PhD theses

Biomechanics of the flexor tendon sheath of the long fingers

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Introduction

The role of the tendon sheath and the necessity of its restoration after flexor tendon injuries of the fingers have been subjects of debates among researchers during the last decades.

Surgery on the flexor tendons of the fingers necessitates an approach through the tendon sheath. Efforts are directed toward preserving or restoring the ligamentous elements of the sheath, due to the importance of the integrity of the pulley system with respect to functional outcome, according to numerous anatomical, biomechanical, and clinical studies. The significance of preserving the membranous sheath, however, has remained unclear.

Proximal gliding of the flexor tendons in the fingers results not only in bending but also in shortening of the tendon sheath. During flexion, the closing pulley system eventually forms a purely ligamentous tunnel. Because axial shortening of the pulley elements is limited during flexion, the vast majority of the shortening occurs as a result of folding of the membranous parts on the outer aspect of the ligamentous tunnel. The controlling mechanism of the folding and unfolding of the membranous sheath has not yet been studied in detail.

Aims

We have aimed to

1. investigate of the anatomy and the physiologic movements of the human flexor tendon sheath,

2. modeling the impact of the pathologic changes in the biomechanics of the tendon sheath after trauma or flexor tendon surgery,

3. define the direction toward a minimally invasive tendon surgery in the light of the biomechanics of the sheath and the surrounding tissues.

I. Human anatomy and biomechanics

1. Tenography of the flexor tendon sheath

Materials and methods

Tenography has been performed on eight long fingers of fresh cadavers after disarticulation at the carpometacarpal joint. Lateral views were examined after filling the sheath with different amounts of contrast material. Series of films were taken at several joint positions including extension and full flexion. Further two hands were examined without disarticulation of the fingers.
Joint positions, distance of the flexor tendons from the joint axes, and the displacement of the proximal cul de sac were measured and recorded.

Results

The tenographic appearance of the tendon sheath was dependent on the filling volume of the contrast material. The ligamentous structures were identified as lack of filling on the palmar aspect of the sheath. 0.2 ml of contrast material filled the synovial recesses only, while 0.5 ml volume depicted the membranous parts as cuffs around the flexor tendons. Flexion and extension of the fingers revealed a pump mechanism between the proximal cul de sac and the membranous pockets in the free finger. Straight bridging of the flexor tendons was found above the PIP and DIP joints between 40 to 80 degrees and 40 to 60 degrees respectively, thus indicating no loading of the pulleys above these joints. The moment arm of the flexor tendons above the MP, PIP and DIP joints proved to be increasing by one third during flexion.

2. Macroscopic studies on the inner surface of the flexor tendon sheath

Materials and methods

18 long fingers of fresh cadavers have been examined using fine instruments, binoculars and operating microscope. Methods included creating bone windows through the phalanxes and removal of the flexor tendons in order to observe the undisturbed movements of the sheath. Movements of the sheath were also observed

through direct lateral access. Finally the skin-subcutaneous tissues-sheath flap was examined after removal from the rest of the finger. Special attention was paid to the folding of the membranous sheath and sliding the pulley system during the passive flexion-extension of the joints. Movements of the sheath were recorded on photos and video films.

Results

The pulleys and the membranous sheath were easily distinguishable through the bone windows created across the phalanxes.
Passive flexion of the PIP and DIP joints resulted in gradual disappearance of the synovial lining on the outer aspect of the forming ligamentous tunnel. At full flexion the newly formed synovial recesses could be visualized by probing the interligamentous spaces. The palmar folding of the synovial sheath was a consequent phenomenon during several repeated flexion and extension of the joints. Inward folding or catching of the synovial lining between the ligaments has never occurred. Sliding of the proximal lashes and the central crossing part of the C1 pulley behind the distal edge of the A2 pulley on its outer aspect was observed in one index and two middle fingers.
The direct lateral approach also revealed synovial pockets at the distal edge of the A2 pulley in all of the examined fingers except one small finger, while at the proximal edge of the A1 pulley in one index, one ring and one small finger.
Sliding of the proximal part of the C1 pulley behind the distal edge of the A2 one was observable from this lateral view as well.

3. Experimental direct lateral approach

Materials and methods

An approach to the flexor tendons in the midlateral line of the fingers, without elevation of the skin – subcutaneous tissues flap, have been performed on three index and two middle fingers of cadaver hands. The approach left a one – one and a half millimeter of the edge of the sheath undisturbed for suture anchorage. The deep flexor of the finger concerned was axially loaded until full flexion after closure of the sheath with 5/0 monofil suture material. Then the suture line was examined from inside through a palmar midline incision.

Results

The undulating course of the flexor tendon sheath is much different from the straight line of the midlateral skin incision in the extended finger. For this reason safe opening of the sheath can be started only at those parts where it is anchored directly to the bony frame, i.e. at the distal end of the A2 or at the A4 pulley. When the sheath cavity entered, the further incision is guided by the sheath itself.
The remaining edge of the sheath provided a safe closure of the sheath. The suture line was found intact when examined from inside after loading of the deep flexor tendon.

4. Examination of the subcutaneous fibrous system

Materials and methods

Two cadaver hands were detached at the wrist level. The radial and ulnar arteries were cannulated, and the hands were perfused with buffered formalin at 30 cm water pressure. The fingers of the first hand were fixated in full flexion, while those of the second hand were left semiflexed or kept in full extension. After fixation, the finger rays were detached at the metacarpal base level. The bent index, middle, and small fingers were cut in the sagittal midline using a knife and a power saw. The cut surfaces were stained with picrosyrius red and examined under the operating microscope. The same procedure was followed on one semiflexed index and one extended small finger. The palmar soft tissues of the semiflexed middle and ring fingers were removed as one unit at the lateral midline level and cut into 3-mm slices perpendicular to the long axis of the fingers. The slices were stained on both surfaces with picrosyrius red and examined under magnification. The palmar soft tissues of one middle and one index finger amputated due to trauma were fixated and embedded in paraffin. Representative transverse sections were stained with hematoxylin and eosin and examined under the microscope.

Results

The sagittal sections disclosed different patterns of the picrosirius red stained septa of the subcutaneous fat pads over the proximal and middle phalanxes depending on the bent position of the fingers. In the finger fixed in extension the wider septa were straight, running obliquely from the tendon sheath to the skin. The main septa showed

a curved course in the semiflexed finger, while at full flexion those were positioned nearly perpendicular to the sheath.
Probing of the specimens revealed strong adherence of the subcutaneous tissues to the membranous sheath. On the other hand the connection between the A1, A2, A3, A4 pulleys and the subcutaneous tissues was very loose.
In the vicinity of and proximal to the distal interphalangeal joint crease the main septa outlined closed compartments of the subcutaneous fat on the transverse sections. A septum originating from the sheath in the sagittal midline was a frequent finding between the distal interphalangeal joint crease and the proximal digital crease but it was not well demonstrated in the vicinity of the palmar creases. In some occasions crossing of its fibers could be demonstrated.
No septa running perpendicular toward the lateral aspect of the skin were found on the transverse sections. The ones going round the neurovascular bundle on its palmar aspect were originating close to the midsagittal line of the tendon sheath and were curving dorsally and arborizing before reaching the dermis at the level of or dorsal to the palmar digital artery.
Probing of the sheath-subcutaneous tissue interface of the transverse sections resulted in similar findings as of the sagittal ones. The subcutaneous tissues were not easily separable from the pulleys at the membranous regions, while slices of the A2 and A4 pulleys were frequently kept in place only by their connections at their origins.
The hematoxylin and eosin stained light microscopy sections under low magnification showed great similarity to the picrosirius red stained macroscopic sections in terms of the septal arrangement of the palmar soft tissues.
Intermediate magnification revealed collagen bundles in the septa, frequently arranged as layers. These bundles were different from the fibers enclosing the fat lobules as the bundles were more homogenous, more oriented and more intensely stained by hematoxylin. Parallel, layer forming orientation of the collagen bundles was typically observed in length of 600 to 1000 μm, but even 2500 μm long septum-like such a structure was also found. The collagen bundles were found close to the tendon sheath, in the mid-substance of the fat pad and close to the skin too. Their merging with the membranous sheath was commonly seen while above the pulleys those ended in a layer of fibrous tissue rich in vessels which ran parallel with the pulleys.

Based on the findings a model of the palmar soft tissues between the proximal interphalangeal and distal interphalangeal palmar creases of the fingers was created, in which the subcutaneous fibrous system controls the folding and unfolding of the membranous sheath. The key elements of the model are the membranous sheath, the fat pad, the skin and the subcutaneous fibrous system connecting the membranous sheath to the skin. Deformation of the fat pad during joint flexion results in bulging of the skin which in turn tightens the corresponding parts of the subcutaneous fibrous system, including the Grayson's ligaments (Fig 7 and 8). The resulting effect is the palmar and lateral folding of the membranous flexor tendon sheath in accordance with the joint position.

5. Scanning electronmicroscopy of the human flexor tendon sheath

Materials and methods

Index finger amputated due to trauma has been fixated in 10 % of formalin. After fixation 2x2x5 mm tissue blocks containing of the inner surface of the sheath as well have been cut off from the palmar soft tissues. The samples were postfixated in glutaraldehyde, dehydrated in series of ethanol, and after critical point drying coated with gold. Scanning electron microscopy was performed using a 100C/ASID-4 instrument.

Results

Examination of the pulley – membranous sheath transition revealed rounded edge of the ligaments even at those structures where macroscopic observation found an even surface. This finding indirectly supports the concept of controlling of memebranous sheath by the subcutaneous tissues.
The inside surface of the pulleys showed a ribbed pattern perpendicular to the long axis of the finger. The significance of this finding is not clear but might be in kinship with a mechanism described in some animal species where a locking mechanism between the flexor tendons and the sheath is capable to relieve the load on the muscles.

II. Model studies on the toes of chicken

Materials and methods

Midlateral approaches have been performed on 16 middle toes of eight chicken. On the left the skin and subcutaneous tissues were elevated before opening the flexor tendon sheath. On the right the skin, subcutaneous tissues and the sheath were raised as one compound flap. Then transverse incisions were done to model a wound caused by injury. After closure of the sheath with monofil suture material and the skin with interrupted stitches the toes were left to move unrestricted. The pairs of toes were examined from the second up to the tenth postoperative weeks. Changes of the viscoelastic resistance of the toes were studied by loading the longest flexor tendons with different forces. The palmar soft tissues were examined by macroscopic observation. Light microscopy specimens were stained with hematoxylin and eosin as well as samples were studied by scanning electron microscope.
In a second series of experiments the same surgery was performed as above but only on one side in twelve chicken. The viscoelastic properties of the operated toes were compared to the intact toes on the opposite side. Continuous 10 mm/min traction was applied by a mechanical actuator on the longest flexor tendon through a tensile load-transducer. The traction force was registered as a function of the tendon excursion on an X-Y recorder.
Functional anatomic observations were performed on four middle toes of roosters. The inner surface of the flexor tendon sheath was examined through direct lateral approaches. The anatomy of the pulley system and the movements of the membranous sheath were recorded.

Results

In both series of surgeries the viscoelastic resistance of the toes operated by elevation of the subcutaneous tissues from the tendon sheath showed an increase around the fourth postoperative week when compared to the ones where midlateral approach to the flexor tendons was utilized. This difference could not be demonstrated in the immediate postoperative period and gradually disappeared by the tenth postoperative week.

Difference in the position of the scarring of the subcutaneous tissues was demonstrable in the transverse sections macroscopically, by light microscopy and scanning electronmicroscopy as well. The dynamics of the scar formation was found parallel with the changes of the viscoelastic resistance of the toes.
The functional anatomic studies on the inner surface of the chicken toes revealed a synovial pocket formation similar to the one found in human fingers.

III. Human clinical studies

1. Magnetic resonance imaging

Materials and methods

MRI examinations have been performed on 22 fingers of 13 patients and two healthy volunteers. One study was performed preoperatively, six between the 6-10., eight between the 10-12., five between the 26-158. postoperative weeks, respectively. Surgeries performed before the examination included deep flexor tendon suture in eight, deep flexor tendon reinsertion in one, free tendon grafting in two and silicon rod implantation in one case. Head, wrist and TM joint surface coils were used with 1,5 Tesla Siemens Magneton and 1,5 Tesla Signa instruments. Predominantly the T1 weighted sagittal, coronal and transversal sections were evaluated.

Results

The course of the flexor tendons and the sheath in the extended and bent positions of the fingers was found in accordance with those of the tenographic findings.
The position of the tendon stumps could be localized properly by the preoperative examination. Scar formation in late postoperative cases could be localized dorsal to the flexor tendons. The site of the subcutaneous scar formation was depicted well after direct lateral approach. The MRI examination also revealed the pulley insufficiency through the increased distance between the flexor tendons and the corresponding phalanx.

2. Endoscopy of the tendon sheath

Materials and methods

Endoscopy of the sheath has been performed during flexor tendon surgery of three patients. The surgeries consisted of second phase of flexor tendon grafting in one and late flexor tendon reconstruction in two cases. The inner surface of the pseudosheath and the possibilities of endoscopic recanalisation of the injured sheath were examined using rigid and flexible endoscopes (Storz).

Results

Observation of the inner surface of the flexor tendon sheath proved to be possible by endoscopy. Retraction of tendon graft into the sheath could be performed using forceps through the instrument channel of the endoscope. Recanalisation of the sheath however seems to be possible only after further improvement of the instruments.

3. Direct lateral approach of the flexor tendons

Materials and methods

Late primary sutures of flexor tendons have been performed through direct lateral approaches on one index, ring and little fingers of three patients. The approach was started at the distal end of the A2 pulley. The incision of the sheath was extended distally and involved the A4 pulley in two cases. After the tendon sutures the sheath was closed with running monofilament suture and early controlled mobilization was started postoperatively.

Results

The flexor tendon sutures performed by utilizing the direct lateral approach resulted in surgical success. However the method proved to be technically difficult and its use had to be limited to the injuries which occurred in the vicinity of the PIP joint. Further improvement of this minimally invasive approach can be expected by development of a similarly minimally invasive tendon suture.

New results

1. The moment arm of the flexor tendons is increasing during the finger flexion above the MP, PIP and DIP joints.

2. The pulleys above the PIP and DIP joints resist only cyclic loading.

3. The pulleys slide upon each other in addition to their closure during flexion of the finger.

4. Flexion and extension of the finger results in a mixing effect of the synovial fluid.

5. The controlling mechanism of the movements of the membranous sheath is located in the subcutaneous tissues.

6. The subcutaneous fibrous system adheres predominantly to the membranous flexor tendon sheath.

7. Deformation of the palmar fat pads guides the subcutaneous fibrous system and this deformation results in the folding of the membranous sheath.

8. The folding pattern of the inner surface of the flexor tendon sheath in chicken toes is similar to that of the human fingers.

9. Model studies in chicken toes indicate that conventional approaches themselves result in a temporary deterioration in the mobility of the toes.

10. Flexor tendon surgery can be successfully performed through the so called direct lateral approach under certain circumstances.

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