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J. C. GUIMBERTEAU, J. P. DELAGE, D. A. MCGROUTHER and J. K. F. WONG

From the Aquaitaine Hand Institute, Pessac, France, UFR STAPS and INSERM, U688 Physiopathologie mitochondriale, Université Victor Segalen-Bordeaux 2, Bordeaux, France, and Plastic Surgery Research, Faculty of Medicine and Human Sciences, University of Manchester, Manchester, UK

The term 'fascia' has been applied to a large number of very different tissues within the hand. These range from aligned ligamentous formations such as the longitudinal bands of the palmar fascia or Grayson's and Cleland's ligaments, to the loose packing tissues that surround all of the moving structures within the hand. In other parts of the body the terms 'superficial' and 'deep fascia' are often used but these have little application in the hand and fingers. Fascia can be divided into tissues that restrain motion, act as anchors for the skin, or provide lubrication and gliding. Whereas the deep fascia is preserved and easily characterized in anatomical dissection, the remaining fascial tissue is poorly described. Understanding its structure and dynamic anatomy may help improve outcomes after hand injury and disease. This review describes the sliding tissue of the hand or the 'microvacuolar system' and demonstrates how movement of tissues can occur with minimal distortion of the overlying skin while maintaining tissue continuity.

Keywords: flexor tendon, carpal sheath, sliding system, vasculature, collagen fibrillar framework, microvacuoles

#### **INTRODUCTION**

Many structures glide considerable distances under the surface of the skin and still maintain continuity with surrounding tissues. During finger flexion, the flexor tendons at the level of the palm move approximately 35 mm with little skin movement (McGrouther and Ahmed, 1981; Wehbe and Hunter, 1985). This motion is largely attributed to loose areolar tissue, superficial fascia, or loose connective tissue (Ragan, 1952). Mayer (1916) described the different connective tissue layers surrounding tendon which are specialized into paratenon, mesotenon, bursae and specialized sheaths. Currently these structures are poorly defined and the understanding of how these tissues move is unclear.

Anatomical texts give prominence to visceral organs and defined structures, characterizing all the intermediate tissues as 'fascia'. This term encompasses a wide range of tissue organizations in the hand, many of which have mechanical retinacular function during finger movement, like the annular and cruciate pulleys (Doyle, 1989) or Grayson's and Cleland's ligaments surrounding the neurovascular bundles (de-Ary-Pires et al., 2007). Dense fascial structures also serve to keep the hand together, like the transverse metacarpal ligaments, the palmar aponeurosis and the paratendinous septae (Bojsen-Moller and Schmidt, 1974). Such fascial structures are specialized for force transmission and have an organization of predominantly aligned type I collagen fibres, visible to the naked eye as silvery, generally parallel bundles. However there is a different type of fascia, the 'microvacuolar' fascia, which provides lubrication, and allows almost frictionless musculotendinous movement. Our review is based on our own *in vivo* microscopic examination of the flexor tendons without tourniquet, and on biochemical analysis, scanning electron microscopy, and 3D modelling of these gliding structures.

#### **METHOD**

We observed the microvacuolar system during 215 (150 male:65 female) human upper limb operations under regional block, after tourniquet removal, using a standard wrist arthroscope (Karl Storz) at 25 times magnification. We made 65 video recordings of the subcutaneous tissue sliding on flexion and extension of the fingers. All patients were having an ulnar artery retrograde flap reconstruction of injured digits. The mean age of the patients was 45 (range 18–74) years. We also observed ten digital flexor tendon systems in uninjured fingers, explored to harvest the flexor digitorum superficialis tendon for tendon reconstruction of the neighbouring finger. Fifty-five observations were made in the palm, wrist and forearm which had previously not been injured or diseased. All procedures were performed with the patient's consent and local ethical committee approval.

Observations were made of zones I, II, III, IV, and V (Boyer et al., 2003). After video capture, the structures were modelled in computer software packages using '3D Studio Max Design' and 'Cinema 4D'. The skin and tendon were mapped as solid structures and the sliding

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Fig 1 The microvacuolar system over the flexor carpi radialis. Images show the tendon being pulled into flexion with time lapse images every 2 seconds between frames. Transverse vascular channels have been numbered 1, 2, 3, and 4 for ease of identification and tracking. Note how the sliding layers slide at different rates during flexion indicating different deformation.

system was mapped according to deformable vectors which assembled into a framework based on microvacuoles. We obtained more realistic movement of the 'microvacuolar' system in 3D modelling using a random fractal pattern rather than a geometric pattern.

We defined the human tissue architecture at an ultrastructural level in 30 fresh 0.5 cm<sup>3</sup> biopsies of macroscopically normal sliding system tissue from undamaged regions of flexor carpi radialis (FCR) and flexor digitorum superficialis (FDS) and profundus (FDP). These were processed for scanning electron microscopy (Wong et al., 2009) and combined with a

maceration technique (Passerieux et al., 2006). This process allowed preservation of the main fibrous components of the tissue.

The biochemistry was determined using methods described by Nissen and Kreysel (1982). The collagen content was assessed from hydroxyproline levels and the proteoglycan content was measured by hexosamine levels. The types of collagens were separated using salt precipitation (Bilgen et al., 1999).

#### RESULTS

Intraoperative exploration of the flexors in the forearm with endoscopic magnification showed that an amorphous gel like tissue surrounded the tendons and filled the spaces between the skin, muscle and dense fascial structures. Within the web like structure there were intertwining vascular channels, some lying parallel to the underlying tendon, while others traversed across the tendon collagen fibres in a random fashion. This 'microvacuolar' system accommodated blood vessels and gradually became fibrous when it was allowed to dehydrate. When the tendon was made to glide, the blood vessels could be seen to lie in different planes with different excursions (Fig 1). In early observations the sliding system seemed composed of multiple laminar layers which housed blood vessels. However, on radial distraction of this sliding tissue, we could see that it was composed of multiple fibres surrounding polyhedral spaces or 'microvacuoles' in all cases (Fig 2). Closer inspection of the microvacuoles showed droplets of fluid adhering to the fibres. The microvacuolar system provided tissue continuity between the flexor tendon surface and the overlying dermis and skin.

The polyhedral shape of the microvacuoles meant that they were capable of multidirectional expansion, compression and deformation in a fashion similar to a wire frame and due to their elasticity, distraction of the fibres was also possible. The fibrils of the vacuoles provided a framework for branching blood vessels. These tiny dynamic structures were constantly changing shape and position on movement, which, with each deformation, caused neighbouring microvacuoles to change shape.

In the flexor tendon sheath the flexor digitorum profundus and flexor digitorum superficialis were restricted in their excursion by joint movement and the vincula which have enough length to allow the full range of tendon excursion. In all zones the sliding system had sufficient dynamic deformation and available vessel length to accommodate the necessary tendon excursion.

In Zones I and II the tendon was intrasynovial and passed through a specialized flexor tendon sheath with blood vessels lying within the dorsal vinculum (Ochiai et al., 1979). These vincula had different structures but all contained blood vessels which had two fixed points; one near the skeleton and the other on the tendon surface. These vessels moved to and fro, like a windscreen wiper, as the tendon moved proximally or distally. These blood



Fig 2 Distraction of the microvacuolar system. (a) Flexor carpi radialis vascular unit. (b) Radial distraction of the microvacuolar system showing vascular channels. (c) Radial distraction of the microvacuolar system showing microvacuoles. (d) Fibrous hydrated matrix showing polyhedral arrangement.



Fig 3 Flexor tendons in Zone II. (a) Many dorsal blood vessels seen entering the FDS tendon (arrow). (b) On retraction the vinculum brevis (right arrow) and vinculum longum (left arrow) enter the tendon. There is no blood supply or sliding system on the palmar surface.



Fig 4 Typical microvacuolar system arrangement. (a) Start of sliding system at the A1 pulley at the border between Zone II and III. Microvacuolar system and associated vasculature seen around the tendon. (b) Zone V proximal to the carpal tunnel. Multiple collagenous interconnections between the tendons of FDS and FDP housing blood vessels, typical of type 1 microvacuolar system.



Fig 5 Microvacuolar system in the carpal tunnel. (a) The FDS and FDP tendons glide with no collagenous connections with the palmar aspect of the tunnel shown with the carpal ligament removed (CL). (b) The FDS and FDP tendons are interconnected by the microvacuolar system within the tunnel.

vessels were seen in all patients examined entering the dorsum of the flexor digitorum tendons with no microvacuolar system seen on the palmar surface (Fig 3).

In Zone III and V the extrasynovial flexor tendons had a sliding system arrangement with fibres forming multiple microvacuoles between the tendon and surrounding structures. The fibres formed polyhedral compartments, which had an apparent random arrangement, with branching fibres and longitudinal fibres running from tendon to the periphery. The tendon surface was connected by the microvacuolar system to the surrounding tissues. The microvacuolar system in extrasynovial tendon was what Mayer (1916) described as 'paratenon' (Fig 4).

In Zone IV the flexor tendons were connected to one another by a microvacuolar sliding system. Within the carpal tunnel, in all video observations, there were only a few loose filmy attachments dorsally and the tendons were separate from the carpal ligament. A multitude of small blood vessels lie within these filmy attachments and enter the tendons dorsally (Fig 5).

The ultrastructural appearance of the microvacuolar system in all specimens biopsied showed that the patterning apparent microscopically also existed ultrastructurally and was continuous with the dense fascial



Fig 6 Ultrastructure of the microvacuolar system. Scanning electron microscopic images of the sliding system. (a) Multiple microvacuoles of various shapes and sizes filling in the space. (b) The tendon surface has tightly bound collagen whereas multiple radial fibres of the microvacuolar system can be seen extending from the tendon surface in a random fashion.

structures. The tendon surface showed multiple collagenous strands from the microvacuolar system connected to the tendon surface (Fig 6). The microvacuolar system appeared as a series of polyhedral microvacuoles with highly variable shapes and sizes. Polarizing light microscopy of the superficial fascia has shown that the collagen fibres run in all directions in a woven mesh pattern (bu-Hijleh et al., 2006).

Biochemical analysis revealed that the microvacuolar system was made up of 70% proteoglycan, 23% type I and III collagen with some type IV and V collagen, and 4% lipid. In comparison, tendon and deep fascia is composed of 60% type I collagen with some type III and V collagen. Only 0.5–3.5% of tendon is proteoglycan (Wang, 2006).

Modelling was used to recreate the characteristics of the gliding fascia in a virtual environment based on video observations and mapping. The basic 3D model demonstrated how the skin was in continuity with the underlying tendon through the microvacuolar system (Fig 7). The forward and backward excursion of the modelled system demonstrated how the underlying tendon moved without causing any deformation of the overlying skin. This arrangement and its surrounding interactions reached an interface at the A1 pulley with the flexor sheath

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Fig 7 Three-dimensional model of continuity. (a) Between the skin and tendon provided by the sliding system which is also able to sustain independent movement. (b) At the level of the Zone II/ Zone III interface as the tendon flexes, the microvacuolar system deforms producing the cul de sac. (c) In a relaxed state the interface conforms. (d) As the tendon is extended the microvacuolar system deforms. In all positions of tendon excursion the skin moves slightly.

arrangement. Proximally, its arrangement changed within the carpal tunnel. In addition to the fibres deforming, contracting and expanding, the fibres could split and reform (Fig 8). We have defined five types of sliding system arrangement based on surgical observations and computer modelling.

Type 1 typical microvacuolar system with a deformable matrix surrounding the tendon and blood vessels (Fig 9a). Type 2 typical microvacuolar system with one surface adjacent to a synovial filled space, e.g. next to a bursa (Fig 9b).

*Type 3* specialized synovial sheath with specialized dominant vincular blood supply (Fig 9c).

*Type 4* absent microvacuolar system with only intratendinous blood supply (Fig 9d).

*Type 5* A mixture of type 1 and type 3, e.g. within the carpal tunnel where the tendons are interconnected by a

type 1 arrangement but the tendons as a unit are surrounded by a specialized sheath with a dorsal blood supply (Fig 9e).

Based on this classification the flexor zones of the hand can be simplified into:

- Zone I/II with a type 3 microvacuolar system
- Zone III/V with a type 1 microvacuolar system
- Zone IV with a type 5 microvacuolar system

### DISCUSSION

Fascia plays an important mechanical role in containing muscle tissue and optimizing transfer of muscle force (Benjamin, 2009). It can be divided into



Fig 8 Deformation of the microvacuolar system during flexor tendon motion. (a, b, c, d, e, and f) Live video sequences of polyhedral framework deforming. Points of interest highlighted with green dots. Note fibres splitting, deforming and reforming, a feature made possible by fibrous composition and fluid cohesion. (g, h, and i) Computer modelled deformation of the matrix showing framework changes.

superficial and deep components. Deep fascia is the dense connective tissue made up of fibrous layers and the superficial fascia, which has less definition and is frequently called loose areolar tissue, or loose connective tissue (Stecco et al., 2008). The filmy structures of the superficial fascia are often separated to define anatomical structures and provide the plane used by surgeons.



Fig 9 Classification of microvacuolar systems in the hand. (a) Type 1 – typical microvacuolar sliding system. (b) Type 2 – typical microvacuolar sliding system with one surface opposed to a synovial environment. (c) Type 3 – synovial environment with contribution from specialized blood supply. (d) Type 4 – synovial environment with purely intratendinous blood supply. (e) Type 5 – combination of both type 1 and type 3.

We fail to appreciate the gliding layers between the deep fascia and skin. This sliding system is a space filled with a filmy vascularized collagenous network that connects the dermal tissues and tendon/dense fascia/ muscle, but allows them to function differently. Previously we called this the 'Microvacuolar Collagenous Dynamic Absorbing System' but realized that this term, although precise, was not adopted by the clinical and scientific communities (Guimberteau, 2001).

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We have re-named it the 'microvacuolar system'. The microvacuoles help the tissues to withstand compression and expansion and form and reform due to the chaotic fibre arrangement and the hydrophilic extracellular matrix. Cells within these tissues are also interconnected and form a body-wide organ, sensing deformations of these tissues (Ingber, 1997; Langevin et al., 2004). The properties of this loose connective tissue network have been defined by video analysis. Previous difficulties in studying this tissue was due to tissue drying or necropsy. When initially observing this tissue we thought that sliding was due to concentric layers that glided. This notion was incorrect although there is some lamination of the microvacuolar system. Ultrasound and cadaveric studies have shown that three levels of sliding tissue separated by a fine membrane exists in most body sites (bu-Hijleh et al., 2006). The most superficial of these layers has the greatest fat content whilst the intermediate layer harbours the large veins and nerves. The deepest of the layers has the greatest degree of glide and is usually connected to tendons. This can be demonstrated by observing the dorsum of the hand where finger flexion allows the translation of the extensor tendons under the veins and skin, and pinching of the skin leaves the position of the veins and tendon unaltered (Bidic et al., 2010).

The microvacuolar system explains how different interconnected layers move differently. This tissue has high proteoglycan content which explains its unique gliding characteristics and also explains why it can only be reliably demonstrated in living or fresh tissues. Proteoglycans and their subcompositions of glycoaminoglycans (GAG) are strongly negatively charged (Yanagishita, 1993), and hence are capable of drawing in water molecules (Stern and Maibach, 2008). The high GAG content with its viscoelastic properties behaves like a gel, allowing tissue distortion. Dehydration makes this network difficult to assess in the laboratory; however, mathematical computer models allow its function to be understood (Chaudhry et al., 2008).

The microvacuolar system provides lubrication, absorbs shear stresses, contains water, and houses blood vessels, nerves and lymphatics. It fills the spaces between structures and enables vascular continuity between tissues. We found other anatomical sites with this arrangement wherever movement of adjacent tissues against each other was needed (Fig 10). Cadaver dissection and ultrasound studies in living subjects confirm the presence of this deformable membrane layer in other body sites including the foot, leg, thigh, trunk, anterior chest, back, hand, forearm and neck (bu-Hijleh et al., 2006). This system is an integral part of the anatomy that allows the skin to hide numerous tissue movements. In hand surgery, understanding and using the vascular territories of the microvacuolar system has been valuable in restoring function in heavily scarred fingers (Guimberteau et al., 1993). When this sliding system is



Fig 10 Evidence of microvacuolar systems at other body sites. (a) Scalp. (b) Neck. (c) Scapula. (d) Between rectus abdominus muscle and subcutaneous fat.

removed, for example in cases of where the radial forearm flap is harvested and the donor defect skin grafted, cosmetic and functional results are poor (Wong et al., 2008). As it forms the tissue between the dense fascial structures of the hand, in disease processes such as Dupuytren's disease, it is likely fibrosis within this tissue that causes contracture of digits (Holland and McGrouther, 1997). Loss of tissue turgor in aging although associated with loss of elastic tissue may also be related to changes in the microvacuolar system. Indeed volumetric rejuvenation of the dorsum of the hand focuses on the restoration of fat in these atrophied areas (Coleman, 2002). Repetitive strain problems, which are so common in the hand but have little anatomical or physiological basis, may in the future be explained by pathology of the microvacuolar system. Early morning stiffness, which has been attributed to joints, could be due to postural compression of the microvacuolar systems, which require rehydration and re-expansion to restore gliding movement. The adipofascial cross finger flap and the fascial flap are surgical examples of the microvacuolar system being used to reconstruct defects. We anticipate an increase in techniques that respect and preserve microvacuolar system function, and use its features for more complicated reconstructions. This may permit more accurate reconstruction of tissues and provide a focus for research into the behaviour of this tissue.

The microvacuolar system fills the spaces between the tendon and the skin providing tissue continuity in zones III, IV and V. This system counters shear and acts as a shock absorbing system while permitting gliding without translation of the skin yet providing a framework for blood vessels, nerves and lymphatics. It is synonymous with loose areolar tissue, superficial fascia, loose connective tissue, paratenon, subsynovial tissue or more correctly termed 'microvacuolar dynamic absorbing system' but may simply be known as the 'microvacuolar system'.

#### **Conflict of interests**

None declared.

#### References

- Benjamin M. The fascia of the limbs and back a review. J Anat. 2009, 214: 1–18.
- Bidic SM, Hatef DA, Rohrich RJ. Dorsal hand anatomy relevant to volumetric rejuvenation. Plast Reconstr Surg. 2010 [Epub ahead of print].

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- Bojsen-Moller F, Schmidt L. The palmar aponeurosis and the central spaces of the hand. J Anat. 1974, 117: 55–68.
- Bilgen, G., Oktay, G., Tokgoz. et al. Collagen content and electrophoretic analysis of type I collagen in breast skin of heterozygous naked neck and normally feathered commercial broilers. Turk J of Vet Anim Sci. 1999, 23: 483–487.
- Boyer MI, Strickland JW, Engles D et al. Flexor tendon repair and rehabilitation: state of the art in 2002. Instr Course Lect. 2003, 52: 137–61.
- bu-Hijleh MF, Roshier AL, Al-Shboul Q et al. The membranous layer of superficial fascia: evidence for its widespread distribution in the body. Surg Radiol Anat. 2006, 28: 606–19.
- Chaudhry H, Schleip R, Ji Z et al. Three-dimensional mathematical model for deformation of human fasciae in manual therapy. J Am Osteopath Assoc. 2008, 108: 379–90.
- Coleman SR. Hand rejuvenation with structural fat grafting. Plast Reconstr Surg. 2002, 110: 1731–44.
- de-Ary-Pires B, Valdez CF, Shecaira AP et al. Cleland's and Grayson's ligaments of the hand: a morphometrical investigation. Clin Anat. 2007, 20: 68–76.
- Doyle JR. Anatomy of the flexor tendon sheath and pulley system: a current review. J Hand Surg Am. 1989, 14: 349–51.
- Guimberteau JC. How is the anatomy adopted for tendon sliding? In: Guimberteau JC (Ed) *New ideas in hand flexor tendon surgery*. Aquitaine Domaine Forestier, 2001: 47–90.
- Guimberteau JC, Panconi B, Boileau R. Mesovascularized island flexor tendon: new concepts and techniques for flexor tendon salvage surgery. Plast Reconstr Surg. 1993, 92: 888–903.
- Holland AJ, McGrouther DA. Dupuytren's disease and the relationship between the transverse and longitudinal fibers of the palmar fascia: a dissection study. Clin Anat. 1997, 10: 97–103.
- Ingber DE. Tensegrity: the architectural basis of cellular mechanotransduction. Annu Rev Physiol. 1997, 59: 575–99.
- Langevin HM, Cornbrooks CJ, Taatjes DJ. Fibroblasts form a bodywide cellular network. Histochem Cell Biol. 2004, 122: 7–15.
- Mayer L. The physiological method of tendon transplantation. Surg Gynecol Obstet. 1916, 22: 182–97.

- McGrouther DA, Ahmed MR. Flexor tendon excursions in 'no-man's land'. Hand. 1981, 13: 129–41.
- Nissen HP, Kreysel HW. The ratio of glycosaminoglycans to collagen in the skin in malignant melanoma. Arch Dermatol Res. 1982, 272: 67–71.
- Ochiai N, Matsui T, Miyaji N et al. Vascular anatomy of flexor tendons. I. Vincular system and blood supply of the profundus tendon in the digital sheath. J Hand Surg Am. 1979, 4: 321–30.
- Passerieux E, Rossignol R, Chopard A et al. Structural organization of the perimysium in bovine skeletal muscle: junctional plates and associated intracellular subdomains. J Struct Biol. 2006, 154: 206–16.
- Ragan C. The physiology of the connective tissue (loose areolar). Annu Rev Physiol. 1952, 14: 51–72.
- Stecco C, Porzionato A, Lancerotto L et al. Histological study of the deep fasciae of the limbs. J Bodyw Mov Ther. 2008, 12: 225–30.
- Stern R, Maibach HI. Hyaluronan in skin: aspects of aging and its pharmacologic modulation. Clin Dermatol. 2008, 26: 106–22.
- Wang JH. Mechanobiology of tendon. J Biomech. 2006, 39: 1563–82.
- Wehbe MA, Hunter JM. Flexor tendon gliding in the hand. Part I. In vivo excursions. J Hand Surg Am. 1985, 10: 570–74.
- Wong CH, Lin JY, Wei FC. The bottom-up approach to the suprafascial harvest of the radial forearm flap. Am J Surg. 2008, 196: e60–4.
- Wong JK, Lui YH, Kapacee Z et al. The cellular biology of flexor tendon adhesion formation: an old problem in a new paradigm. Am J Pathol. 2009, 175(5):1938–51.
- Yanagishita M. Function of proteoglycans in the extracellular matrix. Acta Pathol Jpn. 1993, 43: 283–93.

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E-mail: adf.guimberteau@wanadoo.fr or docjwong@gmail.com.

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Mr J. C. Guimberteau, Aquaitaine Hand Institute, Allée des Tulipes, 33600 Pessac, France. Tel.: +33685209371 or UK +44161 2755076; fax: +44161 275 1591.