Hammertoes

A Case-Based Approach

Emily A. Cook
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Editors

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Preface

As Aesop famously said, “familiarity breeds contempt,” and the ubiquitous hammertoe deformity is proof to this statement as fact. We have attended many conferences, lectures, and workshops throughout our careers. At these meetings, we have often been surprised by the number of practitioners that ask for advice on the management of a complex digital deformity. Our ever-expanding expertise includes complicated multiplane limb deformity correction and ankle joint replacement, yet why should the statement “Nothing is as humbling as a hammertoe that has gone awry” still be true? The fact is that the biomechanics intrinsic to the toes are a marvel. The circumstances that disrupt that balance are equally complex which is why this book has been compiled.

The purpose of *Hammertoes: A Case-Based Approach* is to provide foot and ankle specialists with a comprehensive understanding of digital deformities of the foot and their management. An introductory chapter will establish the functional anatomy, while subsequent chapters provide a compilation of interesting cases and challenging pedal pathologies. The format is such that each case will present relevant clinical details that justify the subsequent decision-making and ultimately the final treatment option. The chapters are intended to be applicable for students and experts alike regardless of educational background.

In the initial stages of the process, it became apparent that to meet our lofty standards, we would need the expertise and most onerously, the time of our colleagues. We have assembled a virtual pantheon of experts and thought leaders to compile the information you now hold in your hands. It is with no small amount of pride that we can say that the contributing authors are drawn from diverse institutions, degrees, and far-flung locales. We cannot fully express our gratitude to them for their participation.

We recognize that surgery has a constantly evolving standard. Our objective is to provide a substantial foundation for the reader to draw from, with the understanding that time and knowledge march on. Although the details may change over time, we believe that principles expressed in these chapters may be applicable regardless of the technique or implant du jour. We encourage you to look at each chapter critically

and see how it supplements your own current understanding. We hope that our efforts help you to continue to provide the exceptional care your patients deserve.

In the course of writing this book, one of the authors passed away. Bruce Richardson, PhD, served as the Dean for Preclinical Affairs at the California School of Podiatric Medicine at Samuel Merritt University. He masterfully taught human anatomy for decades with a kind spirit and a sharp wit. His list of accolades is a chapter unto themselves, but none greater than the living testament that his students, who improve the lives of patients everyday with the knowledge he provided. Several of the authors in this book owe their anatomic understanding to Dr. Richardson. We would like to dedicate this book to his memory and the spirit of education that was such an important part of his life.

Contents

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Chapter 1
Anatomy of the Intermetatarsal, Lesser Metatarsophalangeal, and Lesser Interphalangeal Joints

Bruce A. Richardson, Matthew Knabel, and Eric Swenson

Intermetatarsal Joints

Both the bases and the heads of the lateral four metatarsals are connected by ligaments forming the intermetatarsal joints (IMJ). The adjacent sides of the bases of the second, third, fourth, and fifth metatarsals articulate with one another via plane synovial joints. The synovial joint cavity of the second and third IMJ is continuous with the cavity of the great tarsal joint. The joint cavity of the third and fourth IMJ is occasionally continuous with the cavity of the general tarsal cavity and in other instances is continuous with the cavity of the lateral tarsometatarsal joint. The joint cavity of the fourth and fifth IMJ is continuous with the cavity of the lateral tarsometatarsal joint between the fourth and fifth metatarsal and the cuboid [1].

Articular surfaces do not exist between the metatarsal heads as they do not come close enough to one another to truly articulate. They are held together, however, by the deep transverse metatarsal ligament (Fig. 1.1a, b).

Components of the Intermetatarsal Joints

The bases of the four lateral metatarsals are connected by the dorsal intermetatarsal, plantar intermetatarsal, and interosseous intermetatarsal ligaments. The first metatarsal is connected with the second by interosseous fibers only; the fibers are weak and may be largely replaced by a bursa between indistinct facets on the two bones.

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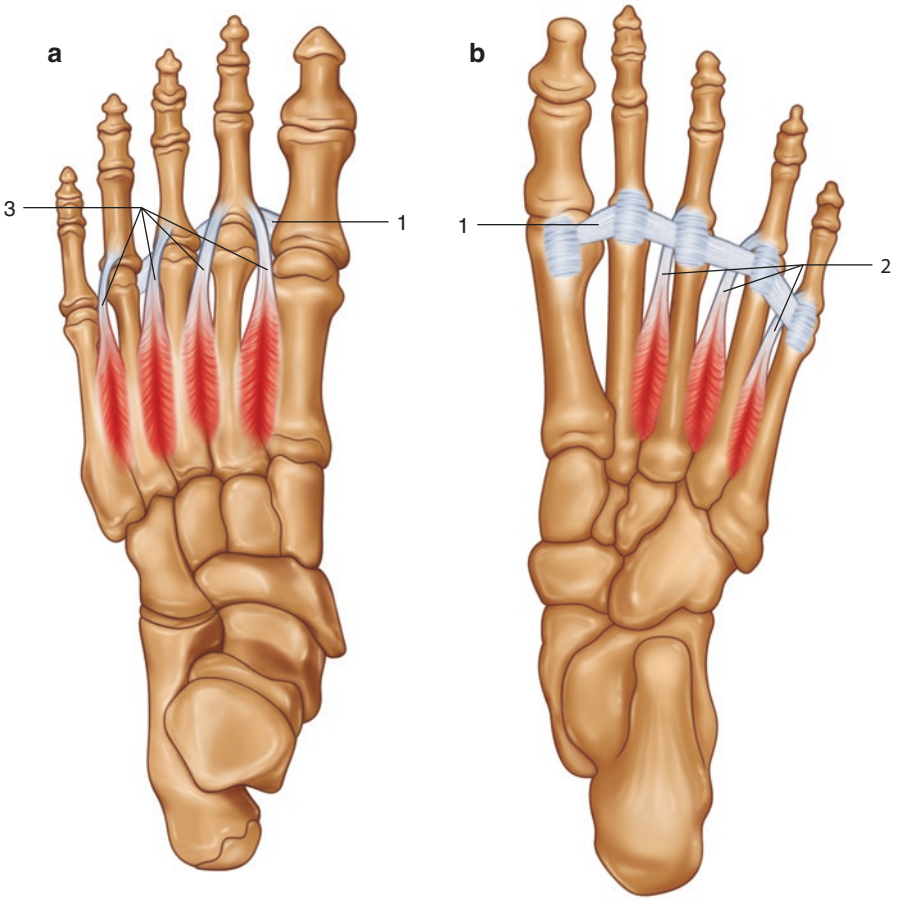

Fig. 1.1 (**a**, **b**) 1. The deep transverse metatarsal ligament connects the metatarsal heads. 2. Plantar interossei adduct toes 3–5 toward the midline of the foot. 3. Dorsal interossei abduct the toes away from the midline (second toe) of the foot. Both dorsal and plantar interossei lie dorsal to the deep transverse metatarsal ligament

The dorsal intermetatarsal ligaments pass transversely between the dorsal surfaces of the bases of the adjacent metatarsal bones. The plantar intermetatarsal ligaments extend transversely between the plantar surfaces of the bases of the adjacent metatarsal bones. The plantar ligaments are the stronger of the two sets being thicker than the dorsal ligaments. The strongest of the ligaments are the interosseous intermetatarsal ligaments. These ligaments attach to the non-articular areas of the adjacent metatarsal bases of the second, third, fourth, and fifth metatarsals.

The deep transverse metatarsal ligament extends medially as far as the lateral side of the head of the first metatarsal and laterally as far as the medial side of the

head of the fifth metatarsal (Fig. 1.1). The fibers of the ligament are primarily connected to the plantar aspects of the metatarsophalangeal joints via the edges of the plantar plates.

Movements of the Intermetatarsal Joints

Gliding movements between the adjacent sides of the bases of the second, third, fourth, and fifth metatarsals occur at the IMJs. Although these movements are slight, they are important in that they contribute to movements of the forefoot relative to the midfoot and hindfoot, especially in forward propulsion and in excess weight-bearing, such as carrying a heavy object [2].

Innervation of the Intermetatarsal Joints

Innervation of the IMJs is provided by branches of the lateral plantar nerve and of the deep peroneal nerve [3].

Lesser Metatarsophalangeal Joints

The metatarsophalangeal joints (MTPJ) are of the condyloidal (ellipsoidal) synovial type. The MTPJs are both anatomical and functional joints in that they are true synovial joints, but each brings about significant movements or functions of the forefoot. They are formed by the reception of the rounded distal heads of the five metatarsal bones in the shallow cavities of the proximal bases of the five proximal phalanges. The lesser MTPJs are the articulations of metatarsals II through V with the corresponding proximal phalanges.

Components of the Lesser Metatarsophalangeal Joints

The joint surfaces of both the metatarsals and proximal phalanges are roughly oval in shape, with the head of the metatarsal contributing to the convex portion of the joint and the base of the proximal phalanx forming the concave portion. While the first MTPJ possesses sesamoid bones that are constant and contribute to the articular surfaces of this joint, the presence of sesamoids within the joint capsules of the lesser MTPJs is variable. The most common occurrence is at the second (1–1.6% of

cases examined), fourth (2%), and fifth (11%) MTPJs. When present, typically there is one sesamoid of the second, one of the fourth, and two of the fifth MTPJ (Fig. 1.2). These sesamoids tend to be embedded within the joint capsules and the tendons of the short flexors of the toes [4, 5].

A loose fibrous joint capsule lined with a synovial membrane surrounds each MTPJ. The capsules are distinct dorsally and are attached further proximally on the plantar surfaces of the metatarsals than on the dorsal surfaces of the metatarsals. Dorsally, the capsule attaches very near the edge of the articular surface of each of the metatarsals and passes distally to attach near the dorsal edge of the articular surface of each of the proximal phalanges. The capsule in this region is very thin and is reinforced by the tendons of the long extensor muscles of the anterior leg. The tendons begin to expand into fibrous sheets at, or near, the MTPJs and are called extensor expansions. Occasionally situated between the tendons and the joint capsule dorsally are bursae [2]. On the plantar surface, the capsule attaches quite proximally on the metatarsal heads, approximately 5 mm posterior to the border of the

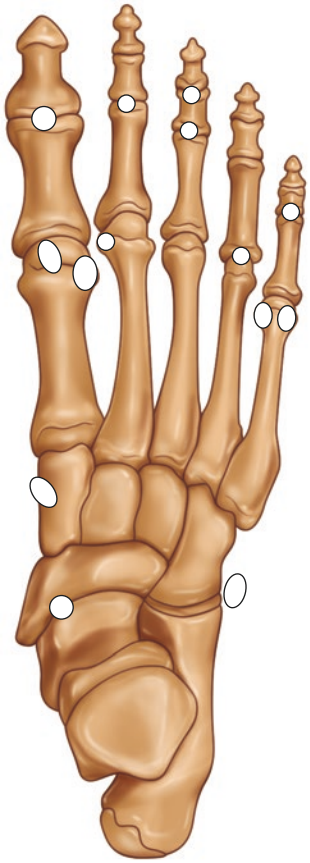

Fig. 1.2 The presence of lesser MPJ and IPJ sesamoids is variable

articular surface. Distally, the plantar portion of the capsule attaches near the plantar edge of the articular surface of the proximal phalanx.

Plantar metatarsophalangeal (MTPJ) ligaments (plantar plates, see below) reinforce the inferior aspect of the capsule and completely blend with it. The capsule is reinforced laterally and medially by strong metatarsophalangeal collateral ligaments as well as lateral and medial metatarsoglenoid suspensory ligaments [6]. The collateral ligaments also serve to restrict abduction and adduction as well as rotation at the joints (Fig. 1.3).

Plantar Plate and Collateral Ligaments

There are many different names for the plantar plates and collateral ligaments, and there is no standardized nomenclature. As described below, the plantar plate has also been called the plantar metatarsophalangeal ligament, plantar pad, and glenoid ligament. The medial and lateral proper collateral ligaments which run from the metatarsal to the phalanx are also simply called the metatarsophalangeal collateral ligaments. And finally, the medial and lateral accessory collateral ligaments which run from the metatarsal to the plantar plate are also called the metatarsoglenoid ligament or suspensory ligament (Figs. 1.3 and 1.4).

There are no dorsal ligaments per se, but the dorsal aspect of the capsules is reinforced by the extensor tendons and their expansions. The plantar metatarsophalangeal ligaments contribute to the overall strength of the plantar aspect of the capsule and are specialized in that they are partially fibrocartilaginous and form the

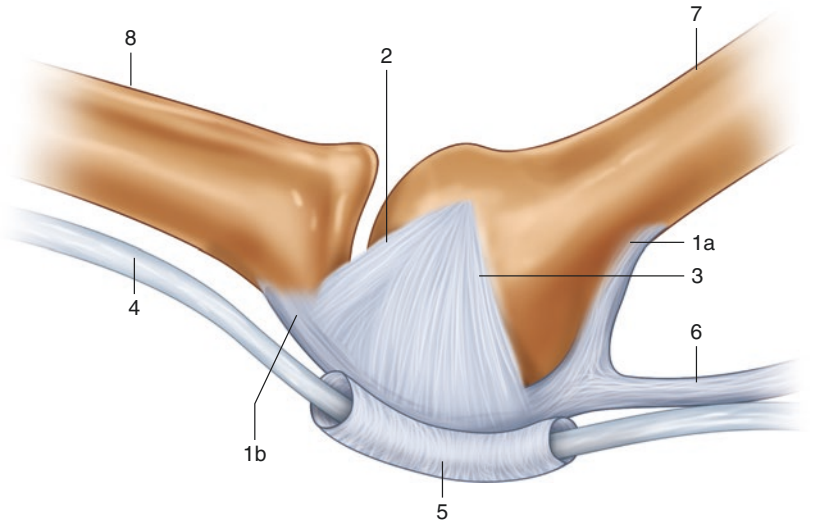

Fig. 1.3 Plantar plate and collateral ligaments. Labels: 1A = plantar plate origin (thinner), 1B = plantar plate insertion (thicker), 2 = proper collateral ligament, 3 = accessory collateral ligament, 4 = flexor tendons, 5 = flexor tendon sheath, 6 = plantar aponeurosis attaching into the plantar plate, 7 = metatarsal, 8 = proximal phalanx

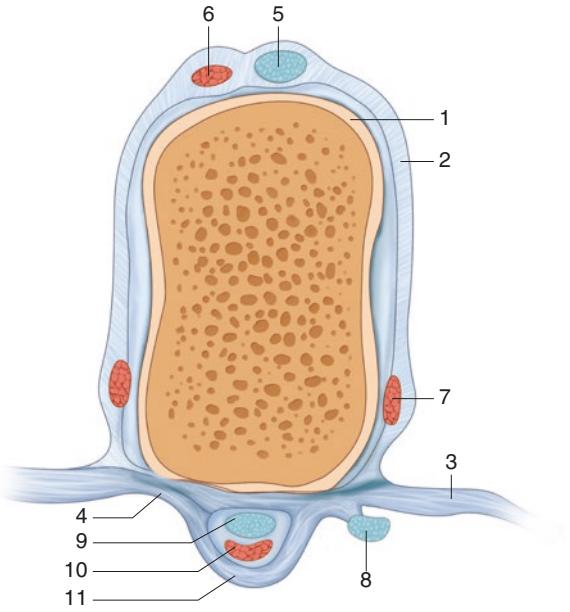

Fig. 1.4 Cross section of the metatarsophalangeal joint. Labels: 1 = joint capsule, 2 = extensor expansion with the sling and wing, 3 = deep transverse metatarsal ligament, 4 = plantar plate, 5 = EDL, 6 = EDB, 7 = interossei within the extensor sling, 8 = lumbrical with connections to the plantar plate, 9 = FDL, 10 = FDB, 11 = flexor tendon sheath

plantar plates, or plantar pads, of the MTPJs. The deep transverse metatarsal ligament attaches to the sides of the plantar plate between adjacent metatarsals (Fig. 1.4). The medial and lateral suspensory or metatarsoglenoid ligaments are also very strong and extend from the more dorsal aspects of the metatarsals to the sides of the plantar plate to which they attach [6] (Fig. 1.4). The plantar MTPJ ligaments, or glenoid ligaments, which form the plantar plate, reinforce the capsule inferiorly and blend with it such that the deep surfaces of these ligaments are lined with synovial membranes. The plantar plates are fibrocartilaginous thickenings within the plantar ligaments that average 18.8 mm in length (mean 20 mm for the second and third toes; mean 17 mm for the fourth and fifth toes) [7]. Most research related to the plantar plates has been carried out on the second MTPJ. The plantar plates are composed primarily of type I collagen and a minimal amount of elastin fibers [8].

In the lesser toes, the plantar plates are located deep to the metatarsal head and serve as the central attachment for ligamentous, tendinous, and capsular structures at the MTPJs (Fig. 1.4). Each plate is tightly bound to the proximal phalanx by a thick medial and lateral longitudinal bundles of fibers that attach directly adjacent to the articular surface of the proximal phalanx, thus forming a socket for the head of the metatarsus. Proximally the plantar plates are loosely bound to the head of the metatarsals but have strong fibrous proximal attachments consisting of the collateral ligaments and plantar fascia [2, 7] (Fig. 1.3). These attachments permit the plantar plates to move with the phalanges during flexion and extension of the MTPJs (e.g.,

during ambulation). The superior surface of the plate is smooth which glides along the metatarsal head during ambulation [9]. The edges of the plantar plates of the second, third, and fourth MTPJs are attached to the deep transverse intermetatarsal ligament (Fig. 1.4). The medial edge of the plantar plate of the fifth MTPJ is also attached to the deep transverse intermetatarsal ligament. The inferior surface of each plantar plate of the lesser digits is marked by a smooth groove formed by the flexor tendons as they cross the joint. The superior surface of the deep fibers of the central slip of the plantar aponeurosis of the foot also attaches to the inferior aspect of each of the plantar plates to form a sheath around the flexor tendons (Fig. 1.3).

The collateral ligaments of the lesser MTPJs are paired and triangular-shaped ligaments that extend from the tubercles on the dorsolateral and dorsomedial aspects of the metatarsals to tubercles on the lateral and medial plantar aspects of the bases of the proximal phalanges (Fig. 1.3). To distinguish the collateral ligaments from the adjacent paired metatarsoglenoid ligaments, Sarrafian refers to them as the metatarsophalangeal collateral ligaments [6]. Deland et al. refer to these ligaments as lateral and medial proper collateral ligaments [7]. Sarrafian describes the metatarsoglenoid ligaments as passing from the inferior aspects of the tubercles on the metatarsals to the medial and lateral sides of the plantar plates. The metatarsoglenoid ligaments are also referred to as suspensory ligaments as they assist in the suspension of the plantar plates [6]. Deland et al. call the suspensory ligaments accessory collateral ligaments [7]. The metatarsoglenoid ligaments fan out as they pass inferiorly to suspend the plantar plates and blend with the more anterior metatarsophalangeal collateral ligaments [6, 10]. Loretz and colleagues found in the dissection of 103 lesser MTPJs that the collateral and suspensory ligaments are distinct structures at proximal attachment to the metatarsal tubercles and blend distally with one another in 68% of the cases. In all dissections, the collateral ligaments attached to the tubercles of the proximal phalanges distally. In 32% of the joints dissected, the collateral and suspensory ligaments were fused together throughout their course and appeared as one triangular-shaped ligament [10] (Fig. 1.3).

The four lumbricals insert, in part, into the distal plantar aspect of tibial side of the plantar plate. Both plantar and dorsal interossei possess fibers that insert into the plantar plates as well [7]. Deland and colleagues also reported that fibers of the tendons of the transverse head of the adductor hallucis, flexor digiti minimi brevis, and abductor digiti minimi attach to the plantar plates of the lesser toes. Moreover, the flexor digitorum longus (FDL) and flexor digitorum brevis (FDB) tendons and the extensor hood and sling are also closely associated with the plantar plates of the lesser toes and contribute to the stability of the MTPJs [9]. Johnson et al. observed the flexor tendon sheath is situated centrally within the shallow groove on the superior surface of the plantar plate and is firmly anchored by a fibrous pulley. The FDB tendon, which splits to accommodate the FDL tendon at the proximal interphalangeal (PIP) joint, is inferior to the FDL tendon with the FDB inserting bilaterally onto the middle phalangeal base and the FDL inserting onto the inferior surface of the distal phalanges [8] (Fig. 1.5).

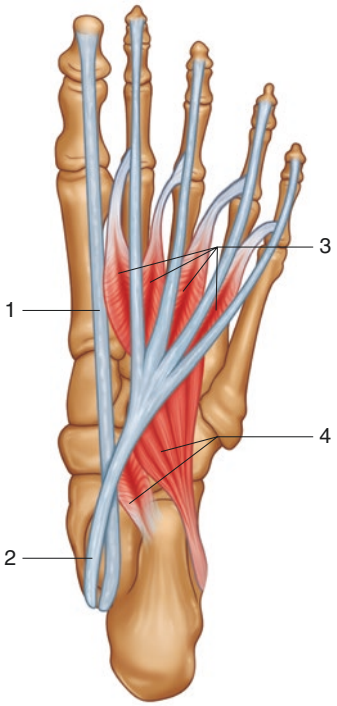

Fig. 1.5 Plantar foot containing the FDL, FHL, quadratus plantae, and lumbricals (not all four layers of the plantar muscles are shown). Labels: 1 = FHL, 2 = FDL, 3 = lumbricals (all four lumbricals lie plantar to the DTML, 4 = quadratus plantae

The extensor hood and sling is the fibroaponeurotic expansion of the extensor digitorum longus (EDL) tendon sheath and insert directly onto the plantar plate, the deep transverse intermetatarsal ligament, and the base of the proximal phalanx (Fig. 1.6a, b). The extensor mechanism, along with the lumbricals and interosseous tendons, contributes to the stability of the MTPJ in stance and during ambulation [11].

The anatomical unit consisting of the proximal phalanx, the plantar plate, the collateral ligaments (both proper and accessory), and the attachments of the above muscles, fibroaponeurotic dorsal expansion, and deep transverse intermetatarsal ligament is referred to by Sarrafian and colleagues as the phalangeal apparatus and represents the main articular unit of the ball of the foot [6].

Functionally, the plantar plates (phalangeal apparatus; see above) of the lesser metatarsophalangeal joints play a significant role in the stability of the lesser MTP joints as well as sustaining substantial tensile loads in the longitudinal direction making up an integral part of the windlass mechanism [7]. In addition, the fibrocartilaginous makeup of the plantar plates permits them to withstand compressive loads, thereby acting supportive articular surfaces for the metatarsal heads, similar to the menisci in the knee. Clinically, the plantar plates are also important in that pathological changes to the plates can lead to metatarsalgia, MTPJ instability, plantar plate rupture, and toe deformities such as hammertoe, claw toe, and medial crossover toe deformity [9].

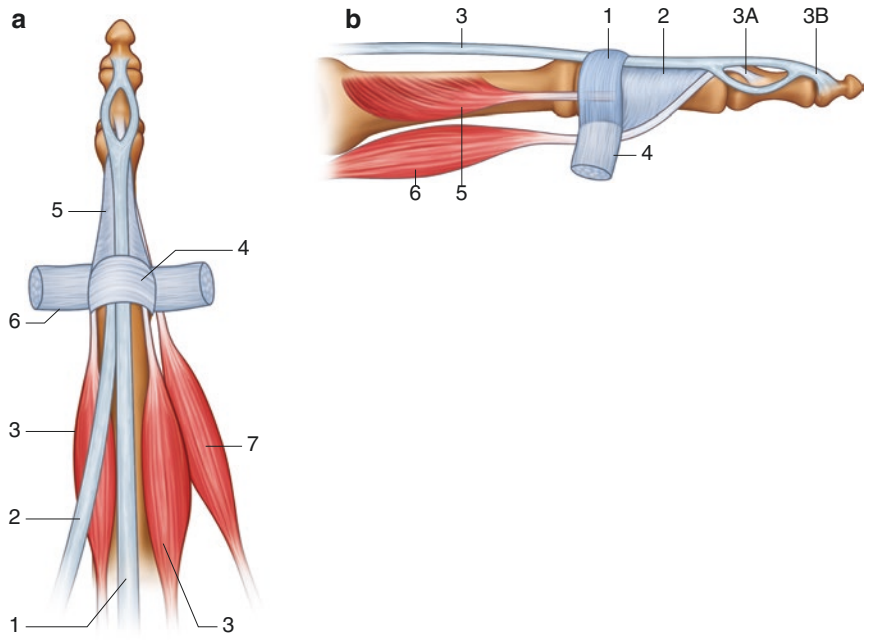

Fig. 1.6 (**a**, **b**) Top and side views. (**a**) top view labels: 1 = EDL, 2 = EDB, 3 = interossei (second MTPJ), 4 = extensor sling, 5 = extensor wing or hood, 6 = DTML, 7 = lumbrical. (**b**) side view labels: 1 = extensor sling, 2 = extensor wing or hood, 3 = EDL, 3A = central slip middle phalanx insertion of the EDL, 3B = terminal slip distal phalanx insertion of the EDL, 4 = DTML, 5 = interossei, 6 = lumbrical

Movements of the Lesser Metatarsophalangeal Joints

The lesser MTPJs are biaxial ellipsoidal joints; therefore movement is about two axes. One axis is in the transverse and frontal planes, perpendicular to the sagittal plane, permitting movements of plantar flexion and dorsiflexion or flexion and extension. The other axis is in the sagittal and frontal planes, perpendicular to the transverse plane, permitting the movements of abduction and adduction. The metatarsophalangeal collateral and suspensory ligaments function to restrict the degree of plantar flexion and dorsiflexion of these joints (Loretz et al. 1984). In addition, the suspensory ligaments, as a result of their attachment to the plantar plate, assist in the control of abduction and adduction. The glenoid ligament/plantar plate unit moves with the MTPJ through extension and flexion.

The range of extension at the MTPJs is much greater than that of flexion, while the range of abduction and adduction is quite small. The range of extension is 50–60°, while that of flexion is 30–40° [2]. When the foot is in the plantigrade position, the MTPJs are extended by about 25°, as the proximal phalanges are angled anterosuperiorly from the metatarsal heads which are in contact with the ground.

Some degree of abduction accompanies extension. Adduction and abduction also occur as independent movements, but their ranges are quite limited. As in the hand, the freest ranges of movement for abduction and adduction occur when the MTPJs are extended as this optimizes the line of pull of the interossei muscles which act to abduct and adduct most of the lesser digits. Even in this position, however, abduction and abduction of the toes is quite limited [12]. The abductor digiti minimi and the third plantar interosseous muscle act to abduct and adduct the fifth toe.

Innervation of the Lesser Metatarsophalangeal Joints

Innervation of the MTPJs is provided by the deep branch of the lateral plantar nerve and the medial plantar nerve to the second, third, and fourth MTPJs. The fifth MTPJ is supplied by the superficial branch of the lateral plantar nerve and the lateral dorsal cutaneous nerve. In addition, the lateral dorsal cutaneous nerve also assists in the innervation of the fourth MTPJ, and the deep peroneal assists in the innervation of the second MTPJ [3].

Blood Supply of the Lesser Metatarsophalangeal Joints

Nonunion, delayed union, and avascular osteonecrosis of the lesser metatarsal head are possible complications of distal osteotomies of the lesser metatarsal. These complications are a result of iatrogenic disruption of the blood supply [13]. Thus, knowledge of the vascular supply to the MTPJs is important when correcting various deformities such as claw toe deformities and metatarsalgia by distal osteotomies of the lesser metatarsals.

The metatarsal heads receive their blood supply from two main sources: the dorsal and plantar metatarsal arteries, both of which are branches of the posterior tibial artery. Petersen and colleagues also showed that the intraosseous arterial supply of the metatarsal head differs from that in the diaphysis. There are numerous arterial anastomoses between the vascular network of the bone and periosteum, whereas the arterial supply of the head consists of terminal end arteries. Thus, the metatarsal beads are more susceptible to osteonecrosis as a result of vascular injury than the diaphysis [13].

Interphalangeal Joints

The interphalangeal joints of the toes (IPJ) are the articulations between the proximal and middle and middle and distal phalanges of the lesser toes and between the proximal and distal phalanges of the hallux. They are all ginglymus or hinge

joints that have their axes of movement in the frontal and transverse planes, perpendicular to the sagittal plane, permitting plantar flexion and dorsiflexion or flexion and extension of the toes. Typically, there are nine IPJs per foot, two for each of the lesser digits and one for the hallux. The two in each of the lesser toes are referred to as proximal and distal IPJs. In approximately 40% of the population, the middle and distal phalanges of the fifth toe are fused; consequently, no distal IPJ exists [1].

Components of the Interphalangeal Joints

The head of each proximal and middle phalanx resembles a pulley, and the base of the middle and distal phalanges possesses a reciprocally curved double concavity that fits into the pulley. The phalanges of the toes are smaller than those of the fingers, and often the joints between the middle and distal phalanges in the more lateral toes are ankylosed and nonfunctional (see paragraph above).

Each IPJ possesses a joint capsule that is thin dorsally and thickened by ligaments plantarly and bilaterally. Dorsally, the capsules reinforced dorsally by the long extensor tendons as they pass to their insertion on the dorsal aspects of the middle and distal phalanges. The capsules are strengthened medially and laterally by collateral ligaments. These ligaments for the proximal IPJ extend from the tubercles on the dorsomedial and dorsolateral aspects of the proximal phalanx to medial and lateral tubercles on the plantar aspect of the base of the middle phalanx. For each distal IPJ, the collateral ligaments extend from the dorsomedial and dorsolateral tubercles on the middle phalanx to the medial and lateral tubercles on the base of the distal phalanx.

On the plantar surfaces, the IPJs are reinforced by strong fibrous plantar ligaments, similar to the plantar ligaments of the MTPJs [2]. Moreover, the plantar ligaments of the IPJs may be thickened by cartilage (plantar plates), similar to those of the MTPJs [3]. Generally, the capsules and ligaments of the IPJs are tighter than those of the MTPJs.

Although inconsistent, sesamoid bones may be associated with the IPJs. When present, they are most commonly found in the IPJs of the hallux and the proximal IPJs of the second and third toes (Fig. 1.2).

Movements of the Interphalangeal Joints

As hinge joints, the only movements permitted at the IPJs are flexion and extension. The range of motion for flexion is greater than extension, with the latter being limited by the plantar and collateral ligaments. Flexion and extension are more extensive at the proximal IPJ than the distal IPJ [2].

Innervation of the Interphalangeal Joints

Innervation of the IPJs is provided by the proper plantar and proper dorsal digital nerves. The medial dorsal cutaneous nerve assists in the innervation of the IPJ of the hallux, while the superficial branch of the lateral plantar nerve is sole innervation of the IPJs of the fifth toe [3].

Muscular Involvement in Movement and Stability of the Lesser MTPJ and IPJS

Both intrinsic and extrinsic muscles act on the lesser metatarsophalangeal and interphalangeal joints. This section organizes these muscles into those that are located within the dorsal and ventral surfaces of the foot and those that are located within the plantar surface of the foot.

Dorsal Foot Extrinsic and Intrinsic Muscles

Extrinsic and intrinsic muscles acting on the lesser MTPJ and IPJs are found on both the dorsal and ventral surfaces of the foot. On the dorsum, the following muscles act on the lesser MTP and IP joints.

Extensor Digitorum Longus (EDL)
This pennate muscle is situated at the lateral part of the anterior leg, located laterally to tibialis anterior and superficially to extensor hallucis longus (Fig. 1.7). It takes origin from the lateral condyle of the tibia, the proximal two-thirds to three-fourths of the anterior surface of the body of the fibula, the proximal part of the interosseous membrane, the fascia cruris, and the intermuscular septa between it and the tibialis anterior medially and the fibularis (peroneus) laterally. As the muscle passes distally, it becomes tendinous in the inferior part of the leg and travels deep to the superior extensor retinaculum where it divides into two tendons. Deep to the superior retinaculum, it travels with the peroneus tertius or fibularis tertius. It splits into four tendons as it passes deep to the inferior extensor retinaculum through the lateral loop along with the tendon of the peroneus tertius or fibularis tertius where they are enclosed in a synovial sheath. The four tendons pass distally to each of the four lesser toes (Fig. 1.7). As the tendons approach the heads of the metatarsals, they spread out as membranous extension expansions. Joining the lateral side of the tendons to the second, third, and fourth digits are the tendons of the extensor digitorum brevis (see below). The four tendons split further to insert on both the distal and middle phalanges forming parts of the extensor expansion complex (Fig. 1.6a, b). Extensor digitorum longus extends the

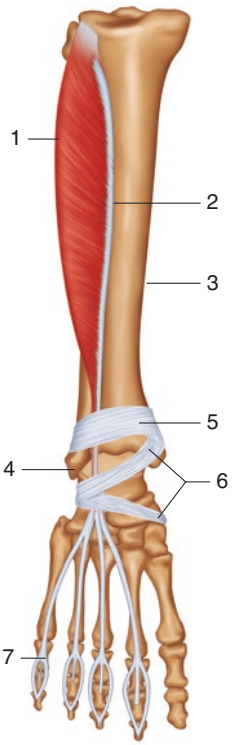

Fig. 1.7 Extensor digitorum longus. Labels: 1 = EDL, 2 = interosseous membrane, 3 = tibia, 4 = fibula, 5 = superior extensor retinaculum, 6 = inferior extensor retinaculum, 7 = EDL trifurcation with central slip insertion into the middle phalanx and terminal slip insertion into the distal phalanx

four lesser toes at the IP and MP joints. It also dorsiflexes the ankle and may al so be a minor evertor and/or pronator of the foot [12]. EDL is innervated by the deep fibular (peroneal) nerve and is provided with arterial blood from the anterior tibial artery.

Extensor Digitorum Brevis (EDB)

This muscle is broad and thin. It takes origin from a tubercle on the superolateral aspect of the calcaneus just anterior to the sinus tarsi. It also partially arises from the interosseous talocalcaneal ligament of the sinus tarsi and from the stem of the inferior extensor retinaculum. It passes diagonally across the dorsum of the foot medially and divides into four bellies and tendons which continue distally toward the first, second, third, and fourth digits. The most medial and largest tendon inserts onto the dorsal surface of the base of the first phalanx of the hallux and is called *extensor hallucis brevis*. The remaining slips insert into the lateral sides of the extensor digitorum longus tendons to the second, third, and fourth toes just distal to the MPJs of these digits and contribute to the extensor expansion (Fig. 1.6a, b).

EDB acts to assist the extension of the phalanges of the second, third, and fourth toes at the IPJs and MPJs. If EDL and EDB work alone without contribution of the plantar intrinsic muscles of the foot (e.g., lumbricals), they extend the MPJs by tightening the extensor sling and pulling the plantar pad up against the proximal

phalanx and metatarsal. When in this position, they are unable to extend the IPJs because the wing of the extensor expansion is loose and the distal portions of the tendons are slack.

EDB is typically innervated by the lateral terminal branch of the deep fibular (peroneal) nerve (S1, S2). However, when an accessory fibular (peroneal) branch of the superficial fibular (peroneal) nerve is present, it may help to innervate EDB [14]. Blood is supplied by the lateral tarsal branch of the dorsalis pedis artery as well as the perforating fibular (peroneal) artery as it anastomoses with the lateral tarsal branch.

Plantar Foot Extrinsic and Intrinsic Muscles

The extrinsic and intrinsic muscles on the plantar surface of the foot that act on the IPJs and MPJs are as follows.

Flexor Digitorum Longus (FDL)
Found in the deep posterior compartment of the leg, this muscle is long and thin and takes origin from the posterior surface of the tibia, distal to the soleal line and medial to the vertical line, and from the fascia covering the muscles as well as the adjacent intermuscular septum. It is located medial to the tibialis posterior and flexor hallucis longus at its origin. As FDL narrows to a tendon distally, it passes superficial to the tendon of the tibialis posterior just superior to the medial malleolar sulcus. It then passes posterior to the medial malleolus in a groove along with tibialis posterior. At this point it is separated from the tibialis posterior tendon by a fibrous septum from the flexor retinaculum with each tendon being housed in its own synovial sheath. The FDL tendon continues distally into the foot to lie adjacent to the medial side of the sustentaculum tali, superficial to the calcaneotibial ligament. As it does so, it passes deep to the abductor hallucis and pierces the medial intermuscular septum of the plantar surface of the foot. At this point it also lies superficial to the tendon of flexor hallucis longus from which it frequently receives a tendinous slip (vinculum). It then expands, is joined by the quadratus plantae, and divides into four tendons which insert into the bases of the distal phalanges of the second, third, fourth, and fifth toes (Fig. 1.5). Each of these tendons passes through an opening in the corresponding tendon of the flexor digitorum brevis (see below) opposite the base of the proximal phalanx (Fig. 1.8).

FDL functions to flex the lesser four toes at the distal interphalangeal joints and, as it continues to contract, at the proximal interphalangeal joints and at the metatarsophalangeal joints, and, finally, it assists in plantar flexion of the ankle. FDL is innervated by the tibial nerve (S2, S3) and receives its blood supply via a muscular branch of the posterior tibial artery.

Flexor Digitorum Brevis (FDB)
The flexor digitorum brevis is situated deep to the central portion of the plantar aponeurosis from which it takes partial origin. It is also located between the medial

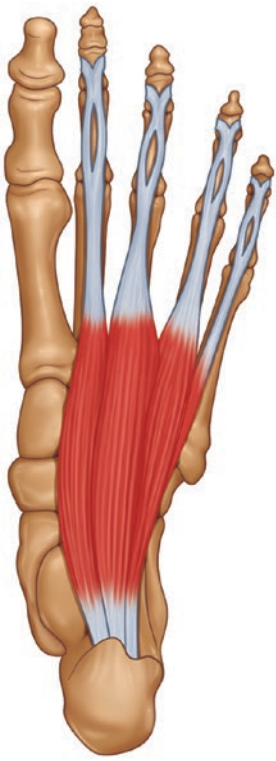

Fig. 1.8 The flexor digitorum brevis originates from the calcaneal tuberosity and plantar aponeurosis, divides into four tendon slips, and inserts into toes 2–5. Within each tendon slip, the FDB splits into two slips at the level of the proximal phalanx base, then reunites, and then splits again to insert onto the sides of the middle phalanges

and lateral intermuscular septa from which it also takes partial origin. Its deep surface is closely associated with the lateral plantar vessels and nerves by a thin fascial layer. It arises by a narrow tendon from the plantar aponeurosis, the medial and lateral intermuscular septa, and the medial process of the calcaneus tuberosity. The muscle runs distally in the center of the plantar aspect of the foot, and in approximately the middle of the sole of the foot, it divides into four tendons, one for each of the lateral four toes. Each of these tendons continues distally to run within the tendon sheaths of each of the corresponding tendons of FDL. At the bases of the proximal phalanges, each tendon splits into two slips. These slips diverge from one another to allow the passage of the tendons of FDL and then reunite distally, partially crossing over one another or decussating as they reunite and assist in forming a groove or channel for the tendon of FDL to which they now lie deep. The tendons of the FDB divide again and insert on the sides of the middle phalanges of the lesser toes (Fig. 1.8).

The FDB functions to flex the lateral four toes at the proximal interphalangeal joints. Continuing to contract, it will flex the proximal phalanges of the lesser four toes at the lesser MPJs. The FDB is innervated by the medial plantar nerve (L5, S1, S2). The medial plantar artery supplies the flexor digitorum brevis muscle.

Flexor Digiti Minimi (FDM)
Located in the lateral aspect of the third layer of muscles of the plantar foot, it arises from the base of the fifth metatarsal and from the sheath of the fibularis (peroneus) longus. It also takes origin from the plantar aponeurosis. The muscle travels distally parallel to the fifth metatarsal and inserts on the lateral side of the plantar aspect of the base of the proximal phalanx of the fifth digit along with the insertion of the abductor digiti minimi (see below). Deeper fibers often pass along the lateral aspect of the fifth metatarsal and may insert as part of the extensor expansion of the fifth digit or on the metatarsal shaft and head as a separate muscle sometimes referred to as *opponens digiti minimi*. The FDM flexes the proximal phalanx of the fifth digit at the MTPJ and helps to abduct the fifth digit.

Abductor Digiti Minimi (ADM)
The abductor digiti minimi lies along the lateral border of the foot with its medial margin adjacent to the lateral plantar vessels and nerves. It originates from the lateral process of the calcaneal tuberosity as well as, to some extent, from the medial process deep to the origin of the FDB. It also arises from the plantar surface of the calcaneus between the two processes, from the plantar aponeurosis as it passes to the fifth metatarsal, and from the lateral intermuscular septum. It then passes distally in the plantar surface of the foot along the lateral border and lateral longitudinal arch of the foot. Prior to its insertion, its tendon runs in a groove on the plantar surface of the fifth metatarsal. It inserts, along with FDM, into the lateral side of the plantar aspect of the base of the proximal phalanx of the fifth toe. The ADM, as its name implies, abducts the fifth toe and also helps to flex the fifth digit. ADM is innervated by the lateral plantar nerve (S 1, S2), the other terminal branch of the tibial nerve. Blood is supplied by lateral plantar artery (the other terminal branch of the posterior tibial artery).

Quadratus Plantae (Flexor Digitorum Accessories)
The quadratus plantae arises by two heads that are separated from each other by the calcaneal attachment of the long plantar ligament. The medial head is the larger and more muscular of the two heads and takes origin from the medial plantar surface of the calcaneus, inferior to the groove created by the tendon of flexor hallucis longus. The more tendinous and flatter lateral head arises from the lateral plantar surface of the calcaneus, just anterior to the lateral process of the calcaneal tuberosity and from the long plantar ligament. The two heads pass distally where they may join one another prior to inserting on the tendon of FDL just proximal to its point of dividing into four tendinous slips (Fig. 1.5). One variation is that the medial head joins the lateral head in part, while a medial tendinous slip extends to the FDL independently. In some cases, the medial head may fail to join the lateral head and, as a tendinous prolongation, may pass deep to the FDL and divide into slips to some of the digital tendons of the long flexor muscle.

Quadratus plantae acts to assist FDL in flexion of the distal phalanges of the lesser toes. It does so by helping to straighten the line of pull of the tendons of FDL so they have a more direct line of pull for flexion of the lesser toes [12]. Innervation is provided by the lateral plantar nerve (S2, S3). Blood is supplied by the lateral plantar artery.

Lumbricals

These are four small worm-shaped muscles that are accessory to the FDL, from which they arise, and are numbered one through four from the medial side of the foot. They tend to decrease in size from medial to lateral. As alluded to above, the lumbricals take origin from the tendons of FDL at the level of the separation of these tendons into four slips. Each lumbrical, except for the first (i.e., the most medial), originates from two adjacent tendons of FDL. The first lumbrical arises only from the medial aspect of the first tendinous slip of FDL. Each lumbrical then passes distally accompanying the tendon of FDL that lies lateral to the lumbrical. For example, the first lumbrical courses distally alongside the first slip of the FDL, while the second lumbrical passes alongside the second slip of the long flexor tendon and so forth. Each lumbrical crosses the medial side of its respective metatarsophalangeal joint and continues alongside the medial aspect of its respective digit (i.e., digits two through five) (Fig. 1.5).

The lumbricals all pass plantar to the deep transverse metatarsal ligament (Fig. 1.4). Each inserts into the medial aspect of the extensor expansion, somewhat more dorsally than plantarly. Thus, the first lumbrical inserts on the extensor expansion of the second toe, the second on that of the third toe, and so on. The lumbricals contribute to the wing portion of the extensor hood of each of these digits (Fig. 1.6b).

The actions of the lumbricals include flexion of the MPJ of digits two through five and extension of the IPJs of the same digits. The first lumbrical is innervated by the medial plantar nerve (L5, S 1), while two through four are innervated by the deep branch of the lateral plantar nerve (S1, S2). Blood supply is from the plantar metatarsal arteries, branches of the deep plantar arterial arch.

Plantar Interossei

Found in the fourth layer of the plantar aspect of the foot, there are three plantar interossei and four dorsal interossei (Fig. 1.1a, b). They are similar to the interossei of the hand, except that those of the hand are arranged relative to the third digit which is the midline of the hand, while those of the foot are arranged relative to the second digit which is the midline of the foot.

Lying inferior to the metatarsals, the plantar interossei take origin from the bases and medial sides of the shafts of the third, fourth, and fifth metatarsals. The second and third plantar interossei, in addition, may arise in part from the tendon sheath of peroneus longus. The plantar interossei insert on the medial sides of the bases of the proximal phalanges, the MPJ joint capsules, and the extensor expansions of the same digits from which they originate. All of the plantar interossei pass dorsal to or deep to the deep transverse metatarsal ligament (Fig. 1.1b).

The plantar interossei adduct (mnemonic, PAD) the third, fourth, and fifth toes toward the midline of the foot (i.e., second toe). They also assist in flexion of the proximal and extension of the distal phalanges of the third, fourth, and fifth toes. Innervation is provided by the superficial (third plantar interosseous) and deep branches of the lateral plantar nerve (S2, S3) (fourth and fifth plantar interossei).

Dorsal Interossei

Four in number, the dorsal interossei are situated more dorsal than the plantar interossei. Each of the four muscles is located in each of the interosseous spaces of the foot. Typically, they are bipennate and arise by two heads from the adjacent sides of adjacent metatarsals (Fig. 1.1a). For example, the first dorsal interosseous originates from the adjacent surfaces of the first and second metatarsals. The plantar interossei lie inferior to the lateral three dorsal interossei.

The posterior perforating arteries and the deep plantar artery pass along the posterior borders of each of the dorsal interossei as the two heads of origin of each muscle merge with one another. The two heads of each dorsal interosseous muscle converge on a central tendon that passes distally to insert on the base of the proximal phalanx and the extensor expansion of a certain digit (Fig. 1.1a). For example, the first dorsal interosseous inserts on the medial side of the proximal phalanx of the second digit, while the second dorsal interosseous inserts on the lateral side of the proximal phalanx of the second digit, the third dorsal interosseous inserts on the lateral side of the proximal phalanx of the third digit, and the fourth dorsal interosseous inserts on the lateral side of the proximal phalanx of the fourth digit. Like the plantar interossei, the dorsal interossei all pass dorsal to the deep transverse metatarsal ligament (Fig. 1.1a).

The dorsal interossei all function to abduct (mnemonic, DAB) the toes away from the midline of the foot (i.e., the second toes). Innervation to the dorsal interossei is provided by the deep branch of the lateral plantar nerve (S2, S3), except to the fourth dorsal interosseous which receives the superficial branch of the lateral plantar nerve. In addition, the first and second dorsal interossei each receive an extra nerve; the first dorsal interosseous receives a branch of the first interosseous nerve of the medial branch of the deep peroneal nerve, while the second interosseous receives a branch of the second interosseous nerve of the lateral branch of the deep peroneal nerve. There is some evidence that these additional twigs from the interosseous nerves are entirely sensory [12].

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