

# Histologic anatomy of the lesser metatarsophalangeal joint plantar plate

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**Abstract** The plantar plate is the fibrocartilaginous structure that supports the ball of the foot, withstanding considerable compressive and tensile forces. This study describes the morphology of the plantar plate in order to understand its function and the pathologic disorders associated with it. Eight lesser metatarsophalangeal joint plantar plates from three soft-embalmed cadavers (74–92 years, two males, one female), and eight lesser metatarsophalangeal joint plantar plates from a fresh cadaver (19-year-old male) were obtained for histology assessment. Paraffin sections (10  $\mu\text{m}$ ) in the longitudinal and transverse planes were analyzed with bright-field and polarized light microscopy. The central plantar plate collagen bundles run in the longitudinal plane with varying degrees of undulation. The

plantar plate borders run transversely and merge with collateral ligaments and the deep transverse intermetatarsal ligament. Bright-field microscopic evaluation shows the plantar aspect of the plantar plate becomes ligament-like the further distally it tapers, containing fewer chondrocytes, and a greater abundance of fibroblasts. The enthesis reveals longitudinal and interwoven collagen bundles entering the proximal phalanx with multiple interdigitations. Longer interdigitations centrally compared to the dorsal and plantar aspects suggest that the central fibers experience the greatest loads.

**Keywords** Fibrocartilage · Enthesis · Plantar plate · Tidemark · Forefoot

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## Introduction

The plantar fascia divides near the heads of the metatarsal bones into five processes, one for each toe. Each of these processes divides into superficial and deep strata. The superficial stratum inserts into the dermis of the skin, and the deep stratum inserts into the interosseous fascia, the deep transverse metatarsal ligaments, the plantar ligaments of the metatarsophalangeal joints (MTPJ), the periosteum and fibrous sheaths at the base of each proximal phalanx forming a slip which embraces the flexor tendons [5]. The plantar plate (PP) has a central location on each metatarsophalangeal joint (MTPJ), with multiple attachments that also include the collateral ligaments (proper collateral ligament, accessory collateral ligament), intermetatarsal ligaments, interosseous tendons, and the fibrous sheath of the flexor tendons. At the lesser metatarsals, the PP

is on average 19 mm long, 10 mm wide, and thickness ranging from 2 to 5 mm [8].

The mechanisms that support the longitudinal arch of the foot have been described as the beam mechanism and the truss, or tie-bar mechanism [14]. Hyperextension of the toes at the MTPJ tenses the plantar aponeurosis, raises the longitudinal arch of the foot, inverts the hindfoot, and externally rotates the leg. This is the windlass mechanism. The windlass effect is greatest in the big toe and is seen in gradually lessening degrees in the second through to the fifth toe. The transverse tie-bar controls the splay of the forefoot. The five longitudinal processes of the deeper layer of the plantar fascia form a longitudinal tie-bar system and are inserted into the whole of the transverse tie-bar. While static stabilization of the MTPJ is primarily the function of the plantar plate, dynamic stabilization is provided by the extrinsic and intrinsic musculature of the foot [17]. The ability of the intrinsic and extrinsic foot musculature to stabilize this joint relies on the integrity of the PP. With rupture of the PP, the proximal phalanx assumes a subluxated (dorsal) position, and the extensor tendons are unable to extend the proximal and distal interphalangeal joints. When the MTPJ is maintained in a subluxed position for a prolonged period this results in a frank dislocation of the toe [17].

MTPJ instability can present as ill-defined forefoot pain or focal joint pain. Physical findings may also include swelling, malalignment of the toe, neuritic symptoms and dysfunction in the normal biomechanics of toe motion [3]. MTPJ instability can also be associated with extra-articular (Morton's neuroma or synovial cyst) and intra-articular disorders (arthritis or Freiberg's infraction) [4]. Evaluation of the plantar plate entheses at the histologic level may shed some light on the susceptibility of this region to degeneration. The aim of the present study is to develop a more complete understanding of the morphology of the PP and the junction between fibrocartilage and bone. We have endeavoured to provide a greater awareness of normal PP characteristics, whereby PP degeneration may be better explained and prevented.

## Materials and methods

### Tissue collection and processing

Eight PPs from three soft-embalmed cadavers (five from the second MTPJ, one from the third, and two from the fourth) and eight PPs from a fresh cadaver (all lesser MTPJs) were obtained for histology assess-

ment. Hospital ethics-committee approval was obtained for the study. Cadavers with evidence of previous lower leg surgery were the only exclusions. The soft-embalmed cadavers (74–92 years, two males, one female) were randomly acquired through the related University Anatomy department. Eight of their lesser MTPJs were randomly excised. From a fresh (refrigerated only) 19-year-old male cadaver, all lesser MTPJ PP samples were obtained following ethics committee approval from the local forensics department and consent from the donor's relatives.

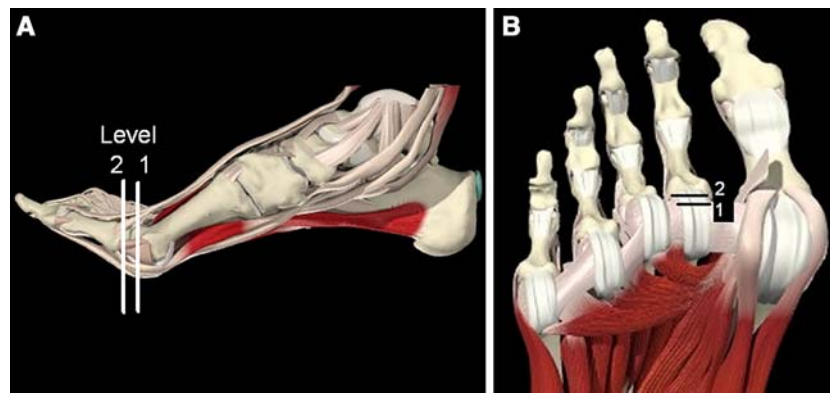
The dorsal soft tissues were removed adjacent to the MTPJs and the extensor tendons severed. The distal metatarsals were cut using heavy duty bolt cutters. The attachments to the plantar plate (collaterals, deep transverse ligament, interossei and lumbrical tendons, plantar fascia) were carefully severed. All samples consisted of the first centimeter of the proximal phalanx and the entire PP. Each PP retrieved was then placed in 10% neutral-buffered formalin and decalcified with EDTA (ethylenediaminetetraacetic acid) and formic acid. Sagittal plane 10  $\mu$ m paraffin sections of the PP fibers from 14 MTPJs and transverse plane paraffin sections of the PP insertion from two MTPJs were stained with Masson's trichrome, or haematoxylin and eosin, and alcian blue. Two levels were evaluated in the transverse plane and taken 100  $\mu$ m apart. The first level is a transverse section just proximal to the insertion onto the proximal phalanx. The second level transects the PP beneath the base of the proximal phalanx (Fig. 1a, b). Sections were analyzed with bright-field and polarized light microscopy.

The histological evaluation defined the structure of the plantar plate. Longitudinal histology sections of the PP were examined with attention to the proximal, mid and distal fibers, at its borders and centrally. Transverse sections of the distal fibers provided correlation with longitudinal findings. The thickness of the collagen bundles was measured from transverse sections taken proximal to the entheses level 1 (second and third MTPJ plantar plates). The direction of collagen bundles was assessed throughout the length of the plantar plate.

## Results

### Anatomy

The gross anatomy of the 16 lesser MTPJ PPs were evaluated in a consistent and predictable pattern. At  $\times 1.2$  magnification, the sagittal sections were observed. The broad ribbon-like disc of the PP is rectangular to



**Fig. 1** **a** Sagittal anatomical section of the foot illustrating the two levels evaluated in the transverse plane, taken 100  $\mu\text{m}$  apart. The first section is a transverse section just proximal to the metatarsophalangeal joint (MTPJ), the second level second level tran-

sects the PP beneath the base of the proximal phalanx. **b** Coronal anatomical section of the foot illustrating the two levels evaluated in the transverse plane. Reproduced with permission from Primal Pictures Ltd, London

trapezoidal in shape. The articular surface appears smooth, whilst the plantar surface is well defined but with ill-defined synovial tissue adherent to its surface.

Distally, the articular surface of the PP is concave, forming half of the socket for the metatarsal head (Fig. 2a). There are clear margins between the articular cartilage and the PP. A space between the articular cartilage and the PP was noted in 13/14 mid-sagittal sections (Fig. 2b). This space was also seen nearer its borders but less frequently. The plantar surface of the PP appears to fan-out to form a capsule around the phalangeal base. Extracellular tissue extends into the joint from the PP (Fig. 2c).

In the transverse sections of the PP we observed a bowl-shaped structure, mildly flattened on its central base (Fig. 3a). The borders are indistinct, as they blend with the collateral ligaments. At the first transverse level, just proximal to the enthesis, the PP is thick centrally, appearing only mildly thicker than its borders. The second transverse level shows the hyaline cartilage inserting into the bone from the dorsal direction and the PP inserts into bone from the plantar direction, x1.2 magnification (Fig. 3b). The PP is not as thick at this second level and the borders are thicker than the central aspect.

### Histology

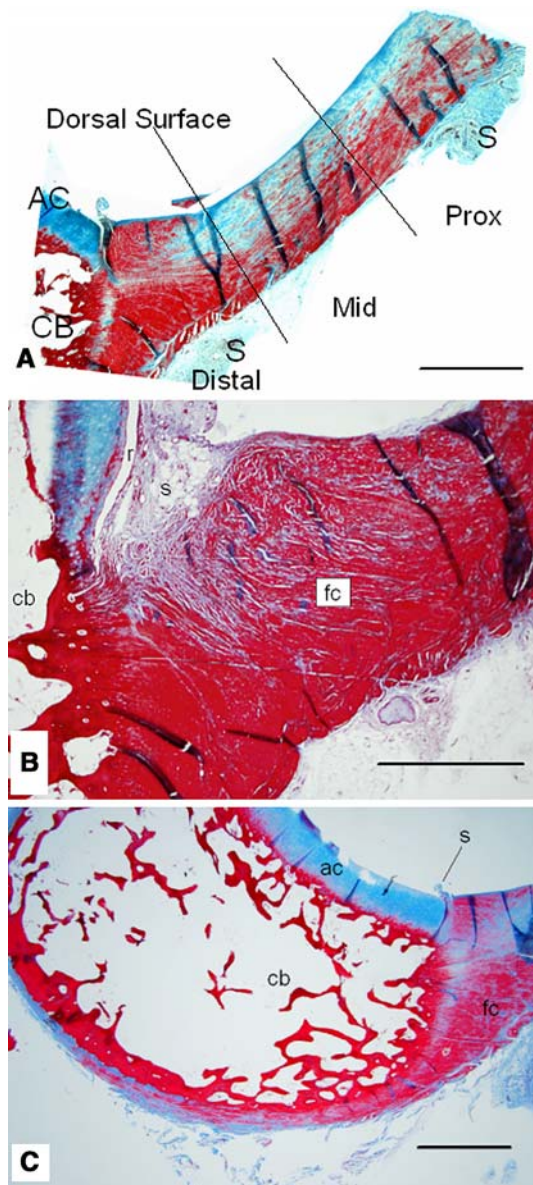
The PP collagen bundles appear interwoven with longitudinally oriented sheets. At higher magnification (x20) the collagen bundles appear separated by loose connective tissue septae (endotenon) with chondrocyte groups interspersed throughout (Fig. 4a). A matrix of proteoglycans surround the collagen and chondrocytes. Fibroblasts are interspersed throughout, with variation in volume proximally to distally with little contact

between cells. In the proximal PP the entire depth of the structure is composed of high numbers of chondrocytes, with minimal fibroblasts, reflecting fibrocartilage. The plantar aspect of the PP becomes ligament-like the further distally it tapers, containing fewer chondrocytes, and a higher number of fibroblasts.

The central fibers of the PP differ somewhat in direction to the medial and lateral borders. For much of the plantar surface, the collagen bundles run longitudinally, especially in the mid-sagittal plane. Nearer the borders the fibers run transversely. The dorsal 2/3rd of the collagen fibers exhibiting a higher obliquity than the plantar third (Fig. 4b). Distally, this ratio of fiber undulation changes to half-and-half; the dorsal half is highly angular and the plantar half is less so. The extracellular tissue lying superficial to the PP introduces vessels via the endotenon into the PP (Fig. 4c).

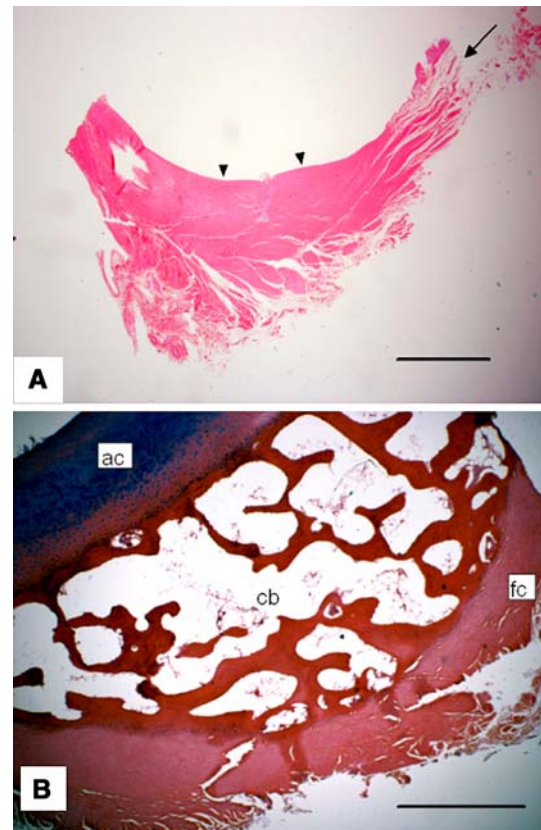
The distal section of the PP includes the insertion onto the proximal phalanx. The PP insertion is comprised of articular (dorsal), central, and plantar sections (Fig. 2b). In the dorsal aspect, the articular cartilage abuts the dorsal enthesis of PP. Articular cartilage, with its spring-like three-dimensional network of collagen fibrils forms a clearly defined margin against the PP (Fig. 5a, b). Collagen fibers of the PP do not penetrate the hyaline cartilage, but are seen to run directly into the bone in an interwoven but longitudinal direction. Interdigitations in the dorsal enthesis are multiple and the calcified zone is short. A thin tidemark is continuous across the PP and hyaline cartilage (Fig. 5a).

The central enthesis reveals longitudinal and interwoven collagen bundles entering the bone with long and multiple interdigitations (Fig. 5c, d). With light microscopy and polarized-light a double tidemark is seen. The tidemark represents the outer limit of fibrocartilage



**Fig. 2** **a** Sagittal histology section of the second plantar plate in the fresh cadaver—extended field-of-view, bar = 200  $\mu$ m, Masson's trichrome. The proximal plate on the right, and the distal insertion involving the proximal phalanx on the left; *CB* cortical bone. The curved articular (dorsal) surface is superior. Synovium is predominantly located on the plantar surface of the plantar plate; *S* synovium. Articular cartilage is separate but adjacent to the plantar plate; *AC* articular cartilage. **b** Dorsal enthesis with extracellular tissue projection into joint; *s* synovial tissue, *cb* cortical bone, *r* recess, *fc* fibrocartilage, bar = 100  $\mu$ m. **c** Distal plantar plate; *cb* cortical bone, *ac* articular cartilage, *fc* fibrocartilage, *s* synovium, bar = 200  $\mu$ m

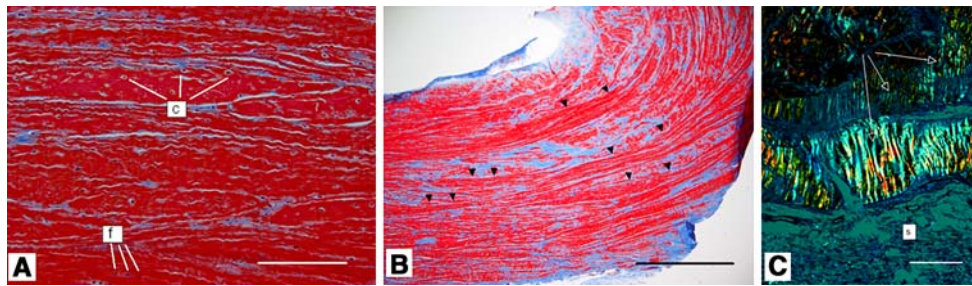
mineralization and appears as a light blue line with haematoxylin and eosin on light microscopy. The more prominent tidemark of the enthesis is immediately adjacent to the bone but a faint second tidemark exists just superficial to this. The tidemark is irregular and devoid of vascular foramina (Fig. 5c). Chondrocytes in



**Fig. 3** **a** Level 1 transverse section of the plantar plate; ill-defined borders (*arrows*), flattened central articular surface (*arrowheads*) alcian blue, bar = 200  $\mu$ m. **b** Transverse section at level 2; *ac* articular cartilage, *cb* cortical bone, *fc* fibrocartilage, alcian blue, bar = 100  $\mu$ m

the uncalcified fibrocartilage are arranged in undulating longitudinal rows separated by parallel collagen fibers. Calcified fibrocartilage was identified by its birefringence pattern with polarized light (Fig. 5d). Calcified zone width was not found to be uniform. Rather, it is thin dorsally, extremely thick centrally and almost non-existent plantarly. The border between the bone and calcified tendon is markedly irregular.

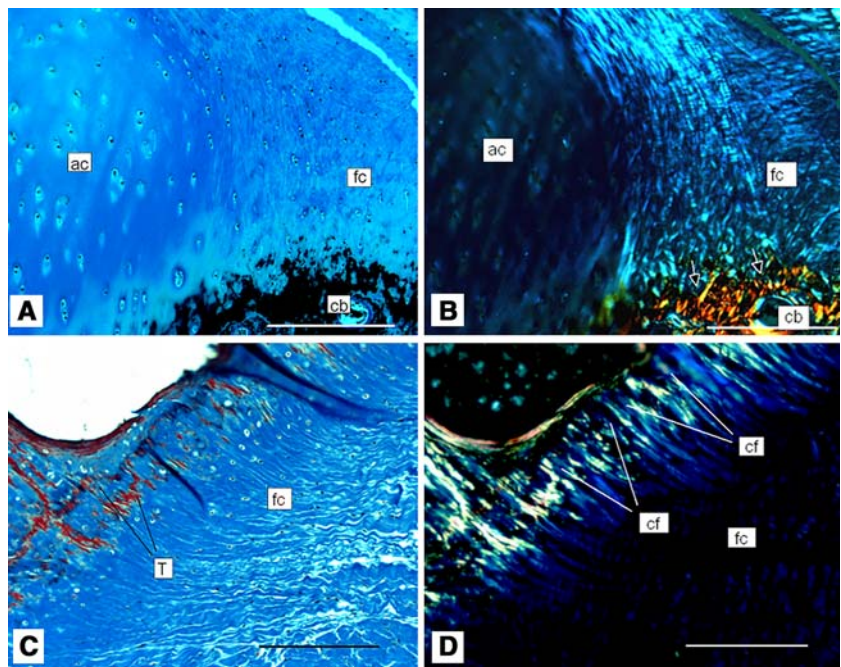
In the plantar section, chondrocytes about the bone and form a shallow and irregular attachment (Fig. 6a, b). Superficially, a higher proportion of the fibers contain fibroblasts compared with the deeper section (Fig. 6c). The PP forms a relatively shallow enthesis proximally with multiple interdigitations. A double tidemark is noted. Appearances of collagen end-on confirm that the central collagen bundles are interweaved and longitudinal (Fig. 6d). A thin layer of the plantar aspect of the PP appears to run transversely to blend with the collateral ligaments. The depth of the collagen bundles was evaluated in the transverse plane. The thickness of collagen bundles both near the borders and centrally was in the region of 20  $\mu$ m.



**Fig. 4** Sagittal section of the plantar plate **a** mid-plantar plate, central fibers; chondrocytes (*arrowheads*); *f* fibroblasts, Masson's trichrome, bar = 10  $\mu$ m. **b** Proximal plantar plate with undulating collagen bundles (*arrowheads*) in the longitudinal (right to left)

plane, Masson's trichrome, bar = 100  $\mu$ m. **c** Mid-plantar plate under polarised light, plantar surface with extracellular tissue entering plantar plate. Vertical crimping (*arrows*) reflecting the longitudinal direction of fibres, *s* synovium, Masson's trichrome, bar = 25  $\mu$ m

**Fig. 5** **a** Dorsal enthesis; *ac* articular cartilage, *fc* fibrocartilage, *cb* cortical bone, Masson's trichrome, bar = 25  $\mu$ m. **b** Dorsal enthesis under polarised light; *ac* articular cartilage, *cb* cortical bone, calcified zone (*arrows*), bar = 25  $\mu$ m. **c** Central enthesis; *fc* fibrocartilage, *T*, tidemark, bar = 25  $\mu$ m. **d** Central enthesis under polarized light; *fc* fibrocartilage, *cf* calcified fibrocartilage, bar = 25  $\mu$ m



## Discussion

Densely arranged PP fibers were seen to insert into the plantar surface of the proximal phalanx (just distal to the articular surface), with a small layer enveloping the phalangeal head to form a capsule. Johnston et al. [8] described the PP thicker at its borders than the central region. Our results, although limited to the distal fibers, showed the borders to be thicker beneath the phalangeal base. However, proximal to this the borders did not appear any thicker than centrally. The individual collagen bundles that make up the PP are of a consistent thickness both centrally and near its borders.

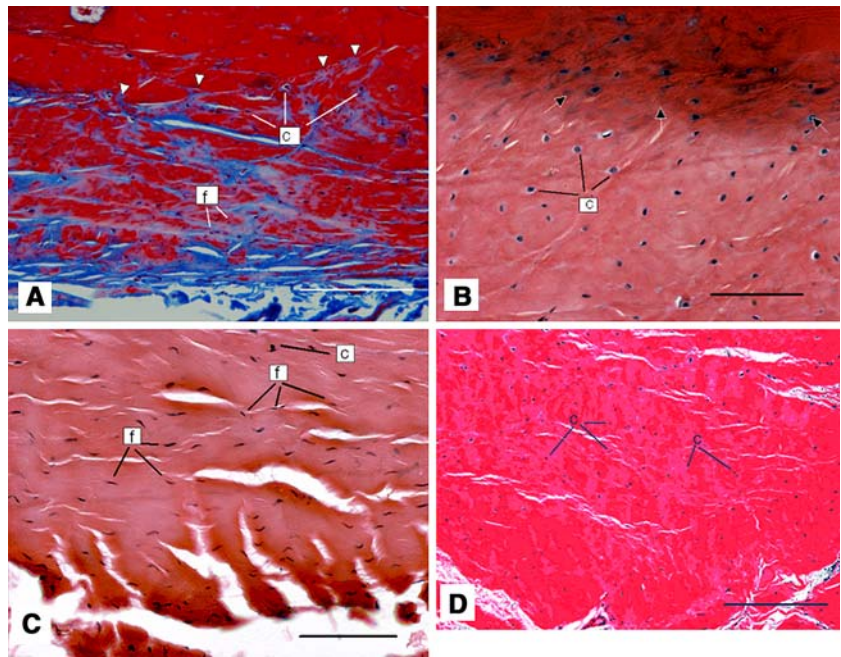
Our results suggest that the vessels appear to enter peripherally, mainly plantarly, and are part of the loose connective tissue septae (endotenon) that surround the collagen fascicles. We also noted a varying degree of vascularized tissue projecting from the PP enthesis into

the joint recess, also reported by Lewis et al. [10] describing the volar plate of the interphalangeal joints. Mohana-Borges et al. [12] documented the recess between the PP and the articular cartilage of the metatarsophalangeal joint at dissection and with MRI. The synovium in this region may line a PP recess or more likely represent a synovialised tear. Further research correlating the histology and imaging findings would be helpful to confirm this.

## Morphology

In general, the crimp morphology of collagen fibers indicates that they become taut before exerting any reinforcement on the tissue, which is consistent with transmitting compressive loads [2, 7]. According to Pauwel's theory of 'causal histogenesis', regardless of their molecular composition, collagen fibrils are always

**Fig. 6** **a** Plantar surface of plantar plate; shallow entheses (*arrowheads*), *f* fibroblasts, *c* chondrocytes, Masson's trichrome, bar = 10  $\mu$ m. **b** Transverse section at level 2, plantar plate entheses; shallow entheses (*arrowheads*), *c* chondrocytes, alcian blue, bar = 10  $\mu$ m. **c** Transverse section at level 2 of the plantar-most fibres; *f* fibroblasts, *c* chondrocytes, alcian blue, bar = 10  $\mu$ m. **d** Transverse section of the central fibers of the centre of the plantar plate at level 1, *c* chondrocytes, alcian blue, bar = 10  $\mu$ m



oriented in the direction of the greatest tension [13]. Previous reports of the PP showed that collagen bundles run longitudinally in the dorsal two-thirds, with oblique bundles interspersed throughout [8, 15]. The bundles run transversely in the plantar third and at the level of the intermetatarsal ligament are continuous with it [6]. Our results differ somewhat. For much of the proximal plantar plate the central fibers also run longitudinally, nearer the borders and distally, the plantar-most fibers run transversely, blending indistinguishably with the collateral ligaments. The PP insertional fibers contain high volumes of chondrocytes to form a strong union with the proximal phalanx. The entheses fibrocartilage has zones of uncalcified fibrocartilage, calcified fibrocartilage and bone. The tidemark in coronal section is thin, but in sagittal section (dorsal-to-mid plantar plate) is thick, reflecting the direction of pull and therefore inherent direction of strength. With longitudinal evaluation, we reported the central interdigitations to be deep, reflecting a high volume of uncalcified fibrocartilage at the entheses. Benjamin and Ralphs [1] suggested that this correlates with the extent of movement that occurs between tendon/ligament and bone. Short and less frequent interdigitations on the plantar surface of the insertion reflect the region of less stress than the central interface. The dorsal interface has a high volume of interdigitations, similar to the central entheses, although not as deep, remains an extremely strong interface.

In the proximal PP the entire depth of the structure is composed of high numbers of chondrocytes, with minimal fibroblasts, reflecting fibrocartilage. Contrary

to earlier reports, our data shows that the plantar aspect of the PP becomes ligament-like the further distally it tapers, containing fewer chondrocytes, and a higher number of fibroblasts. The plantar fibroblasts, or flattened chondrocytes of the PP may serve to integrate the fibrocartilage with its many ligamentous and tendinous attachments. The cells of the plantar plate respond to the loads upon them. Cells that require compressive capabilities (load-bearing tissues) will display a purely fibrocartilage character (predominantly more rounded chondrocytes with a small interspersion of fibroblasts). Mainly tensile forces produce solely ligamentous characteristics, predominantly containing fibroblasts and a higher proportion of collagen [9, 11, 16]. Therefore, the morphology of the PP suggests that the plantar (volar) insertional fibers of the PP experiences mostly tensile forces, whereas the dorsal-to-mid insertional fibres experience both compressive and tensile forces.

The PP appears well suited for general levels of stress and pounding. A comprehensive study involving MRI, ultrasound, anatomic and histologic analysis that includes young adolescent cadavers would provide a more thorough assessment of the PP. The excessive loads borne on this structure with high-heel wear may explain the more prevalent metatarsalgia and toe deformities in the female population. This has been widely reported over the years [3, 15, 17]. Plantar plate degeneration will result in laxity of the MTPJ and capsule, subsequently rendering the metatarsal head vulnerable to damage. This potentially can lead to subluxation and subsequent fixed deformity, but also

result in irreversible arthritic changes. In this context, the importance of education programs featuring the health of feet should not be under-estimated.

## Conclusion

The PP, with its multidirectional fibers, and blend of chondrocytes and fibroblasts confirm it to be a substantial stabiliser and cushioner of the forefoot. The PP entheses are designed to withstand the forces placed upon it, thus reducing the risk of wear and tear. Our study has enabled a review of fibrocartilage entheses, with particular attention to the PP of the lesser metatarsophalangeal joints. With high morbidity associated with PP degeneration, enhancement of current knowledge is essential.

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