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Recent advance

The role and mechanical behavior of the connective tissue in tendon sliding

Le rôle et comportement dynamique du tissu conjonctif dans le glissement des tendons

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Abstract

After carrying out 215 in-vivo dissections, 65 of which were video-recorded, the authors propose that the current representation of the notion of the tendon sliding is incorrect. It is suggested that tendon sliding is explained by the existence of a mechanical adaptable multimicrovacuolar and fibrillar tissue. This tissue enables complete sliding without any dynamic influence on the surrounding tissues. The new theory is based on a polyhedric fibrillar framework, apparently chaotic and complex, subtending the microvacuolar gel, a concept that is to be found everywhere in the human body.

Keywords: Tendon; Carpal sheath; Sliding system; Tendon vascularization; Finger flexor reconstruction; Collagenic fibrillar framework; Microvacuole

Résumé

Aprés avoir réalisé 215 dissections chirurgicales dont 65 ont été enregistrées en vidéo, les auteurs remettent en question la description actuelle du glissement tendineux. Un nouveau modèle basé sur l'existence d'un système multifibrillaire et multimicrovacuolaire est proposé. Les unités fonctionnelles de ce modèle sont des microvacuoles. polyédriques, disposées en réseau, partout dans le corps humain. Sur plan biomécanique, ce réseau a des interconnections dont le comportement non linéaire permet une adaptabilité optimale à la contrainte.

Mots clés : Tendon fléchisseur ; Système de glissement ; Vascularisation tendineuse ; Reconstruction ; Maillage collagène fibrillaire ; Microvacuole

1. Introduction

For many years, the only scientific explanations concerning the natural mechanism of flexor tendon mobility in the fingers was a notion of virtual space or the existence of loose connective tissue organized in layers, but the biomechanical foundations for these theories were rather vague to say the least [1–3].

The strange biomechanical construction and odd histological configuration of this model cause utter confusion between the roles and the definitions of the paratendon, mesotendon, peritendon and sheaths, and has largely influenced present surgical procedures [4–9] (Fig. 1).

When surgical dissection is performed in vivo, visual magnification demonstrates the presence of a vast arrangement of tissue connections, a histological continuum with no clear separation between the skin, the hypodermis, the vessels, the aponeurosis and the muscles. Structures, which allow sliding to take place are present everywhere.

In this paper we present the physiology of flexor tendon sliding in human tissues. As a result of micro-anatomical

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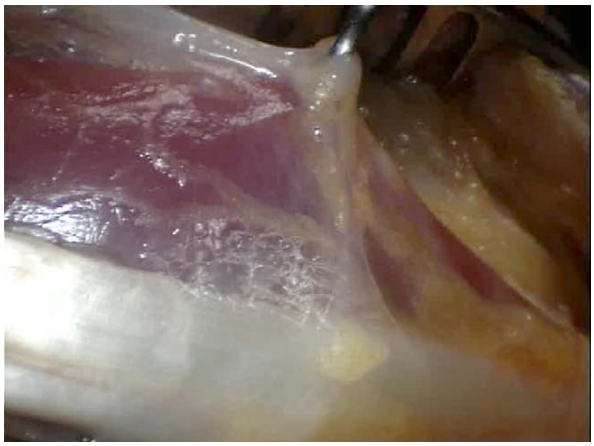

Fig. 1. When the tendon moves, its movement is barely discernible in the neighboring tissue. Tendon may go far and fast without any hindrance. There is an absorbing system (Video clip published online exclusively).

observations we made during video analysis, new hypotheses have emerged concerning the organization of the subcutaneous tissues.

2. Material and methods

2.1. In vitro study of the paratendon

This study was carried out on 30 human upper limb biopsies of flexor digitorum superficialis (FDS) and profundus (FDP) with their surrounding sheaths, and 26 animal samples including the flexor carpi radialis from cattle, in which the organization is very similar to that of the human flexor profondus (Fig. 2).

The preparation was treated with potassium bichromate, placed in formalin and finally in caustic soda, thus allowing softer and more complete hydrolysis (Pr J.-P. Delage, Inserm Laboratories, Bordeaux, France). Then it was frozen and freeze-dried under standard conditions for dehydration. Afterwards, it was dissected under a binocular loupe at 3.5 times magnification. Samples were taken, given a gold-metallic finish and then observed under the electron microscope. The Inserm Laboratories (Pr Herbage, Lyon, France) helped us to analyze the chemical components of this connective tissue.

2.2. In vivo study of digital zones III, IV and V by micro-anatomical videoendoscopic observation

The tendon gliding system was observed and recorded on video in 65 cases of tendon revascularization in Kleinert's zones III, IV and V after releasing the tourniquet.

All patients gave their consent before surgery. Of the 65 cases, 57 procedures were forearm island reverse flaps. The remaining eight procedures were axillary flaps. Static and dynamic observations were carried out using an endoscope with an attached Tricam 221030 fiberoptic camera and Xenon Nova 201315 light source at 25 times magnification.

Continuous sequences were captured on video during flexion of the digital flexors to allow subsequent analysis.

3. Results

3.1. In vivo observations

3.1.1. Macroscopic observations

When the flexor tendon moves, its movement is barely discernible in the palm. There is no dynamic repercussion of the movement on the skin surface. However, the flexor tendon

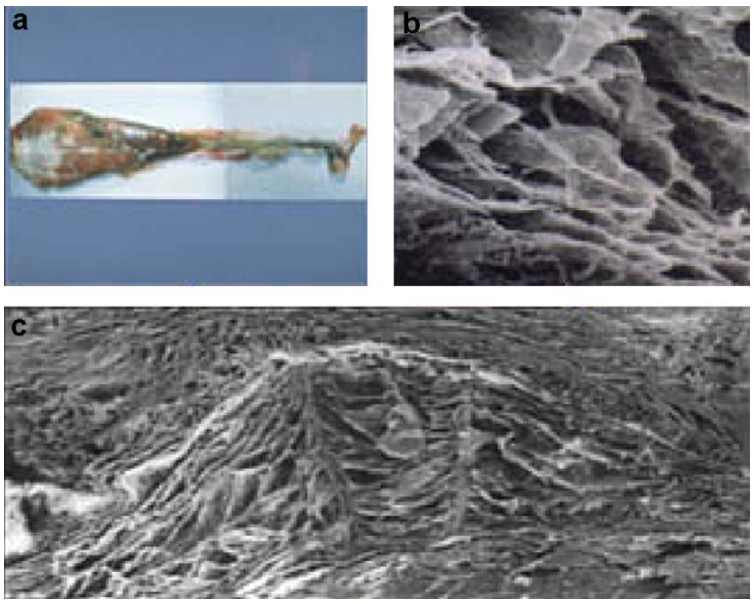

Fig. 2. MVCAS under the electron microscope; a: our basic experimental material: the Flexor Carpi radialis of cattle; b: surrounding tissues composed of microvacuoles; c: MVCAS under the electron microscope, the notion of continuous matter ruling out any lamellar organization.

excursion is at least 2 cm, without any hindrance and without displacing any of the neighbouring tissues in the palmar area or along the common carpal sheath.

This suggests the existence of some sort of shock-absorbing system.

It is clear also from observing the behavior of the common carpal sheath vessels after revascularisation, and during flexion and extension, that there is apparent disorder and irregularity of shape of the microvascular network. There are surprisingly complex forms of vascular distribution, a finesse of the microvascular network, which is much more complex than a simple mechanistic distribution [10–14].

When we observed the area around the tendon, we noted an apparently circular longitudinal and peripheral vascularization, which seemed first to represent a real continuity between the sheath and the tendon, and, which was not interrupted despite the excursion and distension occurring during sliding and subsequent return to the original position.

At first sight, this is not incompatible with classical anatomical descriptions.

3.1.2. Ten-fold microscopic examination

However, during flexion and extension of the tendon, 10-fold microscopic examination of the zones III, IV and V enabled us to observe vascular patterns in different planes of excursion and with different speeds of vessel progression due to modifications in the capillary network, and depending on variations in tendon movements. Small vessels are subjected to deformation during movement, but do not follow any logical or rational sequence. Some vessels progress quickly while others move more slowly, and some overtake other vessels. The diameter of the vessel seems to be of no importance in this process. There is dynamic progression with no apparent order or proportionality (Fig. 3).

Very little research has been done to study this mechanical phenomenon, since the issue was considered by many to have been solved by the concept of a virtual space; i.e., the tendon slides in the carpal sheath like a bullet in the barrel of a gun, without touching the sides, or rather, it slides in membranous or visceral layers like a hamburger or by stratification of different coaxial layers.

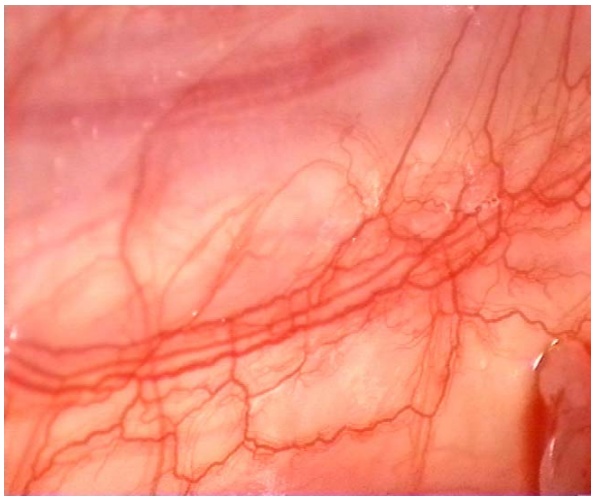

Fig. 3. Intriguing vascular patterns due to modification in the capillary network depending on the varying movements during flexion and extension. They are not all going at the same speed and are in different planes (Video clip published online exclusively).

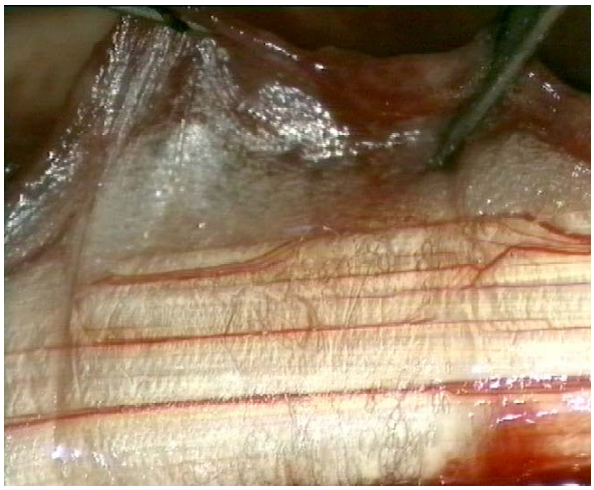

Fig. 4. Searching for a clear field of dissection between the paratendon and the tendon and confronted by an inaccessible micro-anatomical arrangement Network between the tendon and the peripheral system: the MVCAS (Video clip published online exclusively).

In vivo observation has rendered this concept unacceptable because, for example, it is surgically impossible to define a clear field of dissection between the paratendon and the tendon (Fig. 4).

At 10-fold microscopic examination (Fig. 5), video observation at rest showed an inaccessible micro-anatomical arrangement, real tissue continuity, and a gel-like tissue surrounding the tendon. We saw a glossy structure stretching across the tendon. Within this tissue, fibres can be seen framing the vessels in a random fashion. We were confronted therefore with the notion of global dynamics and continuous matter between the tendon and the surrounding tissue, radically opposing the classical descriptions of sliding structures based on the notion of tissue stratification and a virtual space between the tissue layers. Instead, we found total histological continuity. It became necessary therefore to further investigate this tissue in order to gain better knowledge of its properties and its different roles.

3.1.3. Twenty-five-fold magnification

At 25-fold magnification, this glossy system consists of loose connective tissue located between the tendon and its neighbouring tissue, composed of intertwining multidirectional filaments creating partitions, which form three-dimensional microvacuolar volumes. Apart from some adipocytes and fibroblasts, there are few cells in this multifibrillar network (Fig. 6).

We called it the multimicrovacuolar collagenous dynamic absorbing system (MVCAS), in order to emphasize its functional and architectural impact [15–17].

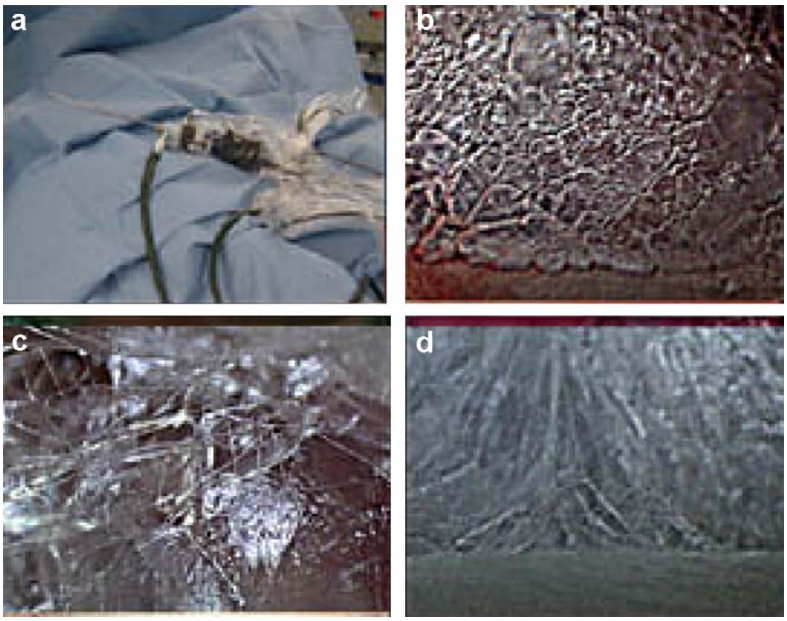

Fig. 5. a: cold light variable magnification endoscope and 3-CCD camera; b; epitendinous dissection exposes the sliding system MVCAS; c: apparent microvacuolar distribution is in the dispersed branching pattern; d: Concept of tissue continuity between tendon and microvacuolar distribution.

This tissue network is a continuous structure composed of billions of microvacuolar components, which must be considered as a basic three-dimensional network. The basic component unit of this sliding framework is the microvacuole.

The microvacuoles size ranges from a few microns to a few hundred microns; they are organized in a dispersed branching fractal pattern. Microvacuoles have a pseudo-geometric shape forming a polyhedron.

A microvacuole has to be considered as a volume (Fig. 7). However, microvacuoles are organized differently, depending on the dynamic role they play. The greater the distance the structure must travel, the smaller and denser are the vacuoles. The major role of this framework is to make sure that when stimulated, the structures can move freely without anything else moving around them. The microvacuolar structure is resistant, adapted to the physical constraints it undergoes, and it

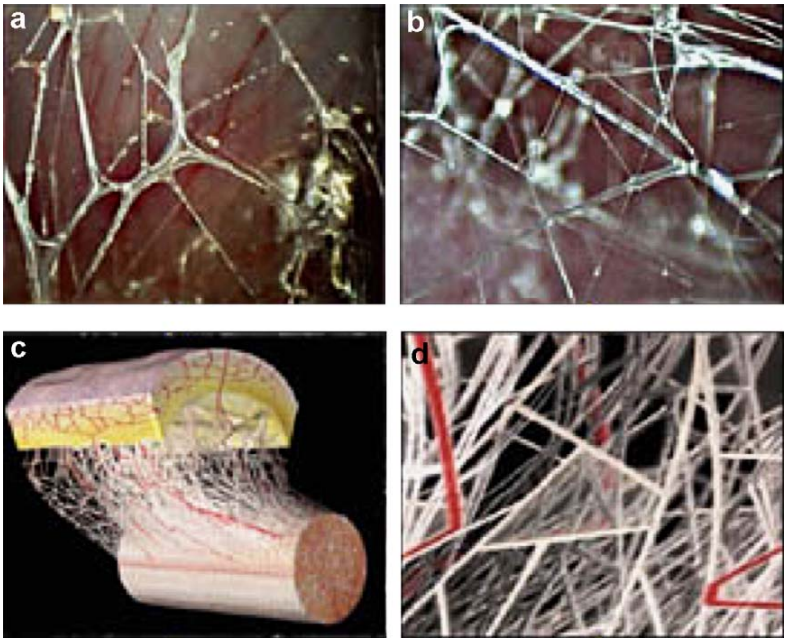

Fig. 6. a: fibrils composed of collagen and elastin delimit the microvacuoles; b: microvacuoles have polyedral shapes resembling scaffolding; c: diagram showing the basic role of MVCAS; d: diagram of the basic building brick of the MCVAS: the microvacuole.

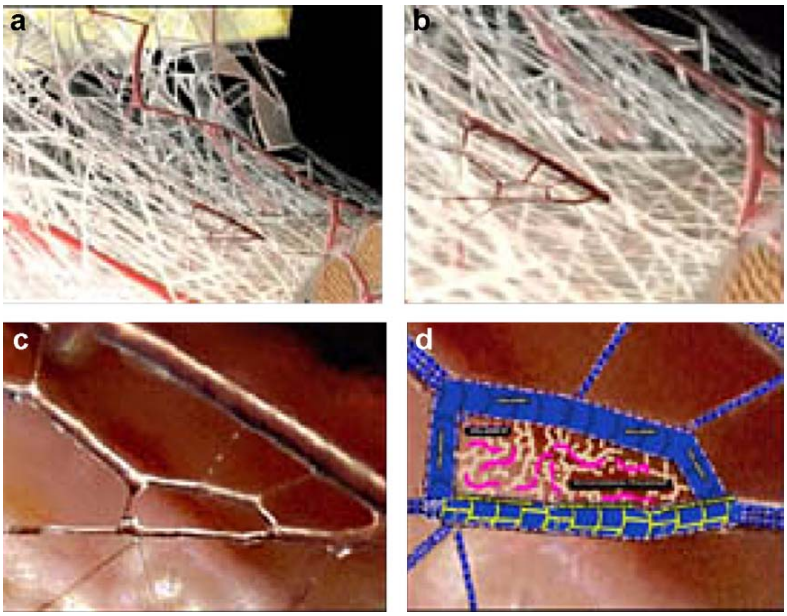

Fig. 7. a: diagrams showing the microvacuoles inside the MCVAS; b: magnification; c: a real microvacuole with a hexagonal shape; d: microvacuole is filled with GAG and the collagen type I, III, IV framework.

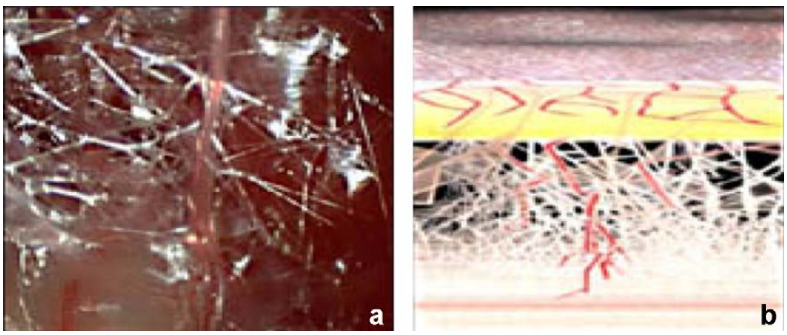

Fig. 8. Collagen framework along fibrils provides information and nutrition.

maintains its shape. In other words, its role is to ensure the dynamics of movement and to absorb the related shocks. The structure also has a memory, so it returns to its initial position, preserving its form and volume. Slight traction on this microvacuolar system reveals mini air explosions, which prove the existence of a tissular pressure that differs from atmospheric pressure.

In addition to providing shape and form, and filling space, this microvacuolar tissue plays two essential roles (Figs. 8 and 9) [18].

This tissular organization is first an information provider. Fibrils serve as a supporting frame for the network of blood supply. This accounts for the huge variety of blood supply shapes. This tissue constitutes the continuum of vascular tissue between the mobile tendon and the neighbouring tissues, but they also ensure the collagenous, vascular, lymphatic and nervous continuity between the tendon, the epitendon and the paratendon. Tissue continuum is complete.

Moreover, this connective tissue has a biomechanical and dynamic behaviour. It has a mixed role that includes combined transmission and absorption of stress. Resulting from this dynamical behaviour, the microvacuolar system permits the transmission and absorption of the constraint across the tissue while at the same time the surrounding tissues are not affected.

During progressive traction (2 N/cm^2) (Fig. 10) the fibres undergo rearrangement in response to local stress. As the stress increases, the fibres line up in the stress direction. All of the component parts then turn, so as to be oriented as much as possible in the direction of the applied force. However, this set of movements is difficult to analyze, so certain fibres have to be selected for analysis on an arbitrary basis. Therefore we coloured some fibres yellow and observed their behaviour.

Nevertheless, other internal factors need to be taken into account.

The fibril struts behave in a very peculiar manner.

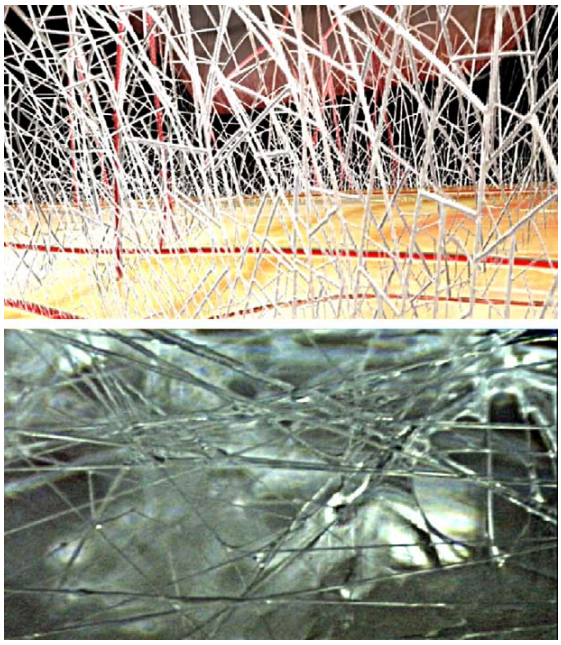

Fig. 9. A chaotic dynamic system with an intriguing pseudogeometric tendency.

First, in response to stretching, a fibril becomes longer by resembling a worm-like chain or a spring, which means that it is capable of molecular rearrangement and can recover its initial form by returning to initial position (Fig. 11). This mechanism seems to be involved in minor forms of tension.

Second, the fibres undergoing mechanical stimulation can divide in space into several other fibrils, which enables immediate dispersion and distribution of the forces across the tissue space (Fig. 12).

Third, the fibres are able to glide over each other around a mobile focal point along the entire length of both fibres (Fig. 13). Since classical linear models based on straight lines cannot account for these movements, fractal and non-linear mathematics are necessary to explain them.

These three dynamic abilities always coexist, allowing the structure to move in three-dimensional space and to respond optimally, whichever the direction it is stretched in (Fig. 14).

We have frequently observed GlycoAminoGlycan gel movements inside the fibres, the sliding of drops along the fibrils, together with dilaceration, absorption and reconstitution. It is impossible to ignore the role of GAG in response to traction (Figs. 15 and 16).

3.1.3.1. A global system. This sliding tissue with its basic polyhedric shaped units is to be found in every nook and cranny of our organism. The tissue that used to be referred to as connective or areolar tissue is totally continuous throughout the fibres and their prolongations. Even the intermediary structures such as the deep pre-muscular fascia are incorporated into this network and are connected with it on their superior and inferior aspects, thereby increasing the shock-absorbing properties of the tissue and allowing the structures to move interdependently. Whether it is in the abdominal, thoracic, dorsal, ante-brachial regions or in the scalp, this tissue network is omnipresent (Fig. 17).

Indeed, there is no space within the body where it is not found. Even structures subject to relatively little movement – such as nerves and the periosteum – are surrounded by this fibrillar tissue network although in these cases there are differences in the network itself and in the size of vacuoles. Indeed, it seems that the MVCAS occurs everywhere in the body.

3.2. In vitro

The sides of the intertwined vacuoles are composed of collagen fibres, mostly type 1 (23%), 3, 4 and 6. Their diameter ranges from a few to several dozen microns and they vary in length, giving consequently an overall disorganized chaotic

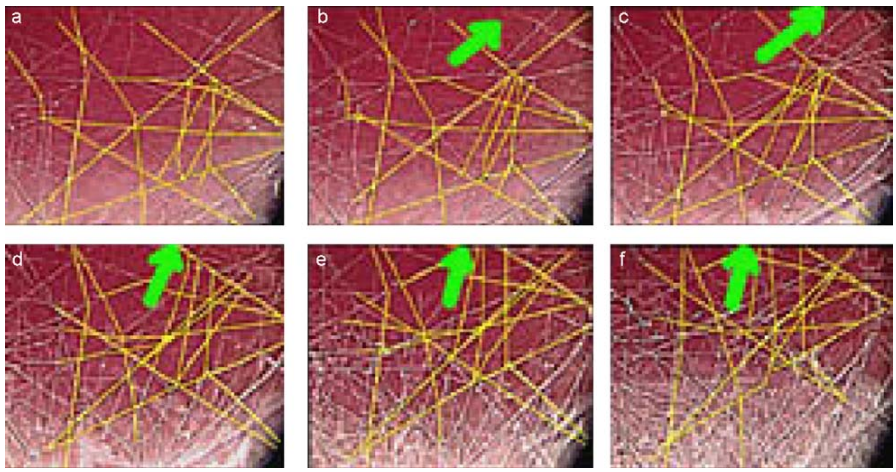

Fig. 10. Two hundred-fold magnification of fibrillary movements during traction. Time span between photos (a) and (f) is 2 seconds. Diameter of fibrils = 10μ. Two-dimensional analysis of what actually occurs in three-dimensions. The fibrils become oriented in the direction of traction but in a less organized manner than the rules of linearity would have it.

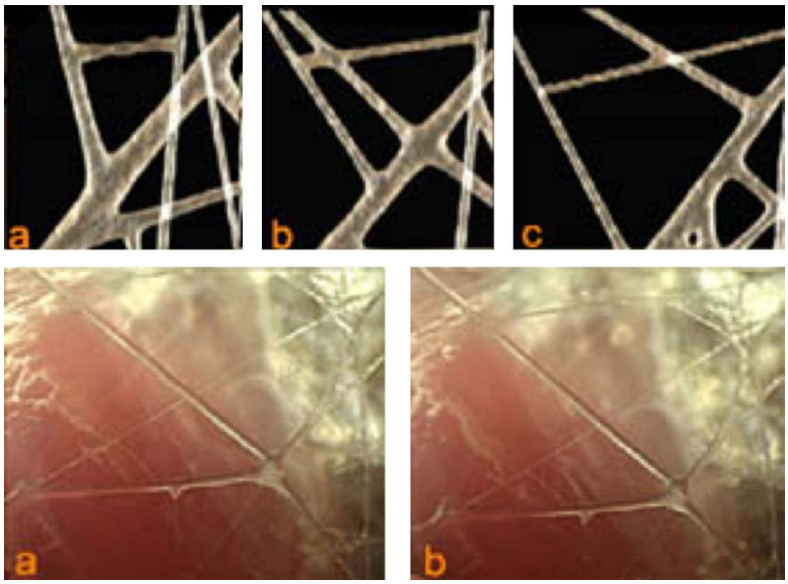

Fig. 11. Distension–retraction of a fiber.

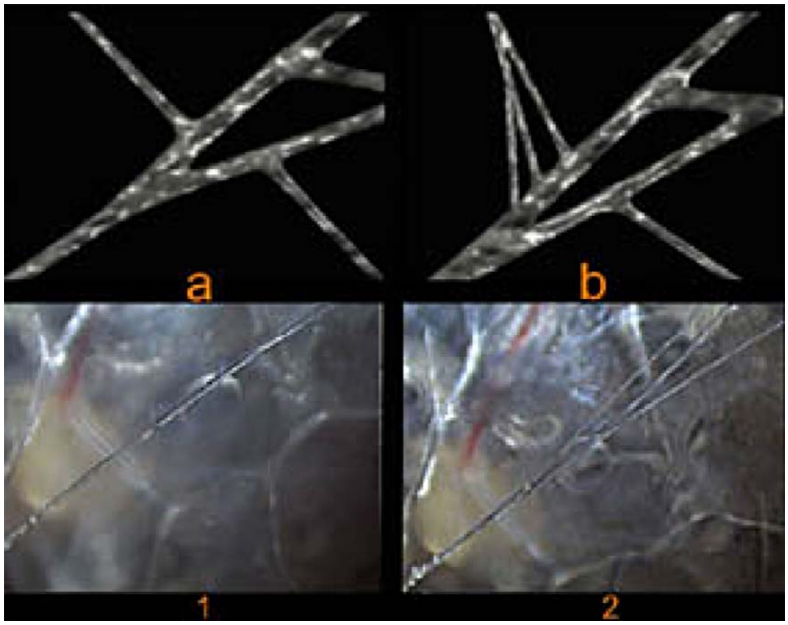

Fig. 12. Division of a fiber into several fibrils that diffuse the stress three-dimensionally.

aspect. These vacuoles contain a highly hydrated proteoglycan gel (70%), which can change shape during movement but of which the volume remains constant. Their lipid content (4%) is high. A major issue in this system is the presence of water, which is omnipresent as soon as the skin is penetrated. (Pr Herbage, Inserm Laboratories, Lyon, France). For this reason, no biomechanical explanation for the sliding of subcutaneous structures can disregard the dynamics of the fluids, which is present, e.g. osmotic pressure and superficial tension.

4. Discussion

4.1. The notion of tissue continuity provided by the multimicrovacuolar collagenic absorbing system (MVCAS)

All our observations support this tissue continuity and the microvacuolar and fibrillar architecture.

In traditional observations of this tissue, sliding was thought to be due to several coaxial conjoined layers with

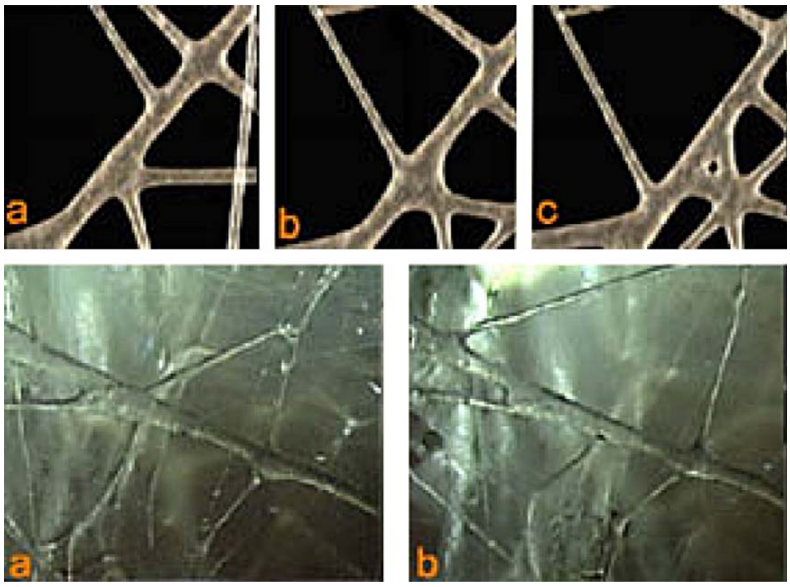

Fig. 13. Fiber moves freely along axis of another fiber.

progressively decreasing diameters framing the vascular structures or to a virtual space between visceral and membranous layers.

The layer, which is the closest to the tendon, would move the fastest, while the one further away would move more slowly. This concept of annular layers sliding between themselves, based on the theoretical concept of virtual space and a hierachical tissue distribution, seems to be incorrect (Fig. 5). For this reason, we have developed the theory of a tissue continuum, which supposes that there is a relationship between the way tissues are organized and how they behave.

It is important to highlight that due to the dispersed pattern of the fibrils and the cohesive nature of the extracellular matrix, the sliding system forms a continuous deformable framework, with three major mechanical roles:

- to respond to any kind of mechanical stimulus in a highly adaptable and energy-saving manner, ensuring the complete movement of the tendon;
- to preserve peripheral tissue stability, structures and shapes, providing information during action and springing back to its original shape;
- to ensure the interdependence and autonomy of the various functional units.

This sliding system and its multifibrillar organisation, participating simultaneously in movement, its restitution and

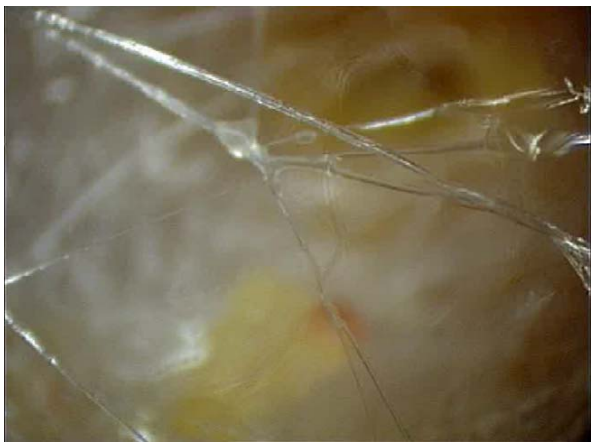

Fig. 14. The chaotic, pseudo-geometric distribution of the structures in vivo and the different ways in which the skeletal fibrils behave require a specific vision of the system (Video clip published online exclusively).

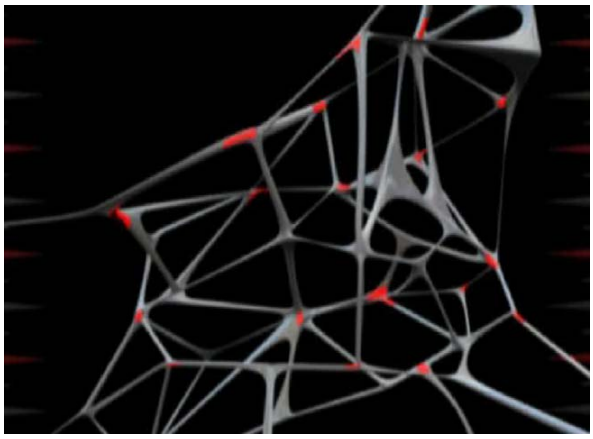

Fig. 15. Three-dimensional sketch showing potential for interfibrillar movement involving the three capacities of the system (Video clip published online exclusively).

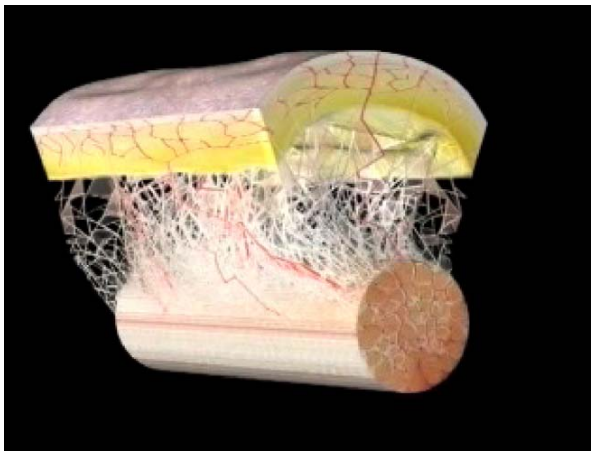

Fig. 16. The multimicrovacuolar system during peritendinous sliding (Video clip published online exclusively).

the transfer of energy, seems to be composed of elements developed from within this tissue, rather than a superposition of different tissues. We get the impression of elements united to compose one sole tissue. There is a real notion of tissue continuity between the tendon, the sliding tissue and all surrounding tissues. The notion of layers is replaced by a greater or lesser densification of the MCVAS with a more or less specific cellularization. However, in vivo observation has rendered the notion of tissue layers unacceptable. This means that we need a new way of thinking, inducing a manner of considering the problem in terms of global dynamics and continuous matter, and a theory involving the concept of a tissue continuum. This is in total contradiction with the traditional view of sliding structures, tissue stratification and a virtual space between tissue layers.

4.2. Microvacuoles as the basic structural unit that enables the MCVAS to achieve its role of filling space and preserving form [19–23]

4.2.1. A polyhedric shape

This multimicrovacuolar collagenic absorbing system is made of microvolumes and microfibrils and is focused around the microvacuole, which we can consider as the basic framework unit. This allows explaining the very notion of form and the fact that this form adapts to its environment but does not change. We need to move to three-dimension to really understand this.

It seems that the polyhedron shape of the microvacuole is the optimal shape for occupying space with minimal arrangement. It is essential to grasp that in order to fill space, living structures tend to adapt geometrically simple forms such as polygons, spirals or cylinders.

By accumulation and superposition, these multimicrovacuolar polyhedric patterns under internal tension will build an elaborate form. The concept of microvacuole explains the ability of the tissues to resist compression and expansion while maintaining stable volume.

4.3. Efficient dynamic behaviour provided by the MVCAS

This behaviour is partially explained by its components.

It was clear, observing the behaviour of the common carpal sheath vessels during flexion and extension, that simplistic mechanistic explanations could no longer account for these phenomena, and that this apparent disorder and irregularity of shapes was in fact the basis of some other form of complexity that is still unclear. Although the overall aspect of the structure is chaotic, with a dispersed pattern of distribution, this flexible,

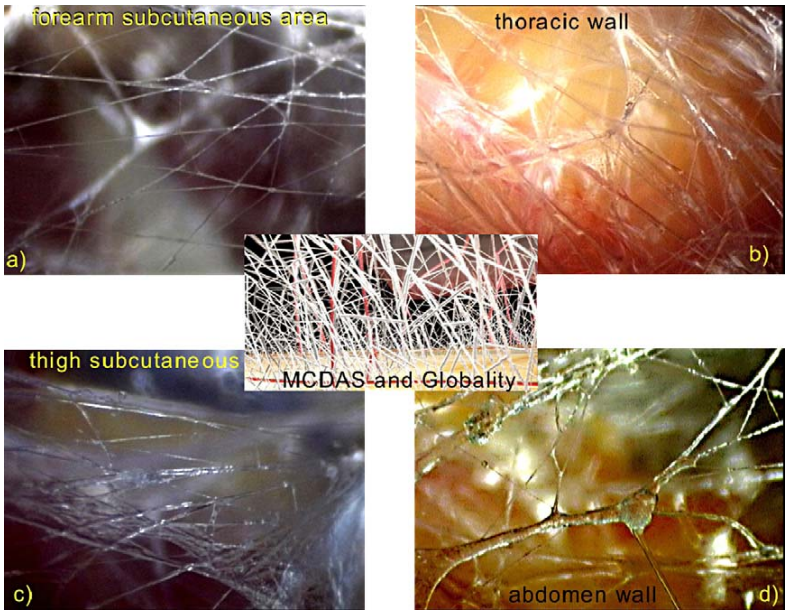

Fig. 17. The absorbing suspension system in different sites: a: forearm subcutaneous area; b: thoracic wall; c: thigh region; d: abdominal wall.

polyhedric architecture is able to assume many shapes, thereby providing stability and efficient sliding.

We are confronted with the dilemma of chaotic architecture and optimal efficiency. Because of the sliding system, traditionally called the paratendon, or areolar, or subsynovial connective tissue (SSCT) (8), the tendon displays optimal sliding and can travel quickly over a long distance without any hindrance, and without disturbing anything around it, allowing the tendon to move freely without transferring the movement to the surrounding structures and without displacing any neighbouring tissue. This accounts for the absence of any dynamic repercussions of the movement on the skin surface.

The bottom line is that the network must ensure its own total movement. Everything must be regulated at the same time, in the same instant, permitting movement while at the same time ensuring shock absorption, which is indispensable to avoid rupture of the mechanical elements within the network. The dynamic consequence must be absolute, and the shock absorption immaculate. The question of how the microvacuolar network behaves as a shock absorber, including the fact that the closest vacuole to the moving structure undergoes maximal deformation while remote structures hardly change shape, remains to be explained. These two apparently conflicting roles must also be accompanied by the spring-back memory function. When tension is applied to the link, the adjacent element undergoes tension and decreases in size little by little until deformation occurs, which is controlled in order to prevent rupture. It seems to be a rubbery, elastic system because its role is to prevent reaching a threshold of resistance at which the collagen might shear. Collagen fibres cannot be stretched indefinitely and may suddenly rupture. Each fibrous element is likely to be connected to its neighbour by a molecular adhesive link under pre-existing internal tissular tension. When stress is applied, the adjoining element may undergo a slightly lesser stress until it attains the required deformation, with the final phase occurring dynamically like the return of an elastic spring due to an apparent state of tissular pretension.

No doubt that these highly efficient flexible pre-stressed fibrillar architectural shapes, associating great mechanical resistance and optimal utilization of matter, are helped by their capacity to take on various shapes that are more stable and adapted to sliding between each other independently. All these sequences of interlacing, intertwining fibrillar structures created by the repetition of movements within other movements, including distension, retraction and division, cannot be accounted for by standard reasoning. The system seems to perform optimally from a thermodynamic point of view as no heat is generated under normal circumstances. This is not the case when tissues are overloaded by abnormal forces, or in the presence of inflammatory pathology, in which case they heat up, become inflamed and oedematous, with changes occurring within the tissue.

Due to the nature of the fibrils arrangement in a chaotic or dispersed pattern, with their three mechanical potentialities, and due to the hydrophilic nature of the GAG in the extracellular matrix, the microvacuole (which is a microvolume) is able to adapt, change form, and return to its original form due to its existing state of pretension. The MVCAS therefore displays chaotic patterns and multi-adaptive efficiency.

The high proteoglycan content with important viscoelastic properties allowing fluid-like tissue distortion gives the sliding system its unique characteristics; it is also the main reason it can only be reliably demonstrated in living or fresh tissues.

Above all, the phenomenon needs to be examined in three-dimensions. This suggests the presence of a viscous fluidity or viscoelasticity capable of fusion and distraction, most likely due to the presence of covalent bonds. Their role is undoubtedly

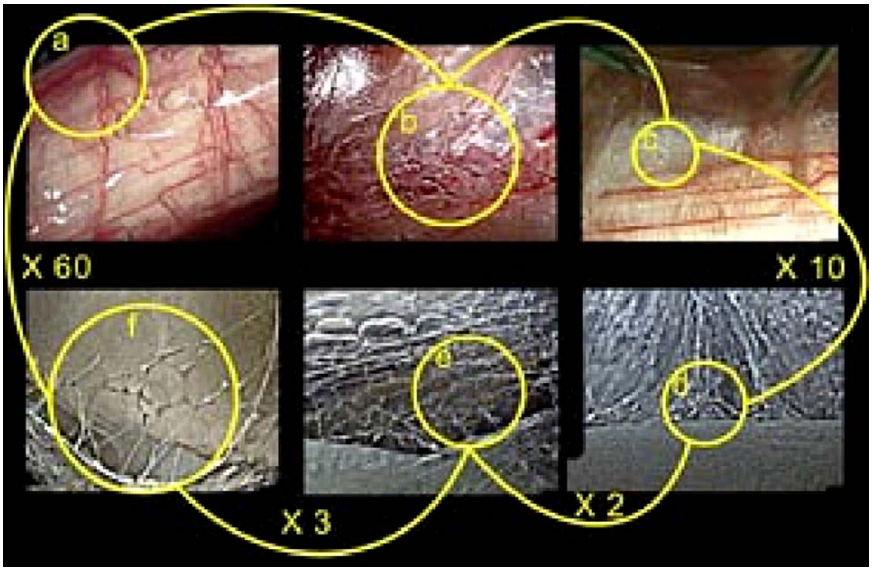

Fig. 18. Progressive 60-fold enlargement of peritendinous area from the macroscopic to the pre-molecular conveys an idea of the total tissue continuity of the sliding system with tendon.

to lubricate and nourish the fibres, and also to absorb pressure, with their strong negative charge attracting counter-ions and water molecules into the tissue. This endows the proteoglycans with unique physical characteristics, allowing them to fill the intravacuolar spaces and to change shape when required, while maintaining constant volume.

The molecular and fibrillar capacity of this tissue provides answers to the questions arising from our microscopic observations in vivo.

4.4. A global system

This internal multifibrillar and microvacuolar architecture is too repetitive to be ignored. Seen in these terms, the whole structure of the body may be considered an immense collagen network. Going from the macroscopic to the limits of the microscopic, this network can be seen to stretch continuously from the peritendinous surface to the finest multimicrovacuolar organization, the ultimate boundary of the mesosphere, before entering the realm of molecular dynamics. Consequently, the entire dynamic and structural continuum may be explained and represented (Fig. 18). It may even be that this fundamental system obeys dynamic and biomechanical principles that are subject to influences other than gravity.

4.5. Anatomical features

Therefore, the sliding mechanism cannot be compared to a piston.

This complex sliding system meant to transmit forces must be resistant and able to adapt to basic environmental and mechanical requirements. It must be able to conserve its mobility while maintaining its architecture and adapting to the mechanical demands imposed on it.

It is therefore modified depending on changing circumstances, and is subjected to the natural laws of change.

This type of microvacuolar sliding we described within a multimicrovacuolar framework can be seen in zones III, IV and V, but it turns rapidly, for mechanical reasons, to a different system in zones I and II as a megavacuole with different physiological rules. Such transformation observed in the digital canal seems to be an efficient adaptation of the multimicrovacuolar sliding system. The digital sheath and the carpal sheath share the same original mechanical behaviour but each has its own specific form and means of differentiation. A new layout of the sliding sheaths in the finger flexion system can be proposed, and the traditional tree trunk configuration has to be revised.

5. Conclusion

In summary, the very notion of virtual space between the common carpal sheath and the flexor tendons, the absence of any connecting tissue and especially vascular tissue must be completely reconsidered, as well as the widely accepted notion of sheaths in the hand. In our opinion, these visions have resulted from hasty anatomical observations performed on cadavers or formalin-treated ones. A different view of the sliding system is therefore necessitated. This sliding tissue system has long been abandoned by research. Its basic framework is the multimicrovacuolar network, which initially seems chaotic and complex. This network comprises a set of elements containing many non-linear interconnections organized with one final objective in mind: to promote life by facilitating sliding adaptation and mobility. Future research in molecular biology and the chemistry of proteins must examine the behaviour of these basic structures of the human body, which, for too long, have remained neglected owing to their apparently self-evident nature.

Appendix A. Supplementary data

Videos associated with this article can be found, in the online version, at doi:10.1016/j.main.2010.04.002.

Conflict of interest statement

The authors have not declared any conflict of interest.

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