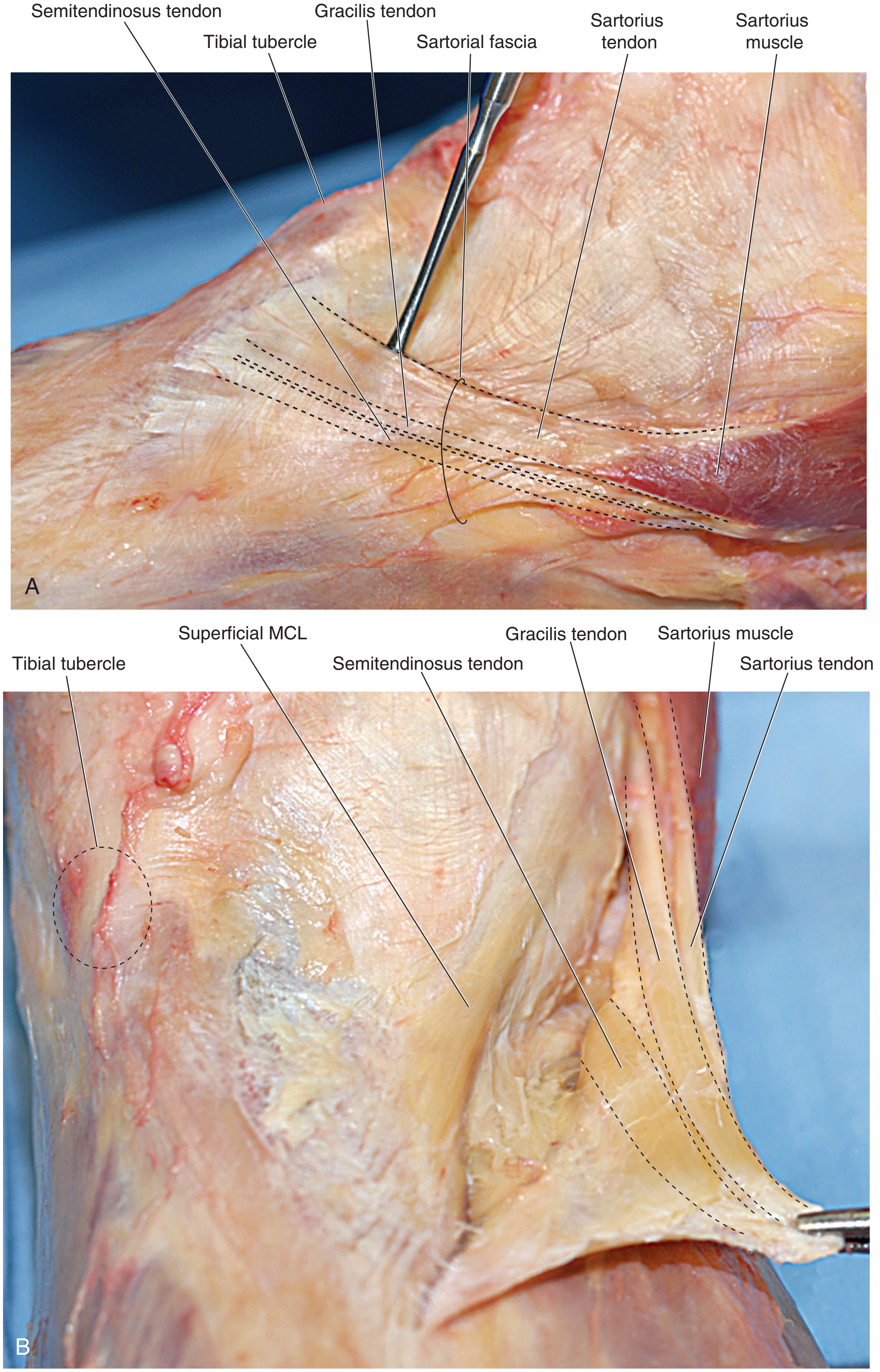

FIG 1-4 **A,** Sartorius fascia of layer 1 overlying the gracilis and semitendinosus tendons. **B,** Gracilis and semitendinosus tendons within pes anserine fascia. *MCL,* medial collateral ligament.

found as discrete structures more posteriorly. Thus, we recommend that when attempting to harvest the semitendinosus and gracilis tendons for an anterior cruciate ligament reconstruction, these tendons initially be identified 2 to 3 cm posterior and medial to the anterior tibial spine. This will allow for easier visualization of the tendons, which can then be traced to their insertions on the anterior tibia to allow for maximal tendon length at the time of harvest.

Layer 2: Superficial Medial Collateral Ligament and Posterior Oblique Ligament

The SMCL is a well-defined structure that spans the medial joint line from the femur to tibia. According to LaPrade and coworkers,[35] the SMCL does not attach directly to the medial epicondyle of the femur, but is centered in a depression 4.8 mm posterior and 3.2 mm proximal to the medial epicondyle center. Other studies have described the MCL attaching directly to the medial epicondyle of the femur.[6,7,29,37,40,42,47,49,55,57] The confusion lies in the confluence of fibers that reside in the area of the medial epicondyle that make it difficult to identify the precise attachment site of the SMCL. As shown in Figure 1-5 the authors agree with LaPrade and coworkers[35] that the main fibers of the SMCL attach to an area just posterior and proximal to the medial epicondyle; but the origin of the SMCL is rather broad and, therefore, there are also superficial fibrous strands attaching anterior on the medial epicondyle and posterior in a depression on the medial femoral condyle.

The posterior fibers of the SMCL overlying the medial joint line, both above and below the joint, change orientation from vertical to a more oblique pattern that forms a triangular structure with its apex posterior,[7,37] eventually blending with the fibers of the posterior oblique ligament (POL) (Fig. 1-6). LaPrade and coworkers[35] described two anatomic attachment sites of the SMCL on the tibia. The first is located proximally at the medial joint line and consists mainly of soft tissue connections over the anterior arm of the semimembranosus. The second attachment site is further distal on the tibia, attaching directly to bone an average of 61.2 mm from the medial joint line. In the authors' experience, there is a consistent attachment of the proximal portion of the SMCL to the soft tissues surrounding the anterior arm of the semimembranosus, but a discrete attachment to bone is found only distally (see Fig. 1-6).

The gracilis and semitendinosus lie between layers 1 and 2 at the knee joint. The sartorius drapes across the anterior thigh and into the medial aspect of the knee invested in the sartorial fascia in layer 1. The insertion of the sartorius, as described by Warren and Marshall,[57] consists of a network of fascial fibers connecting to bone on the medial side of the tibia, but does not appear to have a distinct tendon of insertion such as the underlying gracilis and semitendinosus. However, LaPrade and coworkers[35] located the gracilis and semitendinosus tendons on the deep surface of the superficial fascial layer, with each of the three tendons attaching in a linear orientation at the lateral edge of the pes anserine bursa.

In our experience, the sartorial fascia has a broad insertion onto the anteromedial border of the tibia and, with sharp dissection at its insertion, the underlying distinct tendons of the gracilis and semitendinosus are easily visualized (see Fig. 1-4). At the level of the joint, layers 1 and 2 are easily separated from one another over the SMCL. However, farther anteriorly, layer 1 blends with the anterior part of layer 2 along a vertical line 1 to 2 cm anterior to the SMCL.[57]

Also within layer 2 is the MPFL, which courses from the medial femoral condyle to its attachment onto the medial border of the patella.[5,44,51] This is a flat, fan-shaped structure that is larger at its

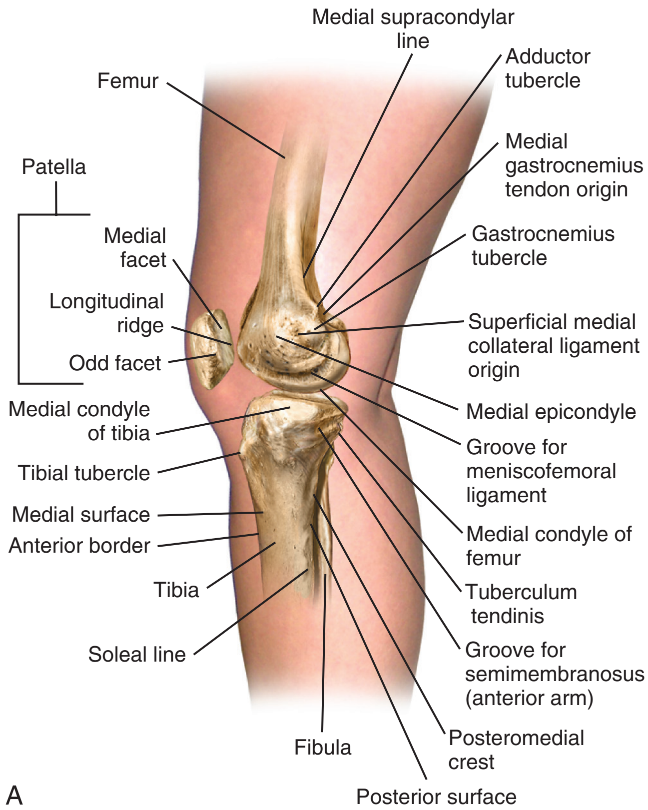

FIG 1-5 **A,** Osseous landmarks of knee (medial view). *Continued*

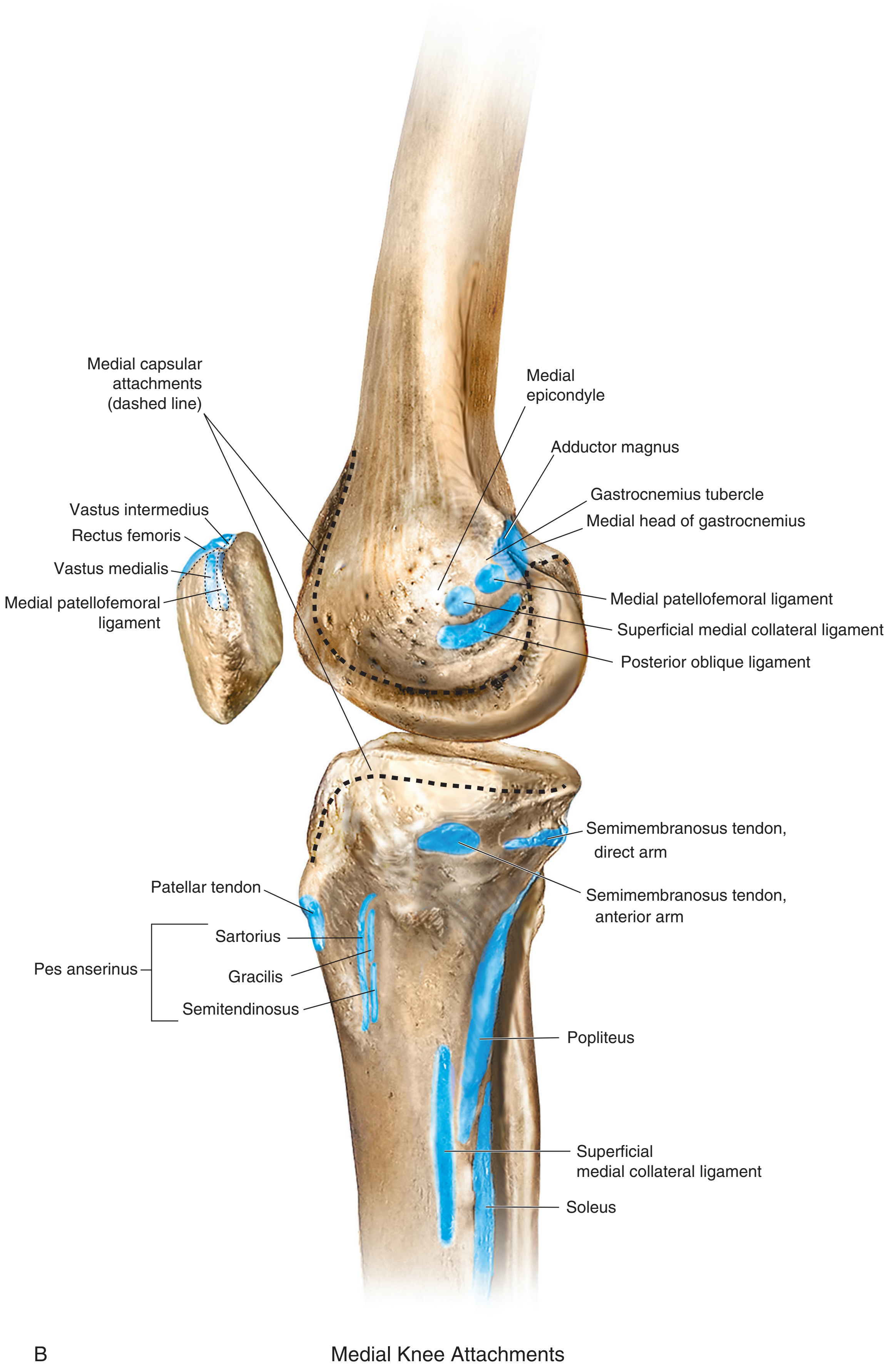

FIG 1-5, cont'd B, Soft tissue attachments to bone (medial knee).

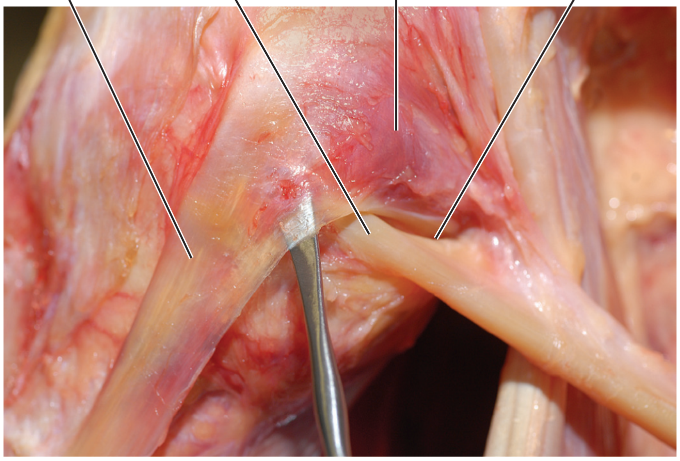

FIG 1-6 Oblique fibers of superficial medial collateral ligament (MCL) blending with the posterior oblique ligament. Note the coronary ligament attachment from the anterior arm of the semimembranosus.

patellar attachment than its femoral origin, with a length averaging 58.3 mm (47.2-70.0 mm).[48] Controversy exists regarding where the MPFL attaches at the medial femoral condyle. Mochizuki and coworkers[41] described the MPFL as a fan-shaped structure with proximal fibers extending to the medial margin of the vastus intermedius, and distal fibers interdigitating with the medial retinaculum without a distinct attachment to the vastus medialis. LaPrade and coworkers[35] noted that the MPFL attaches primarily to soft tissues between the attachments of the adductor magnus tendon and the SMCL, with an attachment to bone 10.6 mm proximal and 8.8 mm posterior to the medial epicondyle. Steensen and associates,[50] from a dissection of 11 knees, believe the MPFL attaches along the entire length of the anterior aspect of the medial epicondyle. Smirk and Morris[48] describe a variable origination of the MPFL on the femur. In dissections of 25 cadavers, the MPFL attached solely to the posterior aspect of the medial epicondyle, approximately 1 cm distal to the adductor tubercle in 44% of specimens. The adductor tubercle was included in the origin in 4%, the adductor magnus tendon in 12%, the area posterior to the adductor magnus tendon in 20%, and a combination of these in 4%. In 16% of the specimens, the MPFL attached anterior to the medial epicondyle. Fulkerson and Edgar[16] described a distinct attachment of the MPFL to the medial quadriceps tendon and named this structure the medial quadriceps tendon–femoral ligament. Kang and associates[30] described the femoral attachment point for MPFL fibers as two "relatively concentrated fiber bundles." The authors identified an "inferior straight" bundle (what is commonly referred to as the *MPFL*) that was the main static soft tissue restraint. The superior-oblique bundle was attached and associated with the vastus medialis obliquus (VMO) and was identified as a dynamic soft tissue restraint. The authors acknowledged that the two bundles were not entirely separable.

In our experience, the MPFL attaches in a depression posterior to the medial epicondyle and blends with the insertion of the SMCL (Fig. 1-7). The anterior attachment of the MPFL consists of both attachments to the undersurface of the VMO and the proximal medial border of the patella. The work of Steensen and associates[50] demonstrated that the VMO does not overlap the MPFL, with the exception in 3 of 11 knees in which only 5% of the width of the MPFL was deep to the VMO. However, LaPrade and coworkers[35] reported that the distal border of the VMO attaches along the majority of the proximal edge of the MPFL before inserting onto the superomedial border of the patella. The midpoint of the MPFL attachment is located 41% of the length from the proximal tip of the patella along the total patellar length. Our experience is that the MPFL attaches to the proximal third of the patella, with the majority of the ligament connected to the distal portion of the VMO with fibrous bands (see Fig. 1-7).

The adductor magnus and medial gastrocnemius tendons also contribute to the medial anatomy of the knee; both attach on the medial femoral condyle. Similar to the SMCL attachment, the confluence of fibers over the medial femoral condyle makes it difficult to precisely identify the exact location of each attachment (Fig. 1-8). The adductor magnus tendon is a well-defined structure attaching just superior and posterior to the medial epicondyle near the adductor tubercle. LaPrade and coworkers[35] reported the adductor magnus does not attach directly to the adductor tubercle, but rather to a depression located an average of 3.0 mm posterior and 2.7 mm proximal to the adductor tubercle. The adductor magnus also has fascial attachments to the capsular portion of the POL and medial head of the gastrocnemius.

The medial gastrocnemius tendon inserts in a confluence of fibers in an area between the adductor magnus insertion and the insertion of the SMCL (Fig. 1-9 *A*). LaPrade and coworkers[35] described a gastrocnemius tubercle on the medial femoral condyle in this region; however, these authors state that the tendon does not attach to the tubercle, but to a depression just proximal and posterior to the tubercle. In addition, fascial expansions from the lateral aspect of the medial gastrocnemius tendon form a confluence of fibers with the distal extent of the adductor magnus tendon in addition to the capsular arm of the POL (see Fig. 1-9 *A*).

Layers 2 and 3 blend together in the posteromedial corner of the knee along with additional fibers that extend from the semimembranosus tendon and sheath that form the posteromedial capsule (see Fig. 1-9). LaPrade and coworkers[35,62] used the term *posterior oblique ligament* (POL) for this same structure and described each of the three fascial attachments similar to Hughston and colleagues' original description.[27,28] The superficial arm of the POL runs parallel to both the more anterior SMCL and the more posterior distal expansion of the semimembranosus. Proximally, the superficial arm blends with the central arm; distally, it blends with the distal expansion of the semimembranosus as it attaches to the tibia.[35]

The central arm is the largest and thickest portion of the POL,[35] running posterior to both the superficial arm of the POL and SMCL. It courses from the distal portion of the semimembranosus and is a fascial reinforcement of the meniscofemoral and meniscotibial portions of the posteromedial capsule. LaPrade and coworkers[35] noted that this structure has a thick attachment to the medial meniscus. As the central arm courses along the posteromedial aspect of the joint, it merges with the posterior fibers of the SMCL and can be differentiated from the SMCL by the different directions of the individual fibers. The distal attachment of the central arm is primarily to the posteromedial portion of the medial meniscus, the meniscotibial portion of the capsule, and the posteromedial tibia.[35]

The capsular portion of the POL is thinner than the other portions of this structure and fans out in the space between the central arm and the distal portions of the semimembranosus tendon. The capsular portion blends posteriorly with the posteromedial capsule of the knee and the medial aspect of the oblique popliteal ligament (OPL).[35] It attaches proximally to the fibrous bands of the medial gastrocnemius tendon and fascial expansions of the adductor magnus tendon, with no osseous attachment identified.

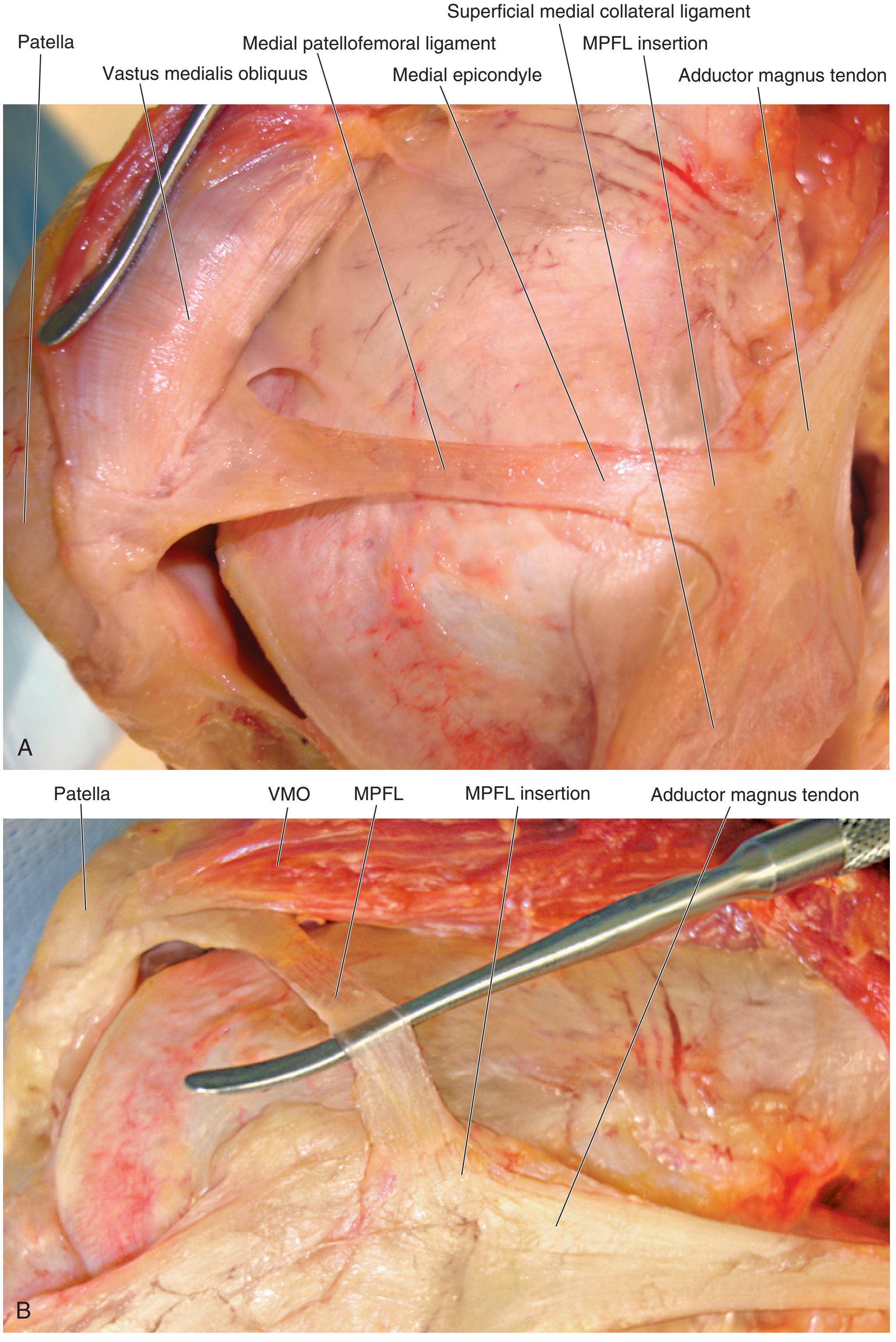

FIG 1-7 **A,** Medial patellofemoral ligament (MPFL) inserts into a depression behind the medial epicondyle and blends with fibers of the superficial medial collateral ligament. **B,** Fibrous bands from the vastus medialis obliquus (VMO) muscle connect to the MPFL before it inserts into the patella.

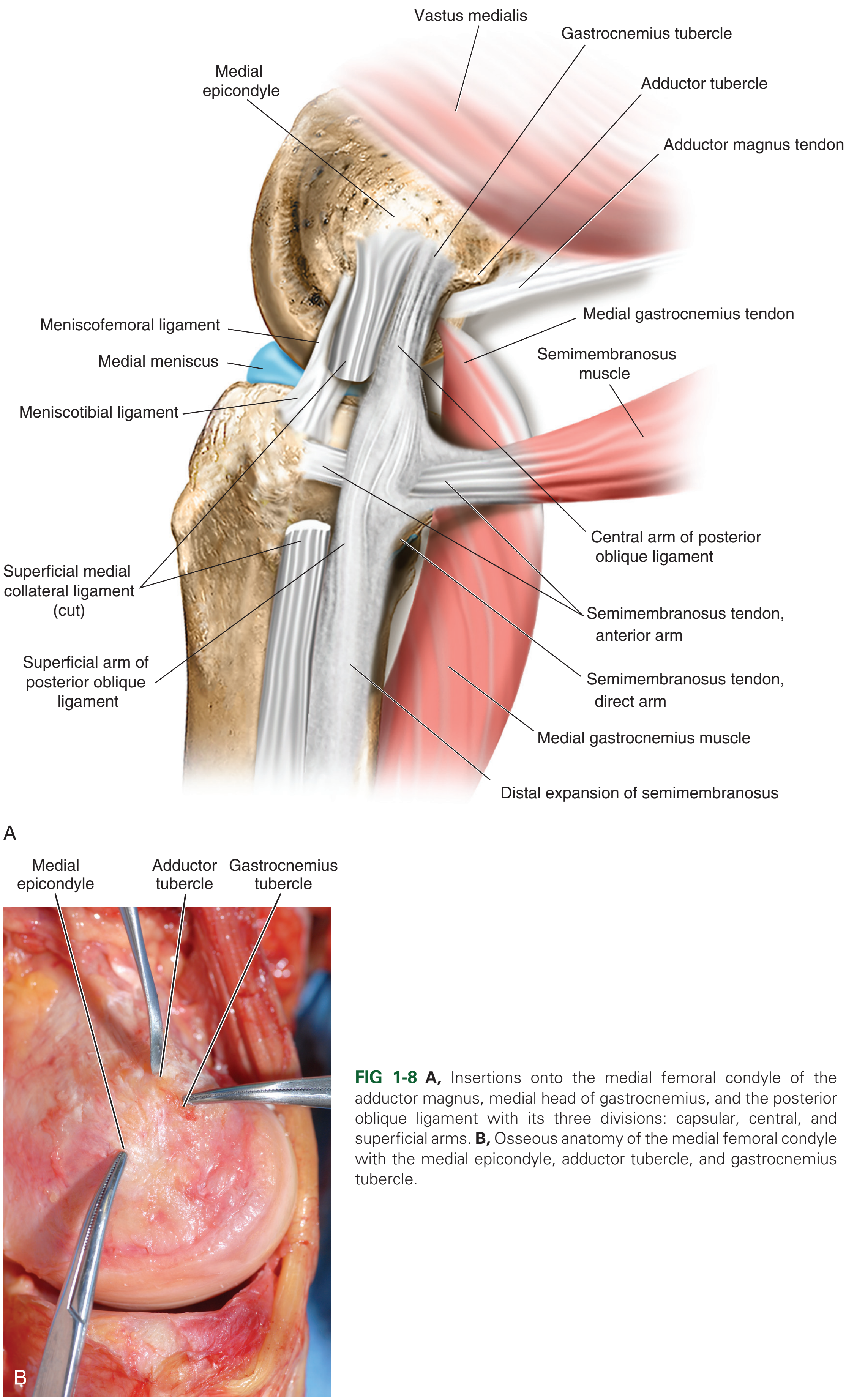

FIG 1-8 A, Insertions onto the medial femoral condyle of the adductor magnus, medial head of gastrocnemius, and the posterior oblique ligament with its three divisions: capsular, central, and superficial arms. **B,** Osseous anatomy of the medial femoral condyle with the medial epicondyle, adductor tubercle, and gastrocnemius tubercle.

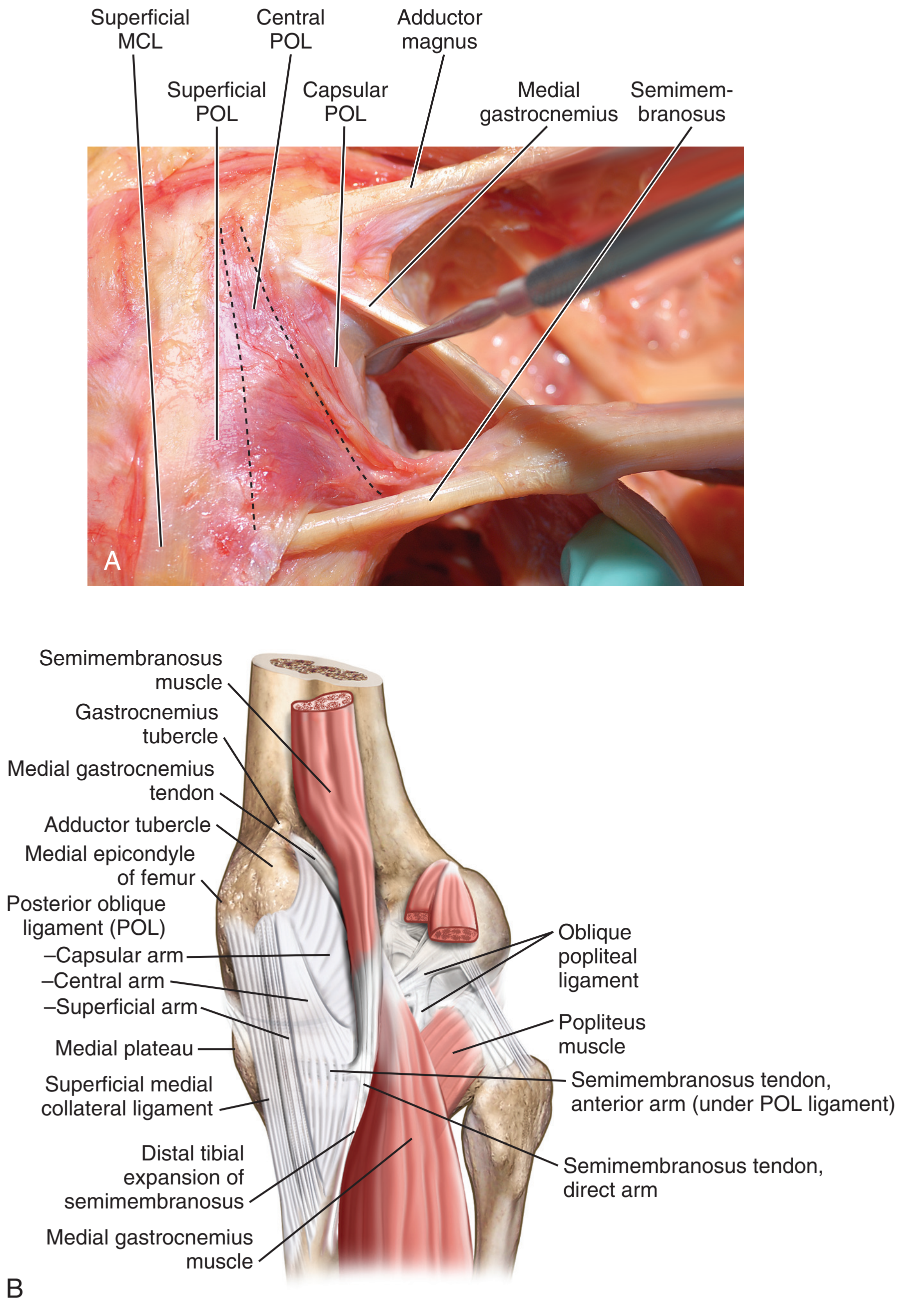

FIG 1-9 **A,** Insertions onto the medial femoral condyle of the adductor magnus, medial head of gastrocnemius, and posterior oblique ligament (POL) with its three divisions: capsular, central, and superficial arms. **B,** Anatomy of the POL with its three divisions. *MCL,* Medial collateral ligament.

The superficial portion of the POL is rather thin and appears to represent a confluence of fibers from the SMCL and the semimembranosus more distally. The capsular portion appears to represent a confluence of fibers from the semimembranosus, adductor magnus, and medial gastrocnemius (see Fig. 1-9). The central arm appears more robust, having contributions from the semimembranosus and medial gastrocnemius.

Controversy remains on whether three separate distinct anatomic structures make up the POL. Other authors[46] have not found three distinct structures and note that with tibial rotation, different portions of the posteromedial capsule appear under tension but are not anatomically separate structures.

Semimembranosus. Controversy exists with respect to the exact number of attachments of the semimembranosus tendon at the knee joint.[8,9,11,28,31,33,34,43,57] However, it appears that three major attachments have been consistently identified. The common semimembranosus tendon bifurcates into a direct and anterior arm just distal to the joint line. LaPrade and coworkers[35,36] described the direct arm attaching to an osseous prominence called the *tuberculum tendinis*, approximately 11 mm distal to the joint line on the posteromedial aspect of the tibia. These authors also note a minor attachment of the direct arm that extends to the medial coronary ligament along the posterior horn of the medial meniscus (see Fig. 1-6). A thinning of the capsule or capsular defect may be identified just distal to the femoral attachment of the medial head of the gastrocnemius and proximal to the direct arm of the semimembranosus. This is often the site of the formation of a Baker cyst.

Warren and Marshall[57] believed the semimembranosus tendon sheath and not the tendon itself extends distally over the popliteus muscle and inserts directly into the posteromedial aspect of the tibia, with some fibers coalescing with SMCL fibers inserting in the same region. These authors contend that these fibers do not have functional significance, because no change was found in position or tension of the MCL when those fibers were transected. LaPrade and associates[36] separated the distal tibial expansion into a medial and lateral division. Both divisions originating on the coronary ligament of the posterior horn of the medial meniscus are located on either side of the direct arm of the semimembranosus. The divisions then course distally to cover the posterior aspect of the popliteus muscle and insert onto the posteromedial aspect of the tibia, forming an inverted triangle in appearance. These authors noted the medial division attaches just posterior to the SMCL, whose fibers coalesce with the superficial arm of the POL (as previously noted by Hughston and colleagues[28]) rather than the MCL.

In our experience, as shown in Figure 1-10, the semimembranosus tendon sheath and not the tendon itself comprises the distal tibial expansion, which includes a medial and lateral division with a central raphae separating the two. The anterior arm of the semimembranosus courses deep to the SMCL and attaches directly to bone just distal to the medial joint capsule on the tibia (Fig. 1-11). There are fibrous connections between the SMCL and the anterior arm of the semimembranosus, but only the anterior arm of the semimembranosus has an osseous attachment in this region. Because both the direct and anterior arms of the semimembranosus anchor directly to bone and attach distal to the tibial margin of the medial joint capsule, they are not considered part of either layer 2 or layer 3 as described by Warren and Marshall.[57]

The third major attachment of the semimembranosus is the OPL. Warren and Marshall[57] described the semimembranosus tendon sheath forming fiber tracts that make up the OPL, although they admit some collagen fibers may come from the tendon itself. LaPrade and associates[36] described a lateral expansion off the common semimembranosus tendon, just proximal to its bifurcation into the direct and anterior arms, that coalesces to form a portion of the OPL, in addition to the capsular arm of the POL. As shown in Figure 1-12**,** it is difficult to appreciate distinct structures comprising the origin of the OPL because of the significant confluence of fibers in the region. However, there are fibers originating from both the semimembranosus tendon and its sheath that contribute to its origin.

The OPL is described as a broad fascial band that courses laterally and proximally across the posterior capsule. LaPrade and associates[36] noted two distinct lateral attachments of the OPL (proximal and distal). The proximal attachment is broad, extending to the fabella, the posterolateral capsule, and the plantaris (see Fig. 1-12). It does not attach directly to the lateral femoral condyle. The distal attachment is on the posterolateral aspect of the tibia, just distal to the posterior root of the lateral meniscus, but not directly attaching to the lateral meniscus as described by Kim and coworkers.[34] It is theorized that this may serve a functional role limiting hyperextension, but this has not been demonstrated in any biomechanic study to date.

LaPrade and associates[36] also described a proximal capsular arm of the semimembranosus as a thin aponeurosis that traverses medially to laterally along the superior border of the OPL. As it courses laterally, it blends with the posterolateral capsule and inserts on the distal lateral femur just proximal to the capsular insertion while at the same time extending fibers to the short head of the biceps femoris tendon (see Fig. 1-12 *B* and *C*).

Layer 3: Deep Medial Collateral Ligament and Knee Capsule

The capsule of the knee joint is thin anteriorly and envelops the fat pad. In this area, the capsule is easily separated from the overlying superficial retinaculum until it reaches the margin of the patella, where it is difficult to separate the capsule from the overlying superficial

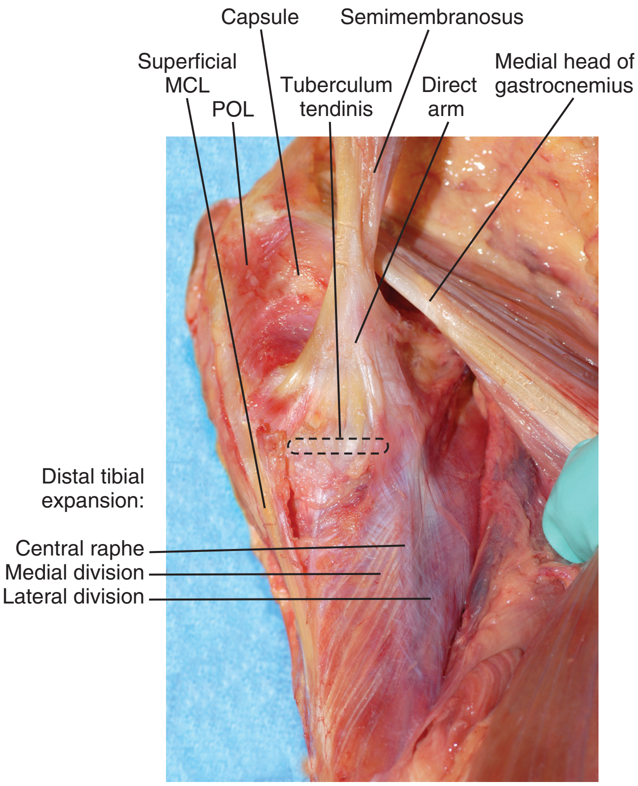

FIG 1-10 Distal tibial expansion of the semimembranosus tendon sheath with its medial and lateral divisions. *MCL,* Medial collateral ligament. *POL,* posterior oblique ligament.

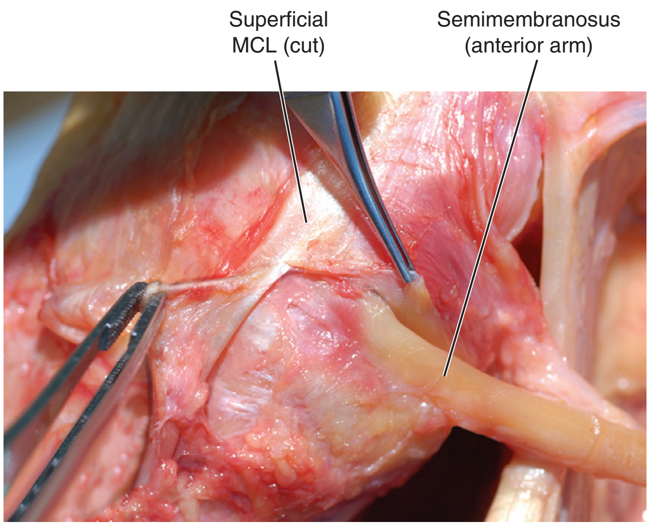

FIG 1-11 Superficial medial collateral ligament (MCL) is cut to show the anterior arm of semimembranosus attachment to bone.

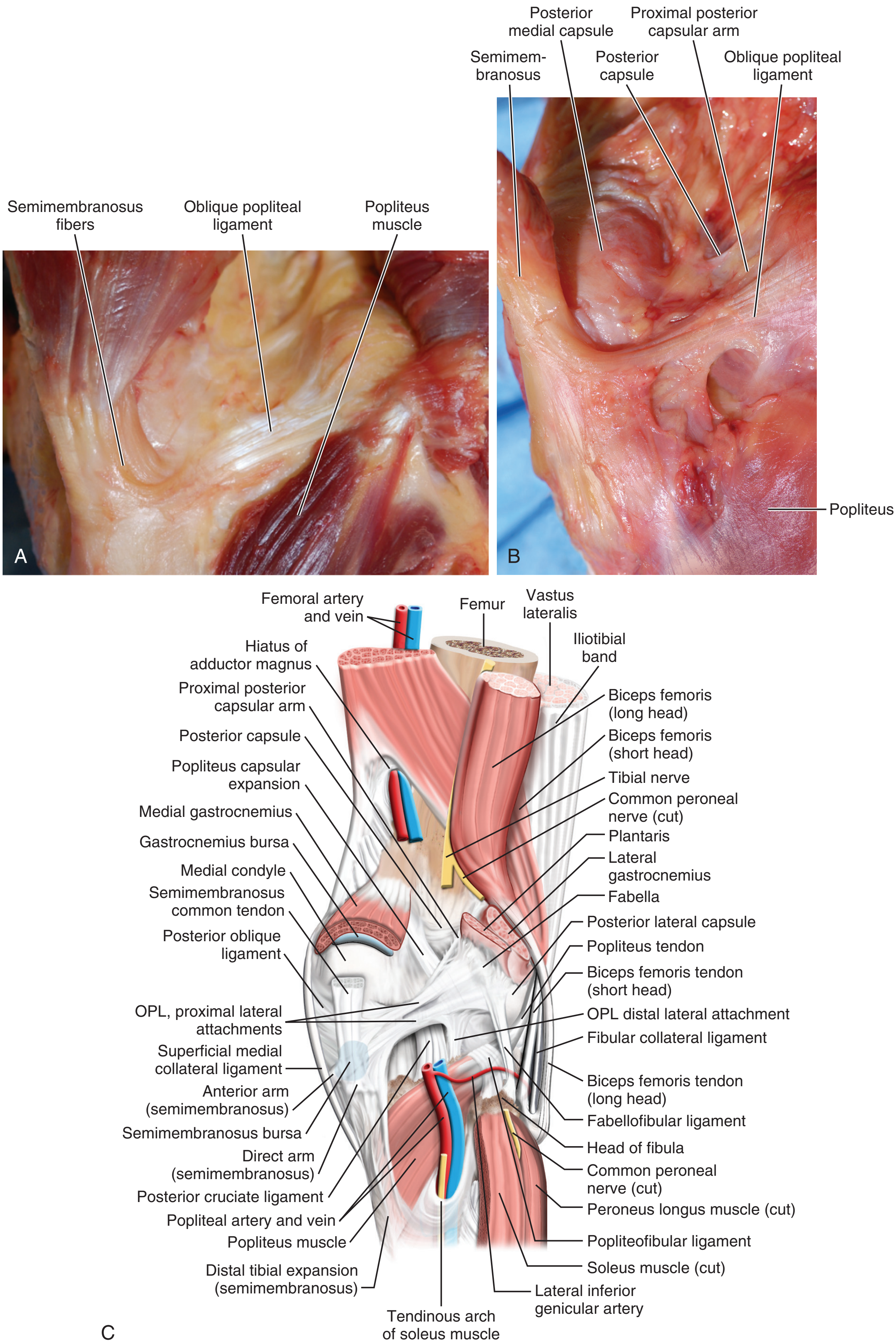

FIG 1-12 **A,** Semimembranosus fibers contributing to oblique popliteal ligament (OPL). **B,** OPL fans across the posterior knee with its multiple fibrous divisions. **C,** Posterior knee showing divisions of the POL.

structures.[57] Under the SMCL lies a vertical thickening of the knee capsule known as the *distal medial collateral ligament* (DMCL). The DMCL crosses the joint from the distal femur to the medial meniscus and inserts into the proximal tibia at sites adjacent to the articular surfaces of the femur and tibia. These separate divisions of the DMCL are named the *meniscofemoral* and *meniscotibial* ligaments. Warren and Marshall[57] noted the meniscofemoral portion of the DMCL had a discrete attachment onto the distal femur at its articular margin. Similarly, the meniscotibial portion of the DMCL, also known as the *coronary ligament*, is easily separated from the overlying SMCL in layer 2 before attaching to the tibia at its articular margin (Fig. 1-13).

The deepest structure on the medial side is the capsule of the knee, which envelops the entire joint and extends proximally up to the suprapatellar pouch and distally to the attachment site of the meniscotibial ligament on the tibia-articular cartilage border.[57]

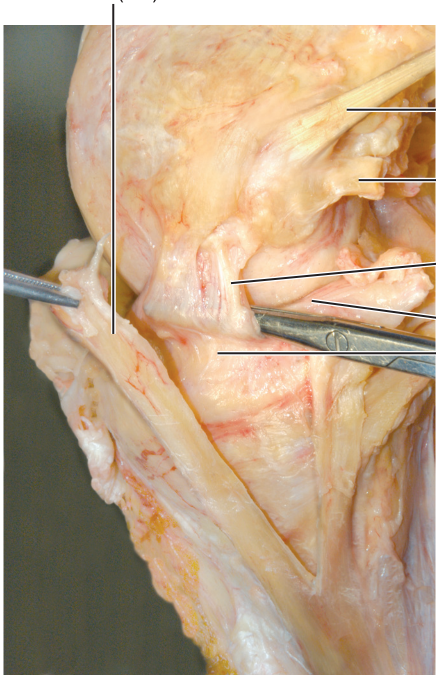

FIG 1-13 Superficial medial collateral ligament (MCL) cut to show deep medial collateral ligament with its two divisions: meniscofemoral and meniscotibial.

ANTERIOR ANATOMY OF THE KNEE

Several anatomic relationships and structures are important to recognize because they are critical to understanding the mechanics of the extensor mechanism and may be involved in several pathologic conditions.

Quadriceps Mechanism

The quadriceps consists of the rectus femoris, adjacent to the vastus medialis and lateralis on either side, and the vastus intermedius deep (Fig. 1-14). The rectus femoris is located centrally and superficially in the quadriceps mechanism and widens distally as is approaches the superior aspect of the patella. Reider and colleagues[45] found the width of the rectus femoris tendon to be 3 to 5 cm at the proximal pole of

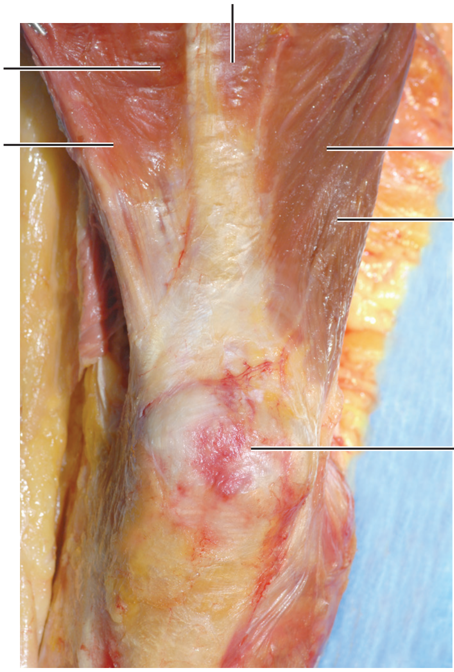

FIG 1-14 Extensor mechanism of knee showing the vastus lateralis, vastus medialis, and rectus femoris. Note the long tendon insertion of the vastus lateralis onto the proximal patella.

the patella. Some of the rectus tendon fibers insert into the superior aspect of the patella, but the majority continue over the anterior surface of the patella and are continuous with the patellar tendon distally. This is in contrast to the other components of the quadriceps mechanism that do not commonly contribute directly to the patellar tendon. The vastus medialis has fibers that run parallel to the rectus femoris fibers, called the *vastus medialis longus*, and others that run obliquely in relation to the rectus, termed the *vastus medialis obliquus* (VMO) according to Lieb and Perry.[38] Conlan and coworkers[10] described the VMO originating from the medial intermuscular septum and the adductor longus tendon proximal to the adductor tubercle. The angle of the obliquity of the VMO fibers varies considerably. Reider and colleagues[45] found a range of 55 degrees to 70 degrees in a cadaveric study. This variability in obliquity has been implicated in patellar maltracking.

The muscle of the vastus medialis extends distally and often becomes tendinous only millimeters from its patellar insertion. Reider and colleagues[45] noted some fibers insert directly into the patella, whereas others course more distally and contribute to the medial retinaculum. Conlan and coworkers[10] contended that some fibers of the VMO extend more distally and actually contribute to the patellar tendon. As shown in Figure 1-14, the vast majority of the VMO fibers either attach directly onto the patella or extend more distally to make up the medial retinaculum. The most medial fibers of the medial retinaculum converge into the medial border of the patellar tendon, but do not provide a significant contribution to the patellar tendon fibers.

The vastus lateralis muscle is divided similarly to the vastus medialis with a longus and obliquus portion. The insertions of the longus and obliquus tendons are quite variable according to Hallisey and associates.[22] These authors contended that the amount of vastus lateralis tendon that travels over the anterior cortex of the patella and contributes to the patellar tendon distally is variable. In some cases, the lateralis tendon fibers remain lateral to the patella and interdigitate with the fibers of the iliopatellar tract without contributing to the patellar tendon (Fig. 1-15). The insertion of the obliquus fibers is also variable according to Hallisey and associates.[22] These authors found that in some specimens, the obliquus tendon fibers insert into the vastus lateralis longus fibers proximal to the patella; in others, they blend into the iliopatellar tract before inserting on the patella. As shown in Figure 1-15, it is our experience that the most medial fibers of the lateralis obliquus tend to coalesce with the fibers of the longus, whereas the most lateral obliquus fibers coalesce with the iliopatellar tract. The vastus lateralis does not provide a significant contribution to the patellar tendon.

The fibers of the lateralis run more parallel to the rectus femoris fibers than the vastus medialis (see Fig. 1-14). The average obliquity of the lateralis fibers is 31 degrees according to Reider and colleagues.[45] The lateralis fibers also become tendinous more proximally than the medialis, an average of 2.8 cm proximal to the patella.[45] The angle of insertion of the obliquus fibers is rather variable, with an average of 48.5 degrees in men and 38.5 degrees in women.[30]

The vastus intermedius is deep to the rectus femoris, inserts directly into the proximal pole of the patella, and blends with the fibers of the medialis and lateralis that insert in similar fashion. Previous descriptions of the quadriceps tendon insertion depict a trilaminar arrangement of fibers, with the rectus femoris contributing the most superficial fibers, the medialis and lateralis contributing the middle layer, and finally, the intermedius contributing the deepest fibers. Reider and colleagues[45] described the inserting fibers as more of a coalescence rather than distinct layers as previously described. It is our experience that the quadriceps tendon is a coalescence of fibers at the proximal pole of the patella, but as one travels a few centimeters proximal, four distinct layers to the quadriceps tendon can be identified and separated from one another (Fig. 1-16). When harvesting a quadriceps tendon graft, it is important that all layers are identified.

Fascial Layers

Confusion arises when attempting to describe the various layers of the anterior knee structures because different nomenclature is used for

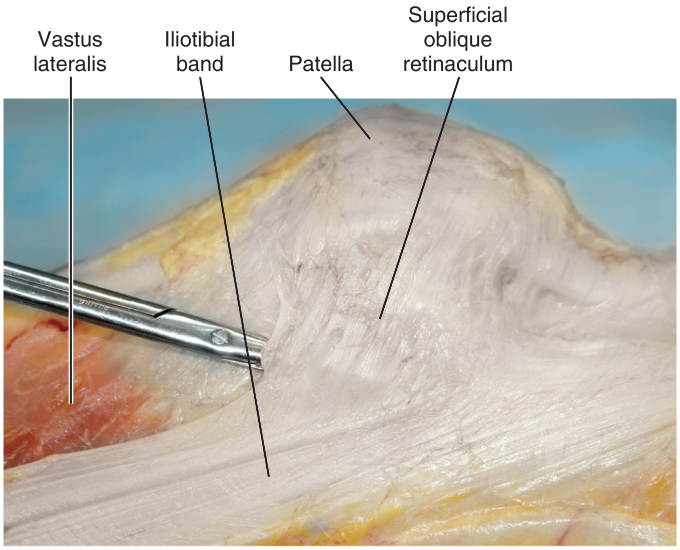

FIG 1-15 Longitudinal fibers of the vastus lateralis blend with fibers of the superficial oblique retinaculum.

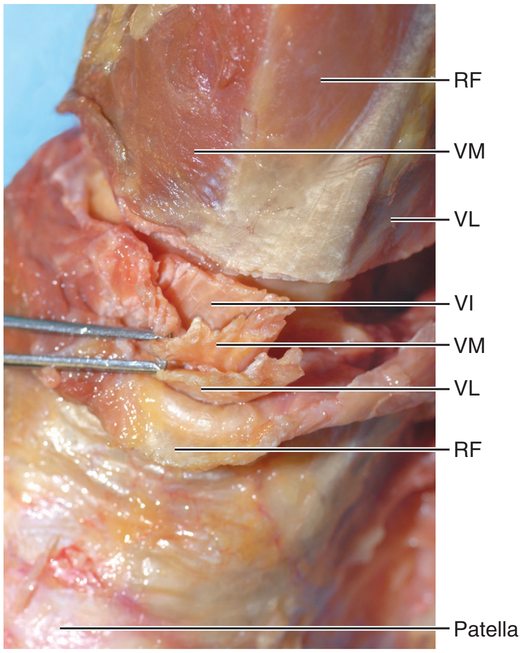

FIG 1-16 Each division of the quadriceps mechanism is dissected proximal to patella. *RF*, Rectus femoris; *VI*, vastus intermedius; *VL*, vastus lateralis; *VM*, vastus medialis.

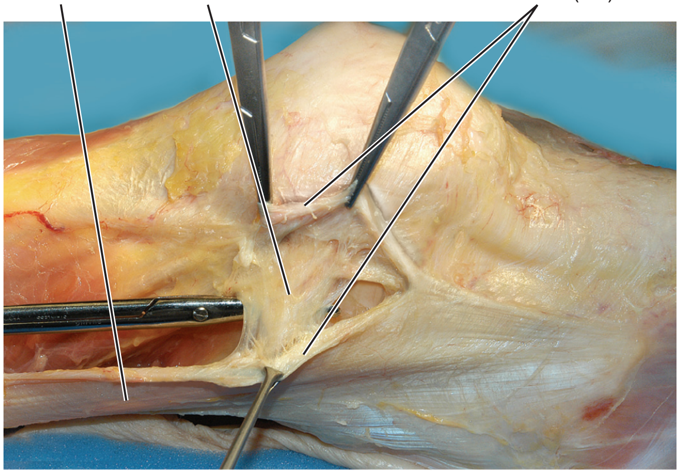

FIG 1-17 Deep transverse fibers of the iliopatellar tract.

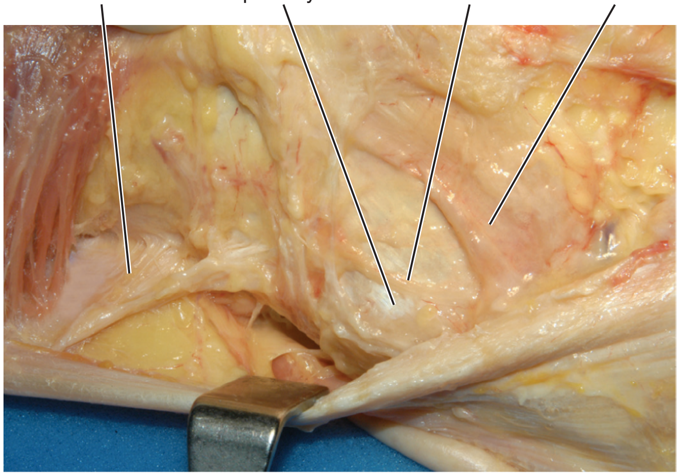

FIG 1-18 Deep lateral view of knee shows capsular-osseous layer of the iliotibial band with bursa.

both the medial and lateral parapatellar tissues. This description will break down the layers both medially and laterally and then attempt to assimilate each as they form a confluence over the anterior aspect of the patella.

Lateral

The most superficial layer laterally, termed the *aponeurotic layer* by Terry and colleagues,[54] is composed of the superficial fascia of the vastus lateralis and biceps femoris. These fibers, termed *arciform fibers*, travel transversely across the anterior aspect of the patella to blend at the midline with the superficial fascia of the sartorius, which begins medially.

The next layer is termed the *superficial layer* by Terry and colleagues.[54] It is made up of the iliopatellar tract, which connects the iliotibial band to the patella.[17,56] The iliopatellar tract has been further subdivided into a superficial and deep layer by Fulkerson and Gossling,[17] who describe two different fiber orientations. The most superficial is termed the *superficial oblique retinaculum* because its fiber orientation is oblique. This tract inserts along the lateral border of the patella (see Fig. 1-15). In addition, there are deep transverse fibers that also connect the iliotibial band with the lateral aspect of the patella (Fig. 1-17). In this deeper, more transverse tract is the patellotibial ligament, which originates just proximal to Gerdy's tubercle on the tibia and inserts on the inferior portion of the lateral aspect of the patella.[17] Just deep to this ligament is the lateral meniscopatellar ligament, which runs between the anterior horn of the lateral meniscus and the inferior aspect of the patella. It is a thickening of the anterolateral capsule. The deepest layer on the lateral side is the capsular-osseous layer, which anchors the iliotibial band to the femur through the lateral intermuscular septum and travels anteriorly to the patella. Some authors[32,54,56] contend that it includes the lateral patellofemoral ligament, but our experience is that a distinct ligament is not present.

As shown in Figure 1-18, the capsular-osseous layer of the iliotibial tract has a femoral attachment proximal to the lateral epicondyle. At the level of the lateral epicondyle is a bursa deep to the iliotibial tract. It is our experience that there commonly is an identifiable nerve, which is named the *lateral retinacular nerve*, within this bursa that may play a role in pain associated with runner's knee. During an iliotibial tract lengthening procedure for recalcitrant runner's knee, we believe that while the iliotibial bursa is excised, the lateral retinacular nerve should be identified and cut posterior to the lateral epicondyle to prevent recurrence of this painful condition.

Medial

The superficial fascia of the vastus medialis and sartorius form the most superficial layer medially. This aponeurotic layer travels laterally over the anterior aspect of the patella to merge with the same layer from the lateral side.

The next layer is considered to be the same as layer 2 as described by Warren and Marshall.[57] This is composed of the MPFL and SMCL. In this layer is the medial retinaculum, which is defined as the VMO fibers running transversely from the anterior border of the SMCL to the medial aspect of the patella. The medial patellotibial ligament is also found in this middle layer (Fig. 1-19). According to Conlan and coworkers,[10] it originates on the inferior portion of the medial aspect of the patella and travels distally and posteriorly to insert on the anteromedial aspect of the tibia. The deepest structure found on the anteromedial aspect of the knee is the medial meniscopatellar ligament, which is a thickening of the capsule that runs between the anterior horn of the medial meniscus and the inferior portion of the medial border of the patella (Fig. 1-20).[10]

Prepatellar

The fascial layer covering the quadriceps is termed the *fascia lata*. Dye and coworkers[14] note that the fascia lata extends distally as the most superficial layer overlying the patella after the skin and subcutaneous tissue. These authors describe the fascia lata as an extremely thin layer with little structural integrity but visible transverse fiber orientation. This is in contrast to the intermediate layer overlying the patella, which has an oblique fiber orientation proximally and becomes more transverse distally over the patellar tendon. Dye and coworkers[14] described the intermediate layer consisting of tendinous fibers from the vastus medialis and lateralis, in addition to the superficial fibers of the rectus femoris that extend over the anterior aspect of the patella.

The deepest layer anterior to the patella is composed of the deeper fibers of the rectus femoris that extend distal to the proximal pole of the patella and are intimately associated with the anterior cortex of the patella as they continue to contribute to the fibers of the patellar tendon (Fig. 1-21).

Dye and coworkers[14] noted these layers form three separate bursae superficial to the patella. The most superficial is termed the *prepatellar subcutaneous bursa* (between the skin and superficial fascia lata). The middle bursa is termed the *prepatellar subfascial bursa* (between the superficial fascia lata and the oblique intermediate layer). Finally, the deepest bursa is called the *prepatellar subaponeurotic bursa* (between the intermediate and deep aponeurotic layers). It should be noted that no bursa exists between the deepest aponeurotic layer and the anterior cortex of the patella, as others have suggested.[1]

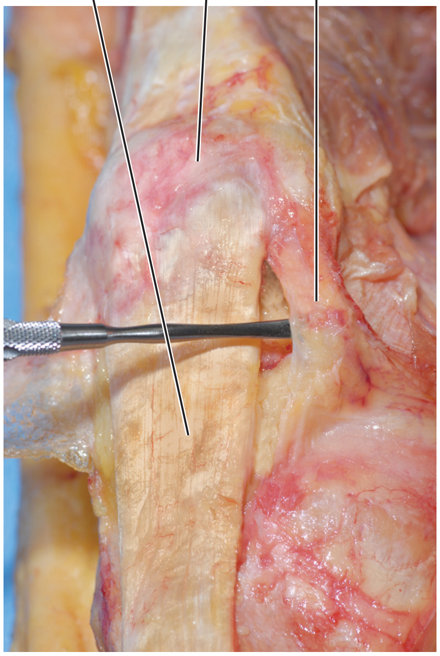

FIG 1-19 The medial patellotibial ligament is adjacent to the patellar tendon.

Patella

The patella is a sesamoid bone deeply associated with the quadriceps tendon, as previously described (Fig. 1-22). The articular surface of the patella is often divided into facets based on longitudinal ridges. The major longitudinal ridge divides the medial and lateral facets of the patella. A second longitudinal ridge near the medial border of the patella separates the medial facet from a thin strip of articular surface known as the *odd facet* (see Fig. 1-20). Wiberg[58] classified the morphology of patellae into three major types based on the position of the longitudinal ridges. Type I patellae have medial and lateral facets that are equal in size. Type II patellae have a medial facet slightly smaller than the lateral facet. Type III patellae have a very small and steeply angled medial facet, whereas the lateral facet is broad and concave. According to Dye and coworkers,[14] type II patellae are the most common (present in 57% of knees) followed by type I (24%) and type III (19%).

Patellar Tendon

The patellar tendon courses between the inferior pole of the patella and the tibial tubercle (see Fig. 1-19). This tendon consists mostly of fibers from the rectus femoris, as previously mentioned. The structure inserts on the proximal tibia, just distal to the most proximal portion of the tibial tubercle. It blends medially and laterally with the fascial expansions of the anterior surface of the tibia and the iliotibial band. Dye and coworkers[14] reported an average length of 46 mm, with a range of 35 to 55 mm.

Infrapatellar Fat Pad

The infrapatellar fat pad is an intracapsular, but extrasynovial structure; the deepest portion is covered by a synovial layer. This structure has been consistently identified to have a thick central body, with

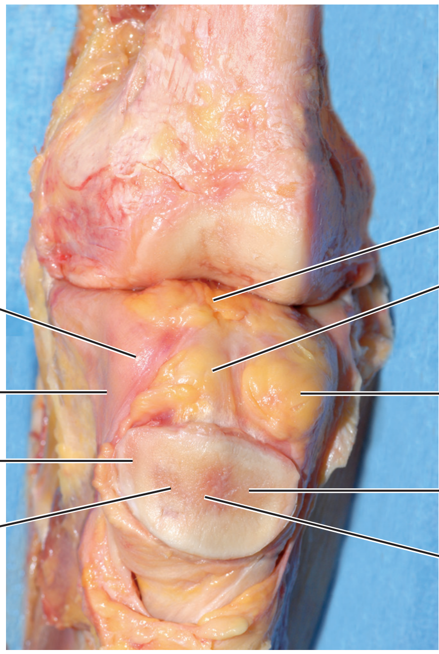

FIG 1-20 Posterior anatomy of the patella with adjacent capsular thickenings and fat pads with medial and lateral meniscopatellar ligaments.

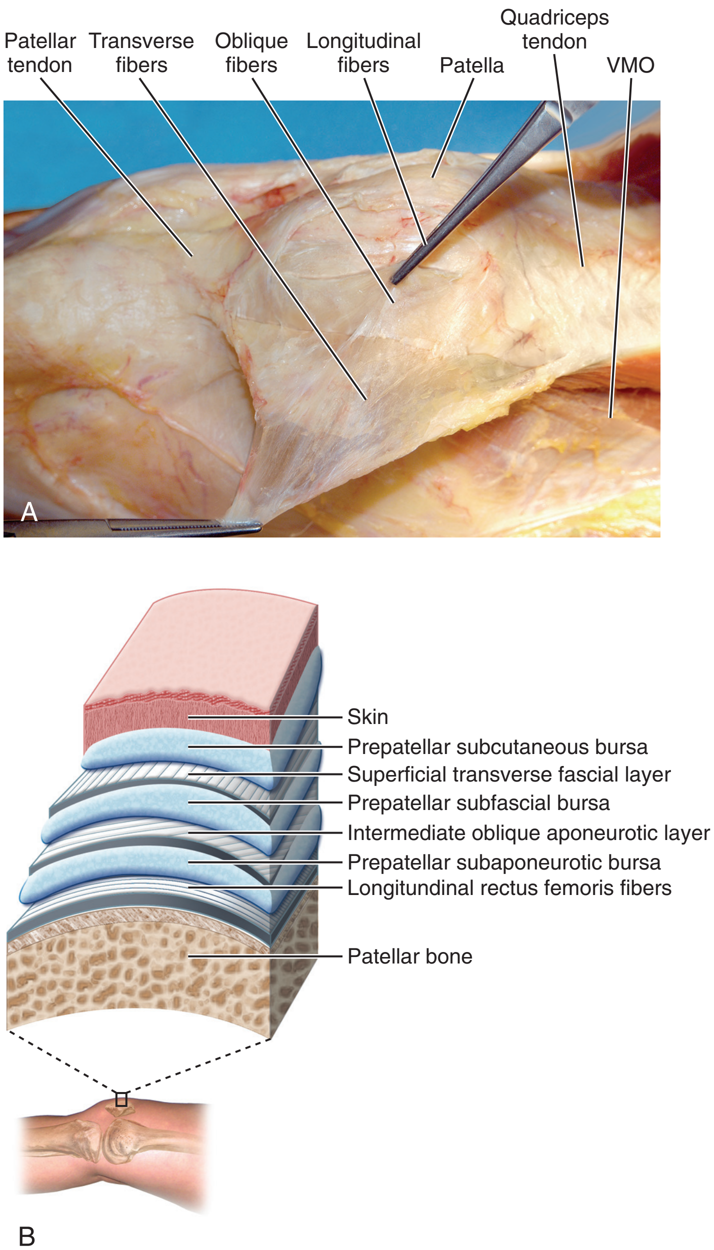

FIG 1-21 A, Fascia layers of the anterior knee. **B,** Layers of the anterior knee. VMO, Vastus medialis obliquus.

thinner medial and lateral extensions (see Fig. 1-20). It has attachments to the inferior pole of the patella proximally, the patellar tendon and anterior capsule anteriorly, the anterior horns of the medial and lateral menisci plus the proximal tibia inferiorly, and the intercondylar notch posteriorly via the ligamentum mucosum.[18] The ligamentum mucosum is an embryonic remnant separating the medial and lateral compartments of the knee. It has two alar folds that attach to the infrapatellar fat pad, allowing it to maintain its position in the joint.[23]

Gallagher and associates[18] identified two clefts in the infrapatellar fat pad: a horizontal cleft found just inferior to the ligamentum mucosum, and a vertical cleft, located anterior to the superior tag of the central body. It has been postulated that these clefts may play a role in reducing the friction between the anterior capsule and the femoral condyles, but they also may be a location for loose bodies to hide.

Inflammation in the infrapatellar fat pad has been implicated as a source of anterior knee pain. Hoffa disease is characterized by inflammation and hypertrophy, with subsequent trapping of the fat pad between the patellar tendon and femoral condyles.[18] The treatment frequently consists of resection of the fat pad, but this has been associated with a decrease in patellar blood supply.[26] The fat pad may also become inflamed after arthroscopic surgery because of portal placement. This may lead to fibrous scarring, which can limit motion and serve as a source for residual pain.[13] Fibrous scars that occur after arthroscopy have a 50% resolution rate after 1 year.[53] It is recommended that portal placement be well medial and lateral to the patellar tendon borders so that damage to the central body and superior tag are minimized to limit this potential complication.[18]

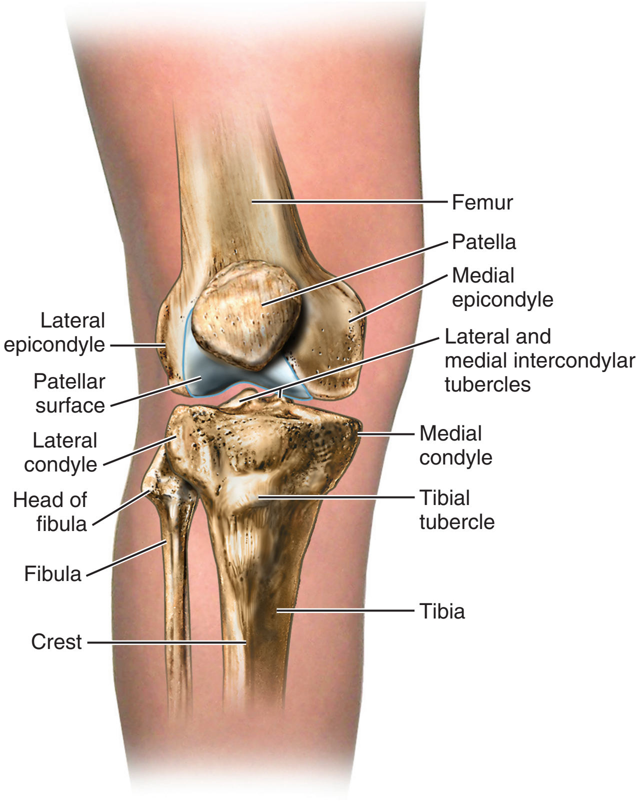

FIG 1-22 Bony landmarks of the anterior knee.

Superficial Neurovascular Structures

The medial inferior genicular artery traverses beneath the SCML after branching from the popliteal artery (Figs. 1-23 and 1-24). It can be visualized on the anterior border of the SMCL as it courses toward the patellar tendon and medial meniscus. This vascular structure may be encountered during any dissection on the medial aspect of the knee, most notably, during a posteromedial approach for meniscal repair. If identified in the approach, it must be retracted or cauterized to provide a clear approach to the medial meniscus.

Other important structures located on the medial side of the knee are the saphenous nerve with its sartorial and infrapatellar branches, the medial femoral cutaneous nerve, and the medial retinacular nerve (Fig. 1-25). These nerves may be easily injured with medial dissection of the knee. It has been reported that injury to the saphenous nerve occurs in 7% to 22% of patients during arthroscopic meniscal repair.[4] According to Dunaway and colleagues,[12] cadaver dissections in 42 knees revealed that the sartorial branch of the saphenous nerve consistently became extrafascial between the sartorius and gracilis. However, this location varied between 37 mm proximal to the joint line and 30 mm distal to the joint line, with the nerve being extrafascial at the joint only 43% of the time and deep to the sartorius fascia in 66% of specimens. Dunaway and colleagues[12] noted that only 2.8% of the specimens dissected had a sartorial branch anterior to the sartorius fascia. These authors recommend that during an inside-out medial meniscus repair, staying anterior during dissection minimizes risk of injury to the sartorial branch. Horner and Dellon[24] described the sartorial branch as the terminal branch of the saphenous nerve that passes 3 cm posterior to the central point of the medial condyle of the femur and continues to the medial aspect of the foot alongside the saphenous vein.

The infrapatellar branch of the saphenous nerve may also be easily damaged with indiscriminate dissection on the medial aspect of the knee, leading to postoperative pain and paresthesia. Postoperative numbness, paresthesia, or hypersensitivity in the distribution of the infrapatellar branch of the saphenous nerve has been reported in the literature[48]: 21% in the Mayo Clinic series, 51.5% in the Iowa series, and 40% in the Alberta series.[25] The risk of damage is increased by the varying course of the nerve. The infrapatellar branch of the saphenous nerve may have four different courses at the level of the medial joint line, which are described by the nerve's relationship to the sartorius muscle. The nerve may be posterior, penetrating, parallel, and anterior to the sartorius, with the most common type being posterior (62.2%).[3] Arthornthurasook and Gaew-Im[3] reported that the infrapatellar branch of the saphenous nerve is an average distance of 40.6 mm from the medial epicondyle when the nerve exits and travels posterior to the sartorius. Horner and Dellon[24] described the infrapatellar branch separating from the saphenous nerve in the proximal third of the thigh in 17.6% of specimens, in the middle third in 58.8%, and in the distal third of the thigh in 23.5%. This nerve innervates not only the patella but also the anterior-inferior capsule.[24]

Horner and Dellon[24] described the medial femoral cutaneous nerve traveling superficially to the sartorius muscle in 39.1% of knees. However, this nerve often travels in Hunter's canal and perforates the sartorius (30.4% of knees) or continues in Hunter's canal and exits deep to the sartorius (30.4% of knees). The termination of this nerve is the most superficial constant branch that eventually bisects the patella to form a prepatellar plexus before continuing to the lateral aspect of the knee and pairing with the infrapatellar branch of the saphenous nerve proximal the knee joint.

The medial retinacular nerve has also been described as residing on the medial aspect of the knee near the vastus medialis. The vastus medialis is innervated by branches from the femoral nerve. The terminal branch of the nerve to the vastus medialis ends at the medial retinacular nerve. According to Horner and Dellon,[24] this nerve may traverse within the vastus medialis (90% of knees) or lie superficial to its fascia (10% of knees). The nerve enters the knee capsule beneath the medial retinaculum, 1 cm proximal to the adductor tubercle, and sends a branch to the MCL.[24] This nerve was not identified in dissections by us.

Indiscriminate dissection on the medial side of the knee could easily damage any one of these described nerves, leading to the pathology already noted. Painful neuromas and complex regional pain syndrome can turn a successful operation into a complicated pain syndrome. Horner and Dellon[24] advised that the surgeon be aware of these pitfalls and recognize the possibility that symptomatology may result from damage to one or more nerves that require diagnostic nerve blocks at multiple sites to identify the pathology. Unnecessary subsequent surgeries for postoperative pain may be prevented by identifying the true cause of pain, which may very well be the result of nerve damage. A neurectomy may be required when a nerve block provides only temporary relief of pain.[24]

CONCLUSION

The anterior and medial anatomy of the knee has frequently been oversimplified or poorly described in the literature. It is our hope that this chapter has allowed the reader a greater appreciation for the anatomic relationships present and their potential implications in various knee conditions. A key to successful operative repair and reconstruction of the medial side of the knee is detailed knowledge of the anatomy of its structures.

Video Content

Video 1-1
Video 1-2

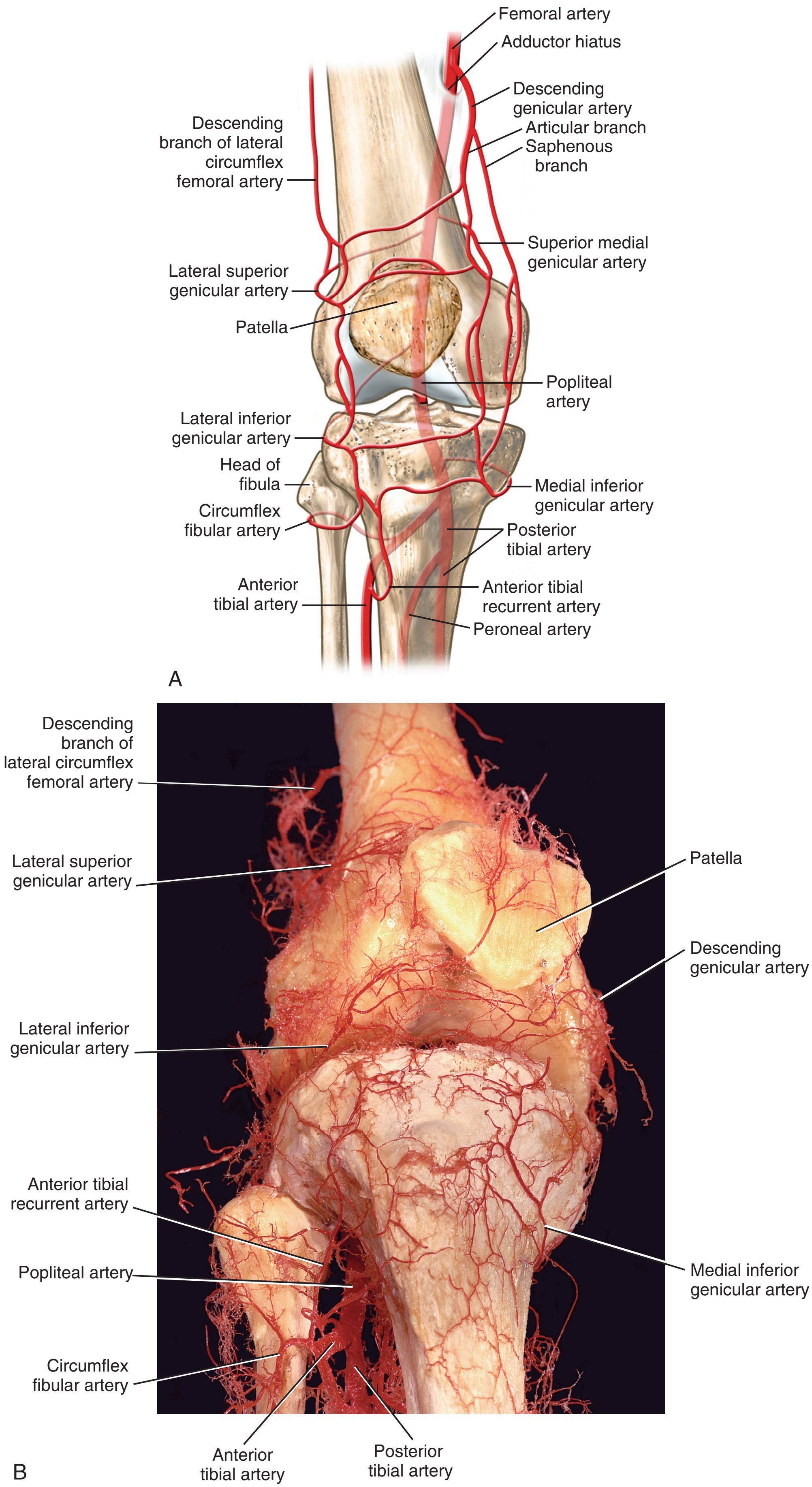

FIG 1-23 **A,** Arterial vasculature of the knee. **B,** Detailed vascularity shown after specialized injection technique. (Courtesy Dr. R.F. Kaderly.)

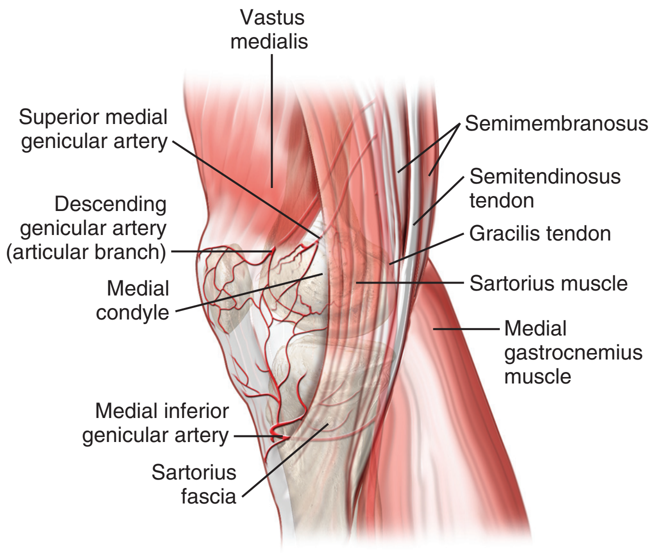

FIG 1-24 Path of the medial inferior genicular artery.

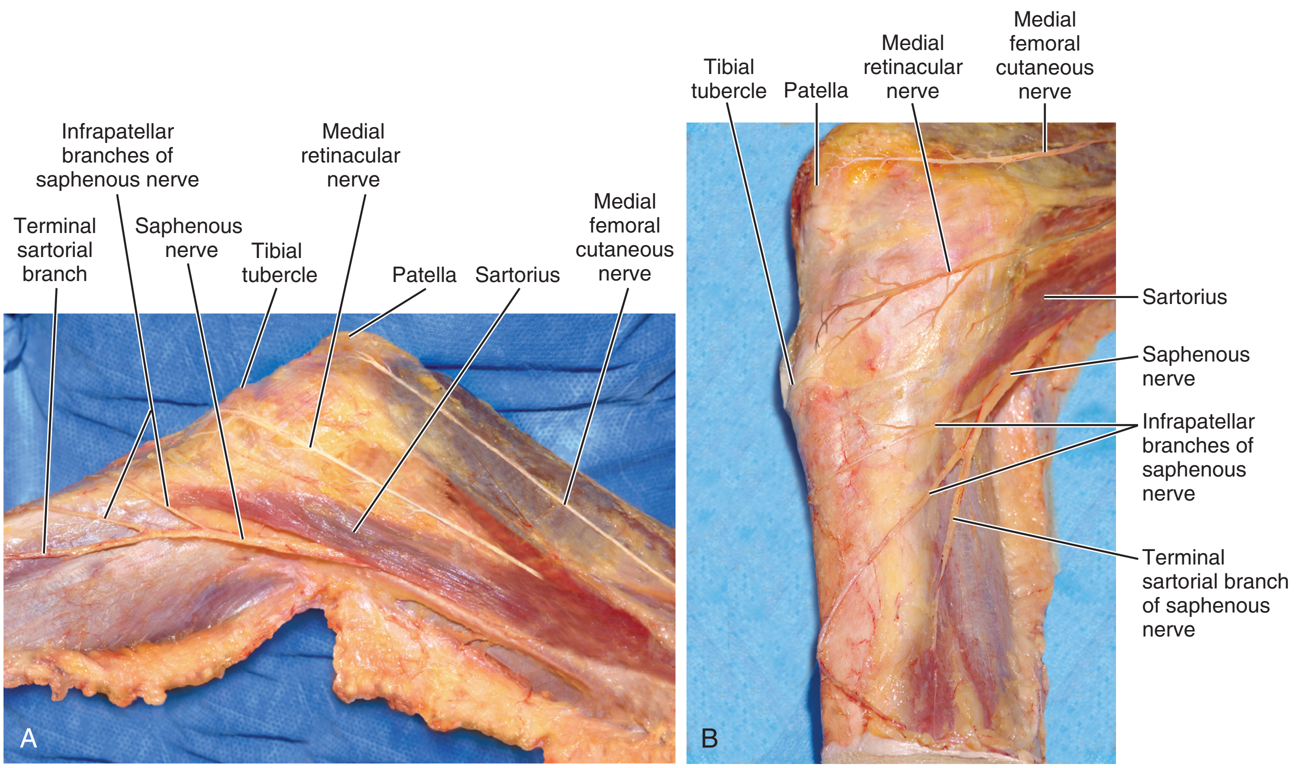

FIG 1-25 **A,** Anteromedial view of the superficial nerves. **B,** Medial view of the superficial nerves.

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