Review paper

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Ultrasound of the plantar foot: a guide for the assessment of plantar intrinsic muscles

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Keywords

hallux valgus; plantar; fasciitis; muscular atrophy; ultrasonography

Abstract

Plantar intrinsic muscles play a pivotal role in posture control and gait dynamics. They help maintain the longitudinal and transverse arches of the foot, and they regulate the degree and velocity of arch deformation during walking or running. Consequently, pathologies affecting the plantar intrinsic muscles (for instance, acquired and inherited neuropathies) lead to foot deformity, gait disorders, and painful syndromes. Intrinsic muscle malfunctioning is also associated with multifactorial overuse or degenerative conditions such as pes planus, hallux valgus, and plantar fasciitis. As the clinical examination of each intrinsic muscle is challenging, ultrasound is gaining a growing interest as an imaging tool to investigate the trophism of these muscular structures and the pattern of their alterations, and potentially to follow up on the effects of dedicated rehabilitation protocols. The ten plantar intrinsic muscles can be dived into three groups (medial, central and lateral) and four layers. Here, we propose a regional and landmark-based approach to the complex sonoanatomy of the plantar intrinsic muscles in order to facilitate the correct identification of each muscle from the superficial to the deepest layer. We also summarize the pathological ultrasound findings that can be encountered when scanning the plantar muscles, pointing out the patterns of alterations specific to certain conditions, such as plantar nerves mononeuropathies.

Introduction

Intrinsic muscles of the foot, particularly the plantar ones, can be considered the "foot core system", since they play a pivotal role in the biomechanics of static posture and dynamic activities[1]. Evidence in the literature suggests that the plantar intrinsic muscles (PIM) of the foot control the degree and velocity of longitudinal and transverse arch deformation, thus contributing to the functional integrity of the multiarticular structure of the foot during gait and balance control. Weakness of these muscles may contribute to the development of degenerative and overuse conditions such as pes planus, hallux valgus, increased navicular drop, osteoarthritis, and plantar fasciitis[2–4]. Foot deformities such as pes cavus varus, claw toes, and hammer toes are associated with the atrophy of the PIM resulting from neurological conditions such as inherited neuropathies, diabetic foot, and traumatic nerve injuries[5,6]. Nevertheless, pathological alterations of the intrinsic muscles are often overlooked. Their clinical evaluation is challenging, since they act as a unique functional unit and it is difficult to assess the strength of each muscle separately[6]. Consequently, a growing interest is given to the imaging evaluation of the PIM as an integration of clinical exams when approaching the musculoskeletal conditions of the foot. Different pathological conditions may cause specific morphostructural alterations in the plantar muscles. Furthermore, the muscle cross-sectional area measured with ultrasound (US) appears to be a good predictor of muscle strength and seems to correlate with the outcome of conditions such as diabetic foot and pes planus[7]. The purpose of this review is to provide a guide to disentangle the intricate PIM sonoanatomy and briefly summarize the main muscular pathologic findings that can be encountered in clinical practice.

Anatomy and scanning technique

The PIM are muscular structures that originate and insert in the foot, differently from the extrinsic muscles that originate in the leg

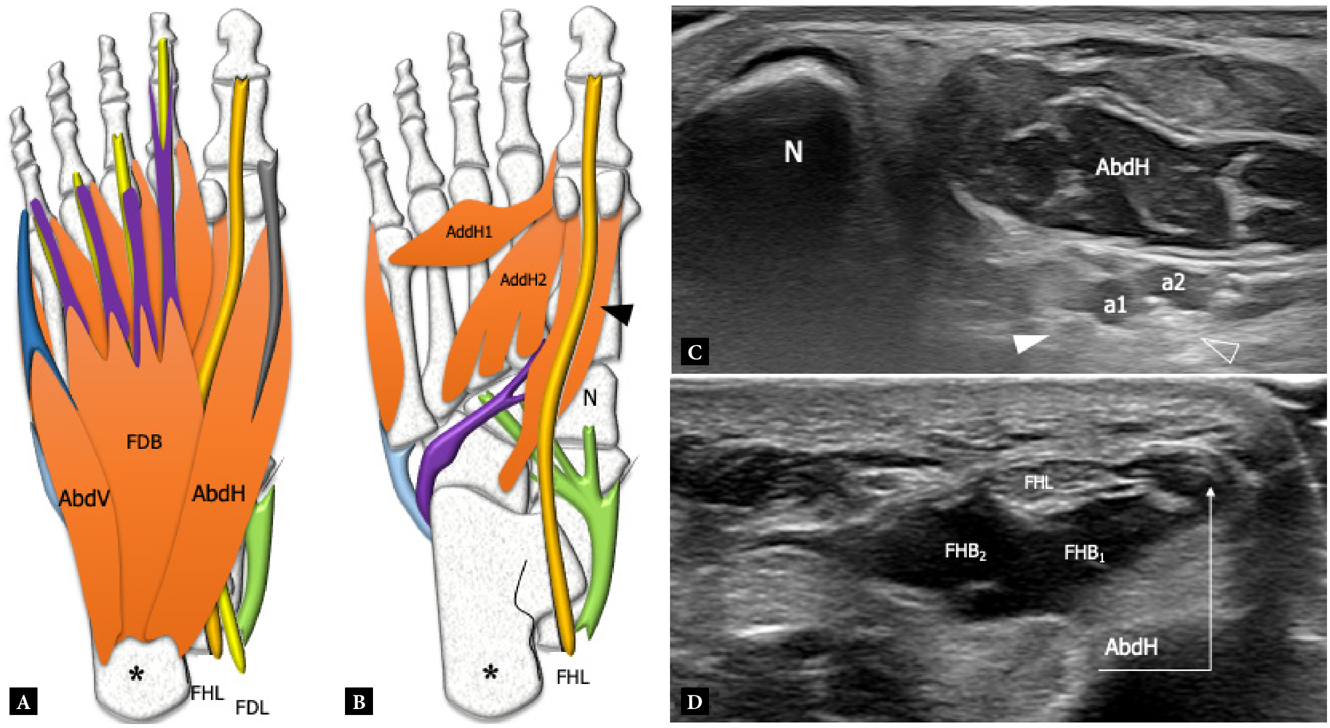

Fig. 1. *In **A** and **B**, the schematic drawings show, respectively, the first and the third layers of the plantar intrinsic muscles (PIM). In **C** and **D**, two 18MHZ ultrasound images demonstrate two axial views at different levels of the medial group of the PIM. In **C**, the AbdH is seen immediately inferior to the navicular tuberosity (N). Note the medial plantar neurovascular bundle (a2 and empty arrowhead) and lateral plantar neurovascular bundles (a1 and white arrowhead) crossing the undersurface of the AbdH. In **D**, a more distal scan shows the two heads of the flexor hallucis brevis (FHB1; FHB2) underneath the FHL tendon. The FHL is a good landmark to identify the FHB, since it runs in between the two heads of the FHB and, more distally, in between the two sesamoids bones. AbdH – abductor hallucis; AbdV – abductor digiti minimi; AddH1 – transverse head of the adductor hallucis; AddH2 – oblique head of the adductor hallucis; FDB – flexor digitorum brevis; FDL – flexor digitorum longus; FHL – flexor hallucis longus; N – navicular bone; * calcaneal tuberosity; black arrowhead – flexor hallucis brevis*

and insert into the foot. In the human foot, two dorsal intrinsic muscles (extensor digitorum brevis and extensor hallucis brevis) and ten plantar intrinsic muscles exist. In this review, the focus is on the plantar intrinsic muscles, which are characterized by a more complex anatomy and function. The PIM are arranged in four layers and can be divided into three groups: medial, central and lateral.

Medial group

The medial group encompasses two muscles, one superficial belonging to the first layer of the PIM, the abductor hallucis (AbdH), and one deeper, included in the third layer of the PIM, the flexor hallucis brevis (FHB) (Fig. 1). The AbdH originates from the tuberosity of the calcaneus, the flexor retinaculum, and the plantar aponeurosis. The muscle belly presents a larger and thicker origin, and it flattens moving distally. It inserts onto the medial aspect of the base of the first phalanx and medial sesamoid in a common tendon with the medial head of the FHB[8]. The FHB takes origin from the plantar medial aspect of the cuboid, the medial cuneiform, and partially from the tibialis posterior tendon. It consists of two heads, the medial one blended with the AbdH, and the lateral one (representing the first plantar interosseous) with the adductor hallucis. The two muscle heads insert respectively on the lateral and medial sides of the base of the first phalanx, and a sesamoid bone is embedded in each tendon at the level of the first metatarsal-phalangeal joint[9]. The flexor hallucis longus tendon runs between the two muscle bellies of the flexor hallucis brevis and then continues its course between the two sesamoids. The FHB and AbdH are innervated by the medial plantar nerve.

Scanning technique

The patient lies supine with the foot flexed dorsally, having the long axis of the foot perpendicular to the bench. A 15 to 18 MHz linear array probe should be used to have a good compromise between the spatial resolution to study smaller structures, such as nerves, and enough penetration to evaluate deeper muscular layers. To identify the AbdH, the probe should be placed over the medial aspect of the foot, perpendicular to its long axis, in correspondence with the palpable navicular tuberosity. The AbdH appears just inferiorly to the navicular tuberosity. Moving the probe toward the muscle origin, the medial and lateral plantar neurovascular bundles can be seen to cross the undersurface of AbdH. The best landmark to visualize the two bellies of the FHB is the flexor hallucis longus tendon. Placing the probe over the navicular tuberosity as above and moving toward the plantar aspect, the crossing point of the flexor hallucis longus and the flexor digitorum longus, also known as the master knot of Henry, can be spotted deep and lateral to the AbdH (Fig. 2). At this level, by passively flexing and extending the distal phalanx of the greater toe, the flexor hallucis longus can be easily identified. Following

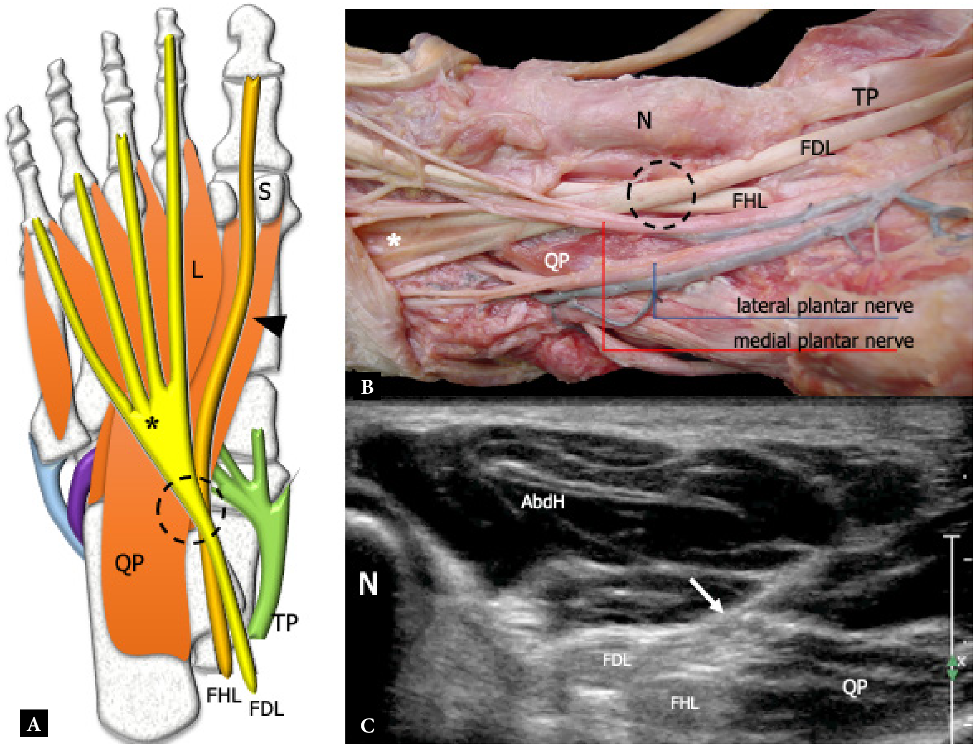

Fig. 2. *The schematic drawing in* **A** *depicts the second layer of the plantar intrinsic muscle (PIM) and the crossing point of the FHL tendon and the FDL tendon (black dashed circle), also known as the master knot of Henry. It represents a valuable landmark to identify the FHL deep and lateral to the AdbH, at the level of the navicular bone undersurface. In* **B**, *an anatomic specimen of the foot is shown: note the spatial relation of the medial plantar neurovascular bundle respect to the master knot of Henry. In* **C,** *a 18 MHZ ultrasound axial view shows the knot of Henry in between the AbdH on the medial side and the QP on the lateral side. The medial plantar nerve (white arrow) can be identified on the plantar aspect of the FHL. AbdH – abductor hallucis; FDL – flexor digitorum longus; FHL – flexor hallucis longus; L – lumbrical muscle; N – navicular bone; QP – quadratus plantae; S – sesamoid bone; TP – tibialis posterior; * flexor digitorum longus tendon slips; black arrowhead – flexor hallucis brevis*

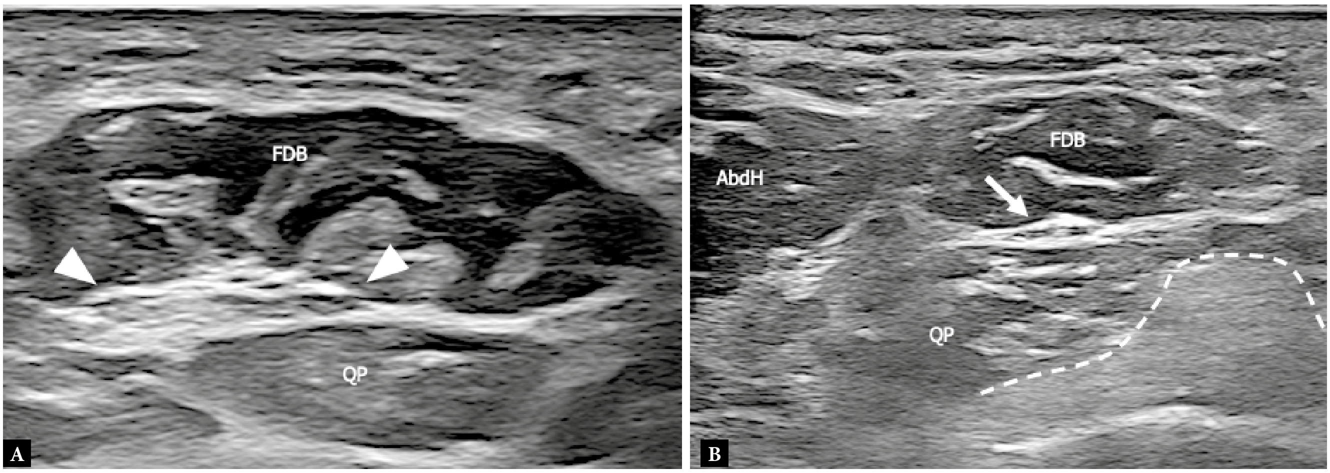

Fig. 3. *In* **A** *and* **B**, *two 18 MHZ ultrasound axial views of the central compartment of the plantar intrinsic muscles are shown. The image* **A** *is obtained at the level of the calcaneocuboid joint. The flattened FDL tendon (white arrowheads) is seen to separate the first layer of muscle (FDB) from the second layer (QP). The image in* **B** *was acquired more proximal than* **A**; *the lateral plantar nerve (white arrow) can be seen running between the FDB and the QP. Note the hyperechoic long plantar ligament (dashed line) that separates the medial and lateral bellies of the QP (in the image, only the medial belly of QP is visible). AbdH– abductor hallucis; FDB – flexor digitorum brevis; QP – quadratus plantae*

the flexor hallucis longus distally, the medial and lateral head of the FHB appears on the two sides of the tendon and can be traced toward the sesamoid and proximal phalanx insertions. The master knot of Henry is also a good landmark to identify the medial plantar nerve superficial to it.

Central group

In the central group, four layers of muscles can be detected. The flexor digitorum brevis (FDB) is the most superficial one, lying immediately underneath the central band of the plantar fascia

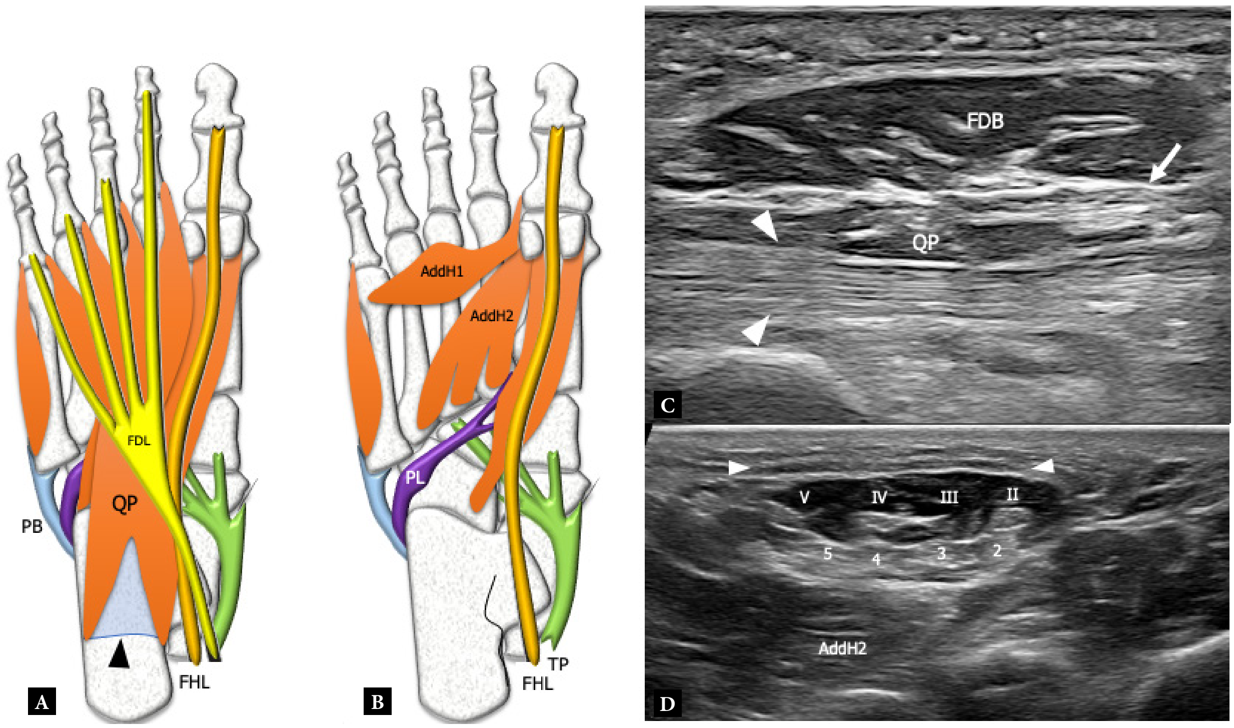

Fig. 4. *The schematic drawings in* **A** *and* **B** *represent the second and third layers of the plantar intrinsic muscles. The QP muscle and the AddH2 overlap for a short tract. In order to accurately distinguish the two muscles, the peroneus longus (PL) tendon can be used as a landmark. It crosses obliquely the plantar aspect of the foot from lateral to medial, and it inserts onto the base of the first metatarsal bone. The oblique head of the AddH appears distally to the PL tendon. The 18 MHZ axial/oblique ultrasound image in* **C** *shows the long axis of the PL (white arrowheads). The muscle tissue overlying the PL is the distal portion of the QP inserting in the lateral margin of FDL tendon (white arrow). The image in* **D** *is acquired distal to the PL, and the oblique head of the adductor (AddH2) is visualized. At the same level, the FDL has already divided into four tendinous bands for the lesser toes (2, 3, 4, 5). Superficial to FDL, the intramuscular aponeurosis of the four tendon slips of the FDB are shown (II, III, IV, V). The surface of the FDB is strictly adherent to the central band of the plantar fascia (white arrowheads). AddH1 – transverse head of the adductor hallucis; AddH2 – oblique head of the adductor hallucis; FDB – flexor digitorum brevis; FDL – flexor digitorum longus; FHL – flexor hallucis longus; L – lumbrical muscle; PB – peroneus brevis tendon; PL – peroneus longus tendon; QP – quadratus plantae; S – sesamoid bone; TP – tibialis posterior; black arrowhead – plantaris longus ligament*

(Fig. 3). The FDB originates from the inferomedial tubercle of the calcaneus, the plantar aponeurosis and the intermuscular septa between it, and the AbdH on the medial side and abductor digiti minimi on the lateral side. Distally, the FDB divides into four tendons, one for each of the four lesser toes. At the bases of the proximal phalanges, each tendon divides into two slips to allow the passage of the corresponding tendon of the flexor digitorum longus. Distal to the splits, the two tendon bundles reunite in a chiasma and divide again to insert into the mid-shaft of the intermediate phalanx[10]. Motor innervation is supplied by the medial plantar nerve. The second layer consists of the quadratus plantae (QP) muscle and the lumbrical muscles (Fig. 4, Fig. 5). These muscles are characterized by having at least one insertion on the flexor digitorum longus tendon. The standard anatomic configuration of the QP consists of two heads separated from each other by the long plantar ligament[11]. The medial one is larger and fleshy. It originates from the medial concave surface of the calcaneus, below the groove that houses the tendon of the flexor hallucis longus tendon. The lateral head, flat and tendinous, arises from the lateral border of the inferior surface of the calcaneus and the long plantar ligament. The two heads coalesce into a flattened aponeurosis that inserts into the lateral margin, the upper and under surfaces of the flexor digitorum longus tendon[11]. Distal to the QP insertion, the flexor digitorum longus tendon separates into four slips for II to V toes that give origin to the four lumbrical muscles. Each lumbrical springs from two adjacent tendons (bipennate), except the first (unipennate). After running inferiorly to the deep intermetatarsal ligament on the medial side of the respective flexor digitorum longus tendon slip, the lumbricals insert in the extensor hood of the phalanges. The second to fourth lumbricals and the QP are innervated by the lateral plantar nerve. The first lumbrical muscle is innervated by the medial plantar nerve.

The adductor hallucis (AddH) is located in the third layer and is comprised of two heads, oblique and transverse (Fig. 4). The oblique head is large, thick and fleshy, and crosses the foot obliquely occupying the hollow space under the metatarsals. It arises from the bases of the II, III, and IV metatarsals, the cuboid and lateral cuneiform undersurface, and the peroneus longus tendon sheath. The insertion is into the lateral side of the base of the first phalanx and the lateral sesamoid, together with the FHB (lateral head). The smaller transverse head (Fig. 5) originates from the plantar metatarsal-phalangeal joints of the II–V toes and the deep transvers metatarsal ligament. After running perpendicular to the metatarsal major axis, it inserts into the lateral side of the base of the first phalanx, blending with the fibers of the oblique head over the lateral sesamoids[12]. The lateral plantar nerve provides motor innervation.

Finally, the fourth layer includes three plantar interossei and four dorsal interossei muscles (Fig. 5).

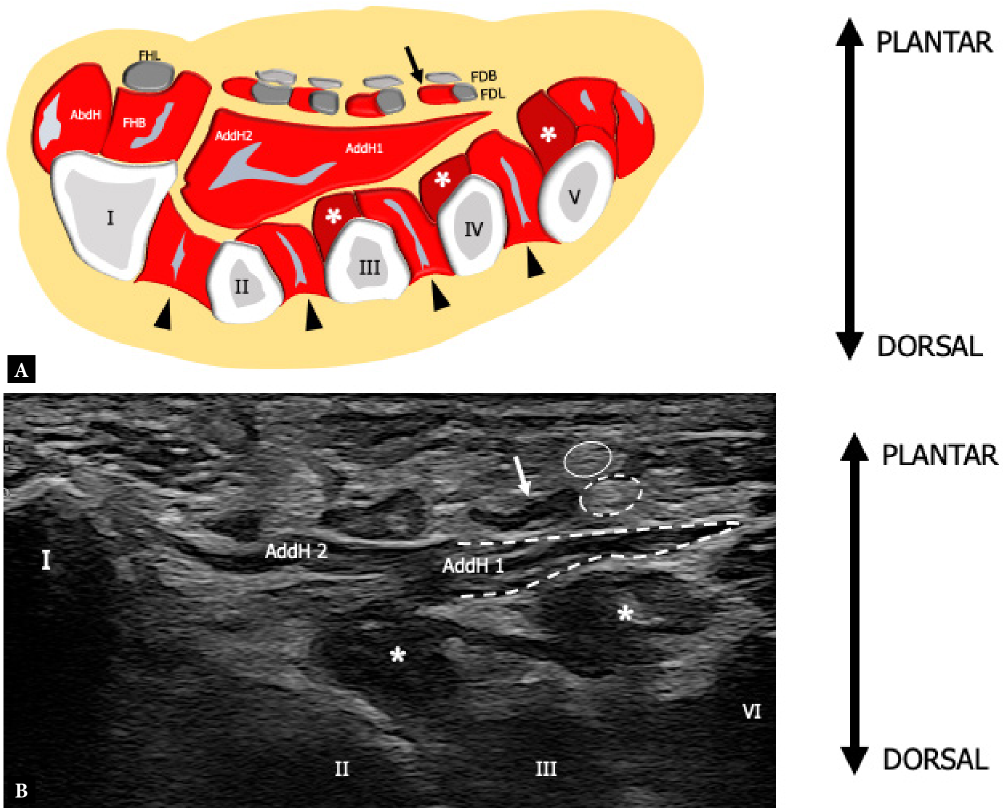

Fig. 5. *The schematic drawing in* **A** *depicts the axial section of the forefoot at the level of the distal metatarsal diaphysis (I, II, III, IV, V). The fourth layer of the plantar intrinsic muscles is represented. It includes four bipennate dorsal interossei (black arrowhead) and three unipennate ventral interossei (white asterisk). The axial 18 MHZ ultrasound image in* **B** *shows, from the superficial to deep layers: the FDB tendons (white circular line), the FDL tendons (dashed circular line) with the lumbrical muscles (white arrow), the transverse head (dashed withe line, Addh1) and distal portion of the oblique head (AddH2) of the adductor pollicis, the ventral interossei (white asterisk) and the metatarsal bones (I, II, III, IV). AbdH – abductor hallucis brevis; FDB – flexor digitorum brevis; FDL – flexor digitorum longus; FHB – flexor hallucis brevis; FHL – flexor hallucis longus; black arrow – lumbrical muscle*

The plantar interossei muscles originate from the bases and medial sides of the third to fifth metatarsals, and they insert onto the medial sides of the bases of the proximal phalanges of the third through fifth digits. The dorsal interossei are bipennate and emanate from the adjacent sides of the first to the fifth metatarsal. Both dorsal and plantar interossei have extensive soft tissue origins as the plantaris longus ligament and the peroneus longus tendon[13]. The first dorsal interosseous inserts on the medial side of the proximal phalanx of the second toe, while from the second to fourth interossei, the insertion is on the lateral side of the second to fourth proximal phalanx. They are innervated by the lateral plantar nerve.

Scanning technique

The patient's position and the US equipment are the same as above. The examination should start by placing the probe perpendicular to the long axis of the foot over the medial process of the calcaneal tuberosity. Moving distally, the short axis view of the central band of the plantar fascia is identified deep to the plantar fat pad, easily distinguishable for its anisotropy. The first muscle underneath the central band is the FDB. The FDB can be traced in the short axis towards the toes until the four intramuscular aponeuroses are clearly seen. At the level of the calcaneocuboid joint, the flexor digitorum longus tendon is seen as flattened to demarcate the cleavage plane between the FDB and the QP. Proximal to this level, the muscle bulk of the QP divides into two muscle bellies separated by the long plantar ligament. The lateral plantar neurovascular bundle is clearly seen in the cleavage plane between the QP and the FDB. Moving distally, the flexor digitorum longus tendon separates into four slips, each giving origin to the lumbricalis. At the level of the calcaneal cuboid joint, dorsally to the flexor digitorum longus and the distal fibers of the QP, the peroneus longus tendon is seen crossing obliquely from the lateral to medial the plantar aspect of the foot to insert on the lateral side of the base of the first metatarsal. This tendon represents a landmark to identify the origin of the oblique head of the AddH (Fig. 4). This large muscle belly occupies the space between the II, III, IV metatarsal base and the QP distally to the peroneus longus tendon. Passive adduction and abduction of the first toe can distinguish the distal portion of the QP muscle belly (unaffected by this maneuver) from the AddH oblique head. The smaller AddH transverse head can be identified immediately proximal to the metatarsal heads, running perpendicular to the metatarsal long axis between the flexor tendons (plantar) and the plantar interossei (dorsal). The dorsal and plantar interossei are easily identified as the deepest muscles filling the space in between the metatarsal bones.

Lateral group

The lateral group, similarly to the medial group, is made up of two muscles acting on the fifth toe. In the most superficial layer, the ab-

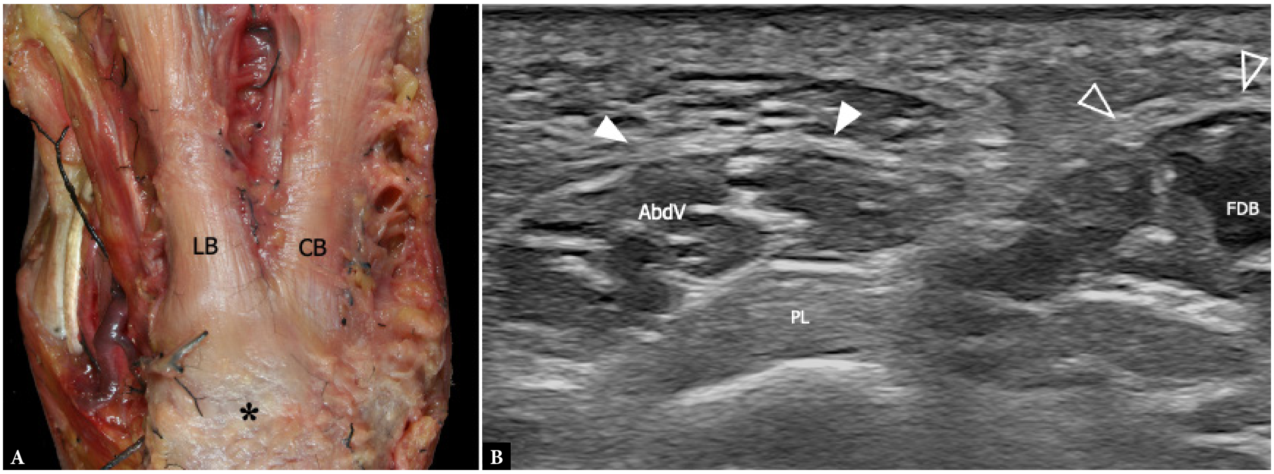

Fig. 6. *The image in* **A** *shows an anatomic specimen of the plantar fascia. In particular, the origins and the proximal tracts of the central and lateral bands of the plantar fascia can be seen. The two bands represent landmarks to identify with ultrasound the FDB (central band) and the AbdV (lateral band). The 18MHZ axial ultrasound image in* **B** *shows the thin hyperechoic structure overlying the AbdV (white arrowheads) corresponding to the lateral band of plantar fascia, and the FDB (empty arrowhead) corresponding to the central band of the fascia. Underneath the AbdV, the peroneus longus tendon (PL) is seen curving in the cuboid groove*

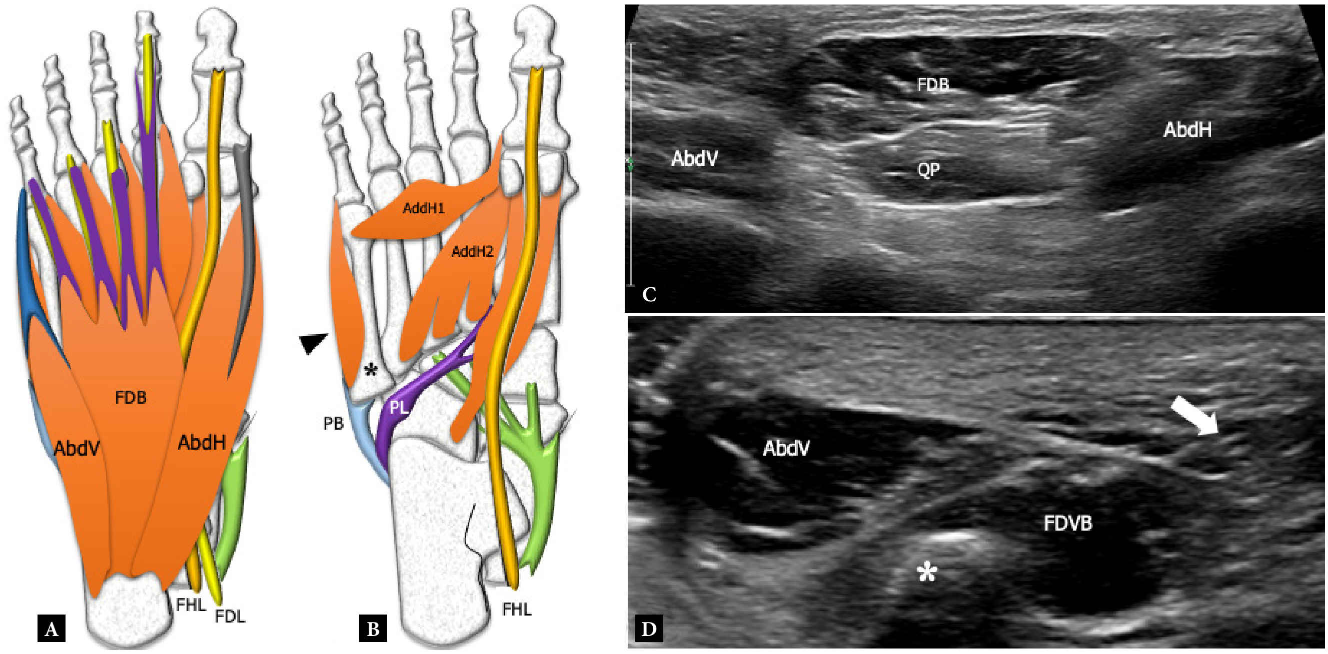

Fig. 7. *The schematic drawings in* **A** *and* **B** *depict the first and third layers of the plantar intrinsic muscles (PIM). The 18 MHZ ultrasound image* **C** *is acquired just distal to the calcaneal tuberosity and shows a panoramic axial view of the PIM at this level. The AbdV is the most superficial muscle of the lateral group and is located on the lateral side of the FDB and the QP. In* **D**, *the US axial view at the proximal third of the fifth metatarsal diaphysis (white asterisk) shows the flexor digiti minimi brevis (FDVB) belly located medial and deeper respect to the AbdV. Along the medial surface of the FDV, the lateral branch of the lateral plantar nerve can be spotted (white arrow). AbdH – abductor hallucis; AbdV – abductor digiti minimi; AddH1 – transverse head of the adductor hallucis; AddH2 – oblique head of the adductor hallucis; FDB – flexor digitorum brevis; FDL – flexor digitorum longus; FHL – flexor hallucis longus; PB – peroneus brevis tendon; PL – peroneus longus tendon; * fifth metatarsal head; black arrowhead – flexor digiti minimi brevis*

ductor digiti minimi (AbdV) arises from the inferior and lateral aspects of the calcaneal tuberosity, the plantar aponeurosis, and the intermuscular septum between it and the FDB (Fig. 6). Some authors describe two heads in the AbdV, the superficial and deep head. The first one is obliquely crossed on its ventral surface by the lateral band of the plantar fascia which inserts in the base of the fifth metatarsal. The deep head rests between the flexor digitorum brevis muscle (lateral) and the long plantar ligament (medial)[14]. The two bellies run distally along the outer border of the foot to end with a slender tendon inserted onto the lateral aspect of the base of the first phalanx of the fifth toe[14]. The flexor digiti minimi brevis (FDVB) runs from the base of the fifth metatarsal and the sheath of the peroneus longus to the lateral aspect of the base of the first phalanx of the fifth toe, where it inserts blending its tendon with the AbdV tendon (Fig. 6). The deeper fibers of the FDVB, inserted into the lateral part of the distal half of the fifth metatarsal bone, are described by some authors

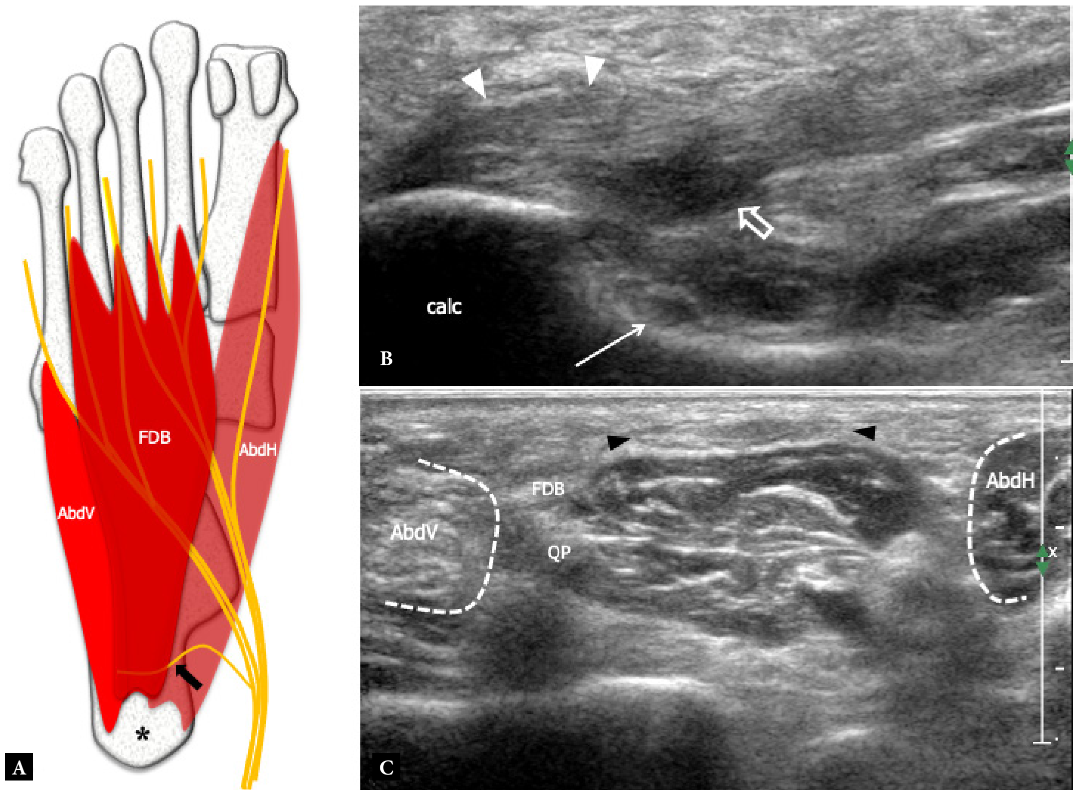

Fig. 8. *The schematic drawing in* **A** *illustrates the anatomy of the inferior plantar calcaneal nerve (black arrow) running anterior to the calcaneal tuberosity, deep to the central band of the plantar fascia and the FDB. The 18 MHZ ultrasound images* **B** *and* **C** *show a case of Baxter's neuropathy. In* **B***, a longitudinal view of the plantar fascia demonstrates an insertional thickening (white arrowheads) of the central band at the level of the medial tubercle of the calcaneal tuberosity. Some fibrotic changes in the underlying FDB muscle (empty arrow) can be seen. An enlarged hypoechoic inferior calcaneal nerve (white arrow) is spotted between the FDB and the calcaneal tuberosity (calc). The compressive neuropathy attributable to the plantar fasciitis has caused atrophy of the AbdV, which appears smaller and more hyperechogenic than the AbdH, FDB and QP. AbdH – abductor hallucis; AbdV – abductor digiti minimi; FDB – flexor digitorum brevis; QP – quadratus plantae; * calcaneal tuberosity; black arrowheads – short axis view of the thickened central band of the plantar fascia*

as a distinct muscle, the opponens digiti quinti. Along its course, the FDVB lies over the plantar surface of the fifth toe and is accompanied on the medial and superficial sides by the lateral branch of the lateral plantar nerve[9]. The motor function of both the AbdV and FDVB is supplied by the lateral plantar nerve. The anatomic situation of the motor branch innervating the AbdV muscle, namely the inferior calcaneal nerve, predisposes the latter to compression injuries causing a painful syndrome known as Baxter's neuropathy[15].

Scanning technique

The examination should start by placing the probe perpendicular to the long axis of the foot, over the lateral process of the calcaneal tuberosity. The smaller anisotropic lateral band of the plantar aponeurosis is a landmark used to identify the underlying AbdV. Moving distally, the lateral band of the plantar fascia is seen to insert onto the base of the fifth metatarsal, and at the same level, a new muscle appears on the medial side of the AdbV and the fifth metatarsal bone, the FDVB (Fig. 7). On the medial side of the FDVB, the lateral plantar neurovascular bundle is identified. The inferior calcaneal nerve can be visualized as a hypoechoic structure by placing the probe along the central band of the plantar fascia and looking at the area anterior to the medial process of the calcaneal tuberosity, deep to the FDB.

Clinical applications and pathological findings

Ultrasound can identify dimensional and echotextural pathological alterations of the plantar intrinsic muscles related to a wide range of conditions. In the case of traumatic or compressive neuropathies, only the group of plantar muscles supplied by the damaged motor nerve shows the typical findings of denervation. An exemplificative condition is inferior calcaneal nerve neuropathy, also known as Baxter's neuropathy, leading to isolated atrophy of the abductor digiti minimi. The nerve may be compressed between the AbdH and the medial plantar margin of the QP[16] or deep to the FDB, where calcaneal plantar enthesophytes and/or soft tissue changes related to plantar fasciitis may occur (Fig. 8). Similarly, mononeuropathy of the medial plantar nerve, also known as jogger's foot, may cause selective denervation of the FHB. In this condition, the medial plantar nerve can be injured at the level of the fascial sling between the spring ligament and the navicular attachment of the abductor hallucis onto the navicular bone, or at the level of the master knot of Henry[17]. In inherited or acquired polyneuropathies, the plantar intrinsic muscle of the foot shows diffuse signs of denervation. Patients affected by inherited Charcot-Marie-Tooth neuropathy commonly develop foot deformities such as cavovarus foot deformity, hammer or claw toes as a consequence of the intrinsic muscle loss of function and the ensuing imbalance between the extrinsic and intrinsic muscles[18,19].

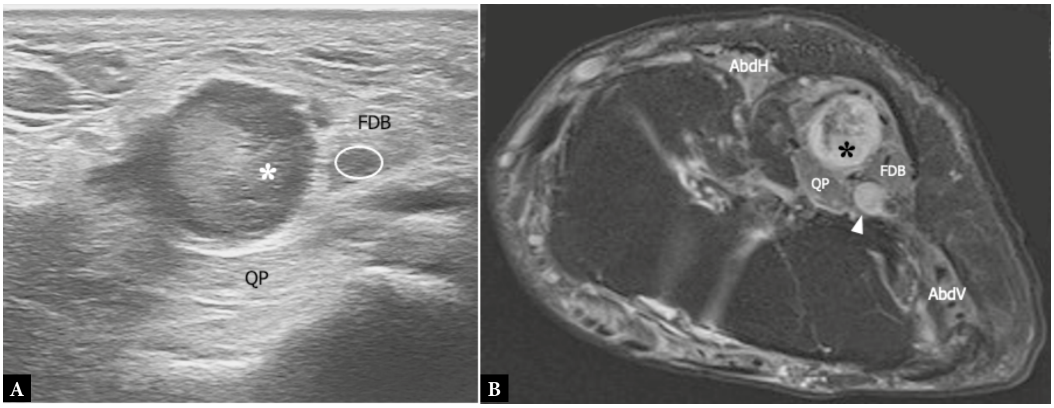

Fig. 9. *The 18 MHZ ultrasound image* **A** *demonstrates an intermuscular inhomogeneous solid mass (white asterisk) between the FDB and the QP. The matched T2-weighted axial magnetic resonance image confirms the presence of a solid expansive mass between the FDB and the QP. The lateral plantar veins (white circular line in* **A**, *white arrowhead in* **B** *is enlarged, probably as a consequence of the mass effect. Note the diffuse muscle atrophy, with the muscles of the three compartments reduced of volume and hyperechogenic in* **A**: *the patient reported not being able to walk properly for months because of the painful mass. Surgery was proposed. At the histology, the mass came out as a benign nerve sheath tumor. AbdH – abductor hallucis; AbdV – abductor digiti minimi; FDB – flexor digitorum brevis; QP – quadratus plantae; black asterisk – solid expansive mass*

Fig. 10. *The picture in* **A** *shows advanced flatfoot deformity with hindfoot valgus. The 18 MHZ ultrasound axial image in* **B** *depicts severe muscle atrophy of the AbdH (curved white line), while the FDB (curved dashed line) and the QP (white arrowhead) show a lower grade of fat infiltration. These findings are consistent with the pattern of muscle alterations reported in the literature for the flatfoot deformity. The strict functional relation existing between the plantar intrinsic muscle function and plantar fascia pathologies is confirmed in the image* **C**. *The image in* **C** *displays a 18 MHZ ultrasound long axis view of the central band of the plantar fascia: the fascia is abnormally thickened (white arrows) distal to the origin from the medial tubercle, likely as a result of mechanical overuse. AbdH – abductor hallucis; FDB – flexor digitorum brevis; QP – quadratus plantae; calc – calcaneus*

The ultrasound semiotics of muscle denervation depends on the timing of the nerve lesion. In the early phase of denervation (2–4 weeks after complete neurotmesis), the muscle size is preserved and slightly increased echogenicity can be noted as a consequence of intramuscular edema[20]. As the denervation process evolves in subacute and chronic phases (>4 weeks), the muscle fibers are substituted by adipose and fibrotic tissue, leading to an increased echogenicity and reduced volume. In chronic conditions characterized by denervation and reinnervation processes, the reinnervated muscle bundles appear hypoechoic, interspersed in a hyperechoic background resulting in the "moth-eaten" pattern to the muscle.

Both acquired and inherited myopathies – such as muscle dystrophies – may involve the distal lower limb muscles and plantar intrinsic muscles, but the differences between the ultrasound features of primary myogenic muscle atrophy and neurogenic atrophy are subtle, when present. In muscle dystrophies, the muscle echotexture has been described as homogenously hyperechoic, with a ground-glass appearance[21]. In the most advanced cases, the upper layer of the muscle reflects the majority of ultrasound waves, thus attenuating the beam and generating hypoechoic areas in the deeper layers. Degenerative conditions such as hallux valgus have been postulated to be related to the strength imbalance of the AbdH compared to the AddH. This hypothesis is supported by the histological findings of muscle atrophy in the AbdH[22], and the ultrasound findings of the decreased cross-sectional area of the AbdH and FHB[23]. A similar pattern of PIM atrophy has also been found in flatfoot deformity[24], which is associated with compensatory hypertrophy of the flexor hallucis longus and the flexor digitorum longus muscles in the attempt to sustain the medial plantar arch (Fig. 9). With plantar fasciitis, the role of the PIM is not completely elucidated. A magnetic resonance-based study by Chang *et al.*[25] found decreased muscle diameters in the forefoot of patients with plantar fasciitis compared to healthy controls. A decreased strength in these muscles results in diminished support to the plantar arch, causing an overload of the plantar fascia. In fact, in patients with diabetes-related neuropathy, the decreased size of the plantar muscle correlates with the thickening of the plantar fascia and the claw toe deformity[26]. US can be used to visualize other pathologic processes affecting the intrinsic plantar muscles beyond muscle atrophy. It is deemed to be useful in detecting complications of the diabetic foot such as soft tissue infections with involvement of the intrinsic muscles[27]. In particular, in the presence of cutaneous ulcers, US may easily detect intra- or intermuscular fluid collections due to abscesses or deep fascial thickening related to necrotizing fasciitis. Finally, US is the first-line imaging modality for masses involving the PIM. US enables the identification of mass location (intramuscular, intermuscular or both) and the differentiation of "no touch lesions" (ganglion cyst, lipoma, vascular malformations, pseudo-mass as congenital muscle hypertrophy) from lesions requiring further imaging studies and histological characterization[28,29](Fig. 10).

Conclusions

The present review aimed to provide a guide for the sonographic assessment of the PIM by suggesting a scanning technique based on easy-to-spot anatomic landmarks and illustrating the most common pathologic findings affecting these muscles.

Conflict of interest

The authors do not report any financial or personal connections with other persons or organizations which might negatively affect the contents of this publication and/or claim authorship rights to this publication.

Author contributions

Original concept of study: FZ, RP, CM. Writing of manuscript: FZ. Final approval of manuscript: RP, FP, MMP, DB, RS, GR, MM, MP, LT, CM. Collection, recording and/or compilation of data: RP, FP, MMP, DB, RS, GR, MM, MP, LT, CM. Critical review of manuscript: RP, FP, MMP, DB, RS GR, MM, MP, LT, CM.

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