



HAL
open science

Tendon networks for artificial ligamentous joints : methods, materials and characteristics

Nick Hockings, Pejman Iravani, Chris R Bowen

► **To cite this version:**

Nick Hockings, Pejman Iravani, Chris R Bowen. Tendon networks for artificial ligamentous joints : methods, materials and characteristics. 2014. <hal-01114009>

HAL Id: hal-01114009

<https://hal.science/hal-01114009v1>

Preprint submitted on 6 Feb 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-ND 4.0 - Attribution - No Derivative Works - International License

Tendon networks for artificial ligamentous joints : methods, materials and characteristics

Nick Hockings, Pejman Iravani and Chris R. Bowen

Abstract—This paper presents a novel method for making tendon networks for robots with ligamentous joints. Unlike tendons commonly used in robots, this technique emulates the material properties and mechanisms of vertebrate tendon networks.

Hyperelastic gels are used as solid lubricants for finite shear, and as matrices for highly anisotropic fibrous soft composites. Flexible composite structures are used to create compact robust compliant mechanisms. Differential miscibility and adhesion of thermoplastics are exploited to control the formation of cavities which facilitate flexion of the mechanisms.

Emulations of the flexor and extensor tendon networks of a human finger and of the paw of a dog were used to qualitatively demonstrate the class of mechanisms and materials. The work shows that it is feasible to produce synthetic composites that approximate the material properties and mechanisms of anatomical tendon networks. Much scope remains to refine the materials and layup techniques.

This approach is expected to be useful for building service robots and for evaluating biomechanics.

I. INTRODUCTION

Tendon actuation is found extensively in vertebrate anatomy. It offers a way to produce compact lower limbs and digits with beneficial underactuation, but requires stabilisation of tendon paths. Tendons are used in many robots in legged locomotion, flexible spines and humanoid hands, however artificial tendons suffer problems of fatigue failure and friction.

Artificial ligamentous joints, as described in [10] require compatible tendon networks and retinacular ligaments to hold the tendons in their correct paths.

This paper presents a method for making tendons that closely match the mechanical properties of the materials and the mechanism of anatomical tendon networks.

A. A brief review of tendon actuation in robots

Tendon actuation is widely used in robotic hands, primarily because it allows the actuators to be situated outside the hand, thereby avoiding the space constraints of intrinsic actuators. However the tendon materials and networks used in robot hands differ substantially from anatomical tendon networks in the composition of the tendons and how they are guided.

The Anatomically Correct Testbed (ACT) hand [4] is the exception in that it sets out to reproduce the topology of human digital extensor tendons. The tendons are braided Spectra^(TM) ultra high molecular weight polyethylene

(UHMW-PE) strings. The extensor hood is implemented by a crocheted nylon structure which aims to reproduce the tension distribution of the anatomical extensor hood. The retinacular constraints are partly implemented by rigid eyelet tendon guides.

The DLR Hand Arm System [9] has a full dexterous hand-wrist system with all actuators located in the forearm. The tendons are braided UHMW-PE. An elaborate system of rolling tendon guides maintains low friction, while incidentally minimising under-actuation at the wrist. Thirty eight tendons are used to actuate the DLR IV hand, as compared to approximately 34 intrinsic and extrinsic muscles of human hands (depending on individual variation and choice of nomenclature).

The IIT/Pisa Soft Hand [3] is a highly under-actuated hand capable of forming strong power grasps on a wide range of objects. It uses a single flexor tendon acting in series through all its fingers, opposed by elastic extensors on each joint. Except for its pulley wheels it is a largely 3D printed structure, that uses low friction Hill-Berry rolling contact joints.

The ‘Highly Adaptive SDM hand’ [6] uses an under-actuated flexor tendon in each finger, opposed by the viscoelasticity of the flexural joints. The mechanism exploits ‘Shape Deposition Manufacturing’ (SMD) to produce a multi-material composite, with additional insert components embedded in the structure. This is a multi-step thermoset casting process.

The MIT Cheetah [1] uses tendons to actuate its joints while minimising bending loads on the compression bearing bones. This emulates the function and geometry of the tendon-bone relationship in vertebrate locomotor apparatus. The tendons of the MIT Cheetah are made from Kevlar(TM) polyaramide braided webbing, and attached by implanting into the bone during the resin transfer moulding manufacture of the bones. The bones are made from thermoset polyurethane resin with a foam core and solid shell akin to the spongy core and lamellar cortex of vertebrae bones.

1) *Difference between robot and anatomical tendons:* Stabilization and control of friction are critical in tendon networks. All of the robot tendons described above use rigid constraints and minimise sliding contact to avoid friction. These tendons are made of spun, braided cord or webbing. This differs markedly from anatomical tendons, which are composed of parallel fibres held together in a hierarchy of bundles by endotendon matrix and epitendon fibrous membrane. Anatomical tendons are in continuous contact with surrounding tissues along their length. They are enveloped

*This work was supported by UK EPSRC DTA

¹ Department of Mechanical Engineering, University of Bath, BA2 7AY, The United Kingdom. N.C.Hockings@bath.ac.uk

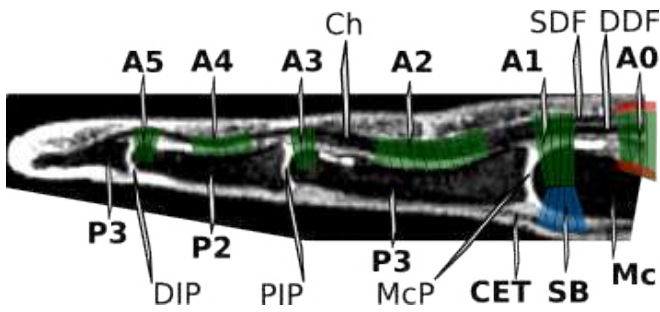


Fig. 1: The undulating path of the flexor tendons of a finger in the extended position seen in an MRI scan, palm upwards in sagittal section. The location of the retinacular ligaments is superimposed on the scan. Labels: A0 'zeroth' annular ligament is formed by the transverse fibres of the superficial palmar fascia and the septae of Legueu and Javara, A1-5 Annular retinacular ligaments, P1-3 phalanges, Mc metacarpal bone, DIP distal inter-phalangeal joint, PIP proximal inter-phalangeal joint, McP metacarpo-phalangeal joint, CET common extensor tendon, SB sagittal bands, DDF deep digital flexor tendon, SDF superficial digital flexor tendon, Ch chiasma where DDF passes between the branches of the SDF. Note the DDF inserts on P3, while the branches of the SDF insert on P2.

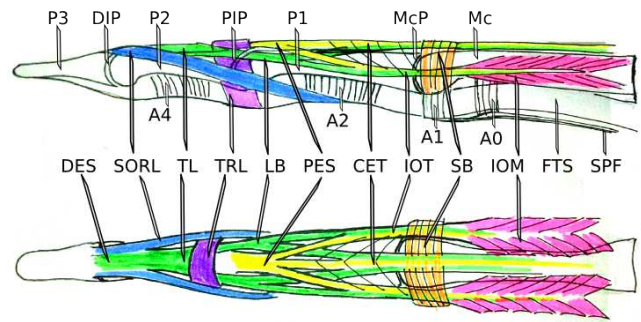


Fig. 2: Topology of extensor tendon hood of the finger, lateral view palm downwards (top), dorsal view (bottom) : A0-5 Annular retinacular ligaments, P1-3 phalanges, Mc metacarpal bone, DIP distal inter-phalangeal joint, PIP proximal inter-phalangeal joint, McP metacarpo-phalangeal joint, DES distal extensor slip, SORL spiral retinacular ligament, TL triangular ligament of DES, TRL transverse retinacular ligament, LB lateral band of DES, PES proximal extensor slip , CET common extensor tendon, IOT inter-osseous tendon, SB sagittal band, IOM inter-osseous muscle, FTS flexor tendon sheath, SPF logitudinal fibres of superficial palmar fascia.

in soft tissue either hyperelastic peritendon loose connective tissue, or fluid lubricated synovial tendon sheaths and bursae formed by extension of the capsule of synovial joints. Unlike Bowden cables, tendon sheaths do not bear compression along their length.

B. Anatomical structures

It has been believed that the materials are not available to allow direct emulation of musculoskeletal fibrous soft tissue structures [5]. It is the purpose of this paper to demonstrate a set of materials that can be used to reproduce the mechanical properties and structures of sheathed and unsheathed tendon networks. The material and mechanical structure of the bodies of vertebrates have been extensively studied in the anatomical sciences. Developing equivalent synthetic materials allows this knowledge to be exploited for robotics.

It is important to appreciate the dominant role of fibre topology and elastic matrices in musculoskeletal tissues. Normal variation in healthy bodies shows the strength and stiffness of tissues can vary by an order of magnitude without disrupting the function of anatomical structures, e.g. hands are fully functional before calcification of the bones of the wrist in late childhood. The critical material factors of joint and tendon mechanisms are strain tolerance and relative stiffness differing by several orders of magnitude between different tissues or directions within fibrous structures.

The anatomy of human hands and dogs paws were used as the template for the demonstration specimens in this paper. Despite their differences of proportion, these share the same topology of bones, ligaments and tendons. This

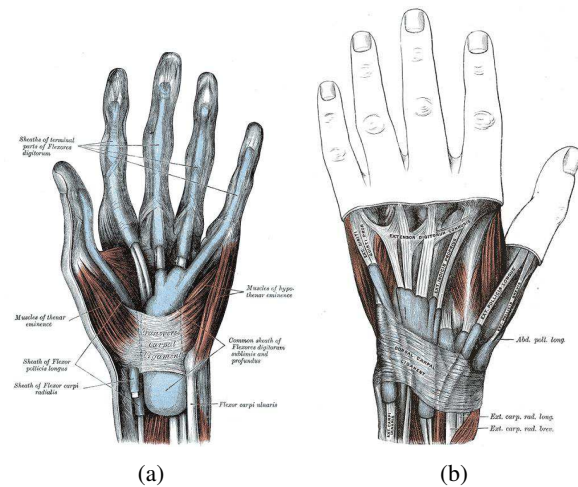


Fig. 3: From Gray(1918) [11] figs 423 & 424 (available on-line at <http://www.bartleby.com/107/126.html#i423>). Tendon sheaths of the hand (a) palmar, (b) dorsal. The tendons are unsheathed in the forearm, mid palm, and distal to the wrist (carpus) dorsally. Note the how the carpal tunnel collects the flexor tendons on the palmar surface of the wrist, causing the fingers to converge when flexed.

section describes the structures that were emulated.

1) *The digital flexor apparatus*: The digital flexor tendons are by far the strongest tension bearing structure in the hands, being several times greater in cross section area than any of the other tendons or ligaments. They connect the extrinsic digital flexor muscles in the forearm to the distal phalanges (deep digital flexor tendon) and the middle phalanges (superficial digital flexor tendon). Consequently they underactuate flexion of all the joints of the fingers, palm and wrist (carpus).

This underactuated tendon topology gives rise to important reflexes [12] - passive dynamic behaviours due to kinematics.

- Pressure at any point on the palmar surface of the hand extends the carpus, and flexes the joints distal to the point of contact, causing the hand to hook around the object,
- The flexor tendons fan out from the carpal tunnel (fig.3a,5a) to the metacarpo-phalangeal (MCP) joints, causing the finger tips to converge when flexed, forming a cage around any object on the palm,
- Flexion of the small and ring fingers also flexes their carpo-metacarpal joints, making the palm concave.

The flexor tendons are lubricated by a synovial tendon sheath (fig.3a) [8] in the fingers and a bursa at the carpus. The sheath is composed of a thin fibrous membrane that is closely adhered to the annular ligaments (fig.1). Between the annular ligaments the sheath is stabilized by a second lighter set of cruciate ligaments.

The digital flexor tendons are held in their correct path by a series of annular ligaments known as "the pulleys of the digits" [7], the palmar fascia (septae of Legueu and Javara, and transverse fibres of the superficial palmar fascia) [2], the transcarpal ligament, and the antebrachial fascia of the distal forearm [15]. Of these the strongest and most critical are the transcarpal ligament, the second and fourth annular ligaments of the fingers.

The annular ligaments are shaped longitudinally such that when the fingers are maximally flexed, the tendons form a smooth helix - thereby maximising the radius of bending of the tendon at all points along its length. The first, third and fifth annular ligaments are located on the palmar plates of the metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints respectively. When these joints are extended the volar plates push the flexor tendons palmar relative to the second and fourth annular ligaments so that the tendons lie in an undulating path (fig.1). This arrangement helps to ensure that the tendons apply torque to the joints throughout their range of motion.

The annular ligaments also serve as the attachment point for other structures. The spiral oblique retinacular ligament (fig.2) [17] originates from the palmar side of the second annular ligament on the proximal phalanx. It passes palmar to the proximal inter-phalangeal joint (PIP) and dorsal to the distal inter-phalangeal joint (DIP), before inserting in the distal extensor slip. The mechanical effect being to limit the phase difference between the flexion of the PIP and DIP.

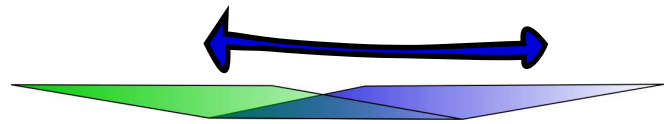


Fig. 4: Elastic shear lubrication : a hyper-elastic lamina with elastic limit 1000% can permit shear $2 \times 1000\%$ times the thickness of the lamina. So a 0.5mm thick layer can lubricate 10mm of tendon excursion. This technique is essential for reproducing the movement of unsheathed anatomical tendons including the digital extensor hood.

The transverse retinacular ligament [14], originates at the level of the third annular ligament on the PIP, and passes dorsally over the finger, stabilising the lateral and medial branches of the distal extensor slip, close to the axis of rotation of the PIP. The ligaments of the skin of the fingers attach to the fascia of the flexor apparatus including : the septae of the digital pads (Grayson's ligaments), palmar crease ligaments, the ligament of the finger webs (natatory ligament), and Cleland's ligaments [19](constraining the lateral margins of the digital pads).

2) *Digital extensor tendons*: The digital extensors have a synovial bursa at the carpus (fig.3b) [16] where they pass under the carpal extensor retinaculum, otherwise their movement is lubricated (fig.4) by hyperelastic peritendon tissue.

The extensor hood of the digit (fig.2) [13] is composed of fibres from the extrinsic extensor dorsally and interosseous tendons laterally, inserting onto the proximal and distal extensor slips of the middle and distal phalanges. At the MCP the interosseous tendons pass through short tendon sheaths. The sagittal bands arise from the first annular ligament, pass over the interosseous sheaths and bind to the extrinsic extensor tendon. A layer of hyper-elastic connective tissue beneath the sagittal bands allows the extrinsic extensor tendon to slide over the MCP, while the bands stabilise it laterally.

The extensor hood is stabilised over the dorsal surface of the digit by the triangular ligament of the distal extensor slip, the transverse retinacular ligament [14] and the interosseous hood - composed of fibres connecting the interosseous tendons [13]. Collectively the mechanism has been described to perform 'anatomical computation' [18] "that nonlinearly enables different torque production capabilities".

II. MATERIALS

A. Fibres and rigid thermoplastics

The tendons and associated retinacular structures were laid up over ligamentous joints, composed of polylactic acid (PLA) 3D printed bones coated in polycaprolactone (PCL) and connected with polyamide fibre ligaments, described in [10]. Tows of parallel non-spun polyamide fibres approximately 25 microns in diameter were used for the tendons and ligaments (polyaramide Kevlar, and polyamide-6,6).

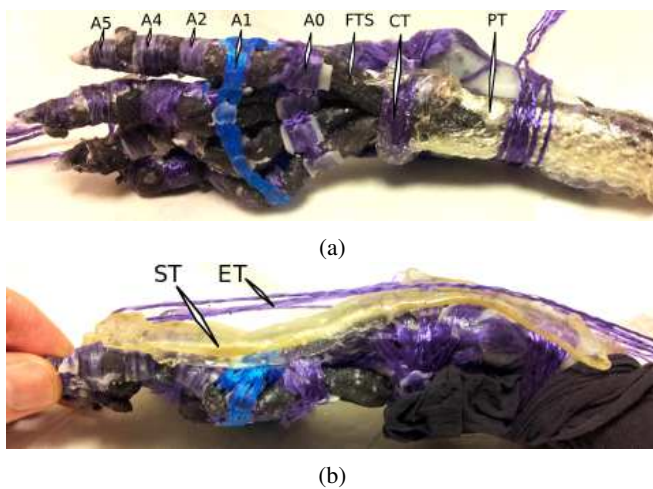


Fig. 5: (a) Paw palmar aspect showing: FTS flexor tendon sheaths, A0-5 annular retinacular ligaments, CT carpal tunnel, and PT peritendon tissue (SEBS-gel) in the forearm. (b) Paw lateral aspect during manufacture, showing: ST soft tissue layer (SEBS-gel) separating ET extensor tendons from underlying skeleton.

B. Hyperelastic Gels

The technique developed here exploits a thermoplastic hyper-elastic gel in homogeneous layers as a solid elastic lubricant and as a matrix for anisotropic composites. The gel used is based on partial solution of Styrene-Ethylene-Butene-Styrene (SEBS) co-block polymer rubber [Elasto 180] in paraffinic oil [WD-40 Co Ltd, 3-IN-ONE 'multi purpose drip oil']. The resulting gel permits strains in excess of 1000% extension and shear.

Two stiffer preformulated SEBS oil-gels were also used, Elasto Dryflex 5000 (Shore A 0 hardness) and Dryflex 880101 (approximately Shore A 40 hardness).

1) *Hyper-elastic solid lubricant*: Varying the ratio of oil to SEBS polymer results in different grades of gel. As the oil content increases the strength and stiffness decrease. Very soft high oil content gels can be used as solid hyper-elastic lubricant for motions of finite shear, (fig.4).

2) *Elastomeric composites*: A fibre reinforced composite material was produced by infiltrating the gel into polyester stocking material. The resulting composite remained hyper-elastic but was easier to handle and less prone to tearing than the homogeneous gel.

C. Ionomer thermoplastic elastomers

Poly(ethylene, acrylic acid, acrylate, zinc) ionomer was used when a thermoplastic elastomer immiscible with SEBS was required. Du Pont Surlyn 9320 was blended with paraffin to make tendon sheath membranes, Surlyn 1706 was used to form articular surfaces on condyles.

III. DESIGN OF TENDON NETWORKS

A. Paw

An emulation of a dog's paw (fig.5) and carpus with ligamentous joints described in [10], was fitted with flexor and extensor tendons including palmar fascia and carpal tunnel.

1) *Flexor tendons*: The tendons were attached by clove hitches to the middle (superficial flexor) and distal (deep flexor) phalanges. The polyamide fibres were then infused with a matrix of SEBS-paraffin gel on a hot plate. The matrix of two branches of the superficial flexor were fused together to form the chiasma through which the deep flexor tendon runs, immediately proximal to the insertion of the superficial flexor on the middle phalanx.

The flexor tendons were then wrapped into a tube of SEBS-gel-stocking fabric composite. This was sealed along its length with a soldering iron to form the flexor tendon sheath. Paraffin oil was then infiltrated down the inside of the sheath to lubricate the excursion of the tendons.

The sheathed flexor tendons of all four digits of the paw were then laid along the palmar aspect of the bones, (fig.5a). Annular ligaments of polyamide tows in a PCL matrix were wrapped around the flexor sheaths at the proximal and middle phalanges. Likewise the septae of Legueu and Javara and transverse palmar fascia were formed by wrapping polyamide-PCL tows around the metacarpals. The natatory ligament was formed by a band of polyamide tows connecting the proximal margins of palmar side of the second annular ligament, palmar to the first phalanx.

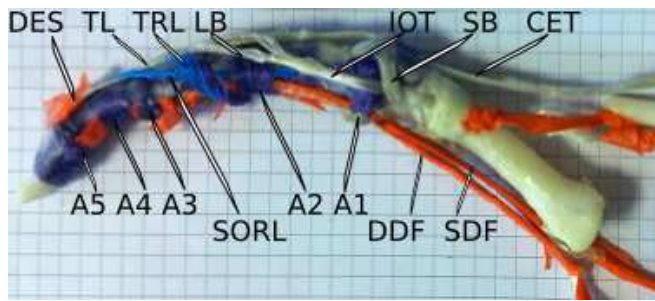
The carpal tunnel was formed by laying the flexor tendons in their individual sheaths across the carpus between the maleolus of the hamate bone and the accessory carpal bone. The transverse carpal ligament was then formed by laying a broad band of polyamide tows across the tendons, connecting the accessory carpal to the hamate.

2) *Extensor tendons*: A layer of SEBS-paraffin gel was laid on the dorsal surface of the paw from the digits to the radius, (fig.5b). The extensor tendons were tied to the distal phalanges, and laid on the gel layer. A series of polyamide tows were then laid orthogonally over the extensor tendons and welded to the annular ligaments on the palmar side of the paw. Lightweight (10 Denier) stocking material was then drawn over the paw. The extensor tendons, orthogonal tows and stocking material were then fused with the gel layer by heating them with a fifty watt halogen lamp until the surface of the gel began to melt.

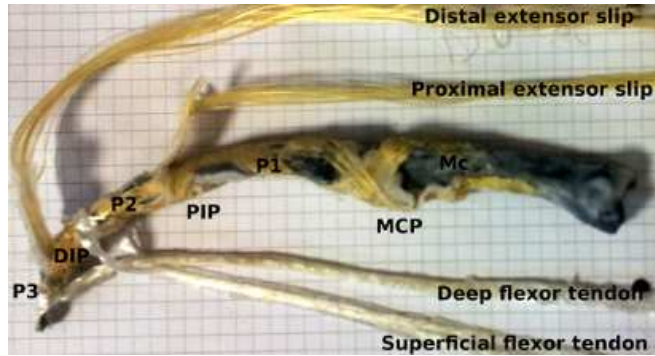
3) *Performance of tendons of the paw*: (See video clip) Both the extensor and flexor tendons provided robust actuation of the carpal, metacarpal, and interphalangeal joints. The major problem with the technique was that several of the joints of the digits were accidentally fused during the attachment of the annular ligaments of the flexor tendons.

B. Finger without soft tissue

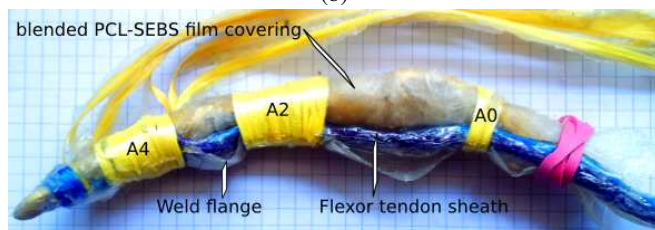
An initial emulation of a human finger was made without soft tissues (fig.6a), to test the layout of the tendon apparatus.



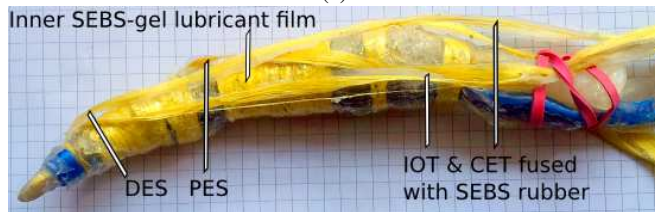
(a)



(b)



(c)



(d)

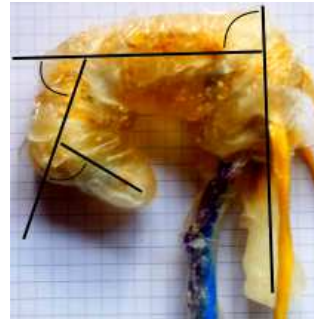


(e)

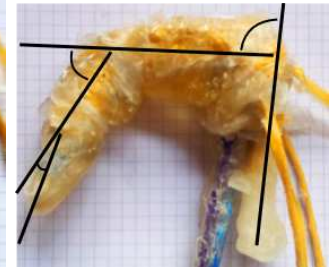
Fig. 6: Layup tendons (a) dry demo, (b) tendons attached & named, (c) flexor sheath, palmar pulley, 2nd and 4th annular ligaments, (d) inner lubricant gel layer under extensor network, (e) outer lubricant gel layer over extensor network. Squares are 5mm for scale. Labels: DES distal extensor slip, TL triangular ligament, TRL transverse reinacular ligament, LB lateral band, IOT interosseous tendon, SB sagittal bands, CET common extensor tendon, SORL spiral oblique reinacular ligament, DDF deep digital flexor, SDF superficial digital flexor, A0-5 annular retinacular ligaments, P-3 phalnges.



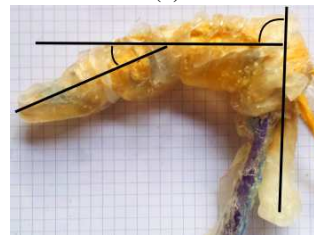
(a)



(b)



(c)



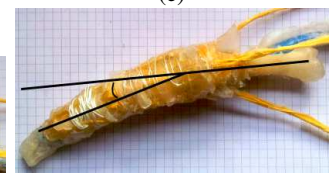
(d)



(e)



(f)



(g)

Fig. 7: Flexion of finger with SEBS-gel pads and SEBS-rubber epidermis (a) Extrinsic extensor and both interosseous tendons contracted, showing gel fingerpads, (b) Deep digital flexor fully flexed, (c) Superficial flexor flexion, (d) Interosseous bilateral contraction, (e) MCP hyper-extension, (f) MCP lateral flexion, unilateral interosseous contraction (g) MCP medial flexion, opposite unilateral interosseous contraction

The phalangeal and metacarpal bones were moulded in PCL and connected with polyamide ligaments as described in [10]. The tendons and retinacular ligaments were made from tows of polyamide, with PCL matrix.

1) *Flexor tendons*: The flexor tendons were made from polyamide tows wrapped in high density polyethylene (HD-PE) film and hot pressed to bond them. This gave a smooth hard surface on semi-flexible thick ribbon-like tendon. These were wrapped in a second layer of HD-PE to form tendon sheaths for each of the annular ligaments.

2) *Extensor tendons*: The triangular ligament of the distal extensor slip, the transverse and oblique retinacular liga-

ments of the extensor apparatus were implemented, but not the dorsal hood connecting the interosseous tendons. The sagittal bands were implemented as a fixed channel through which the extrinsic extensor tendon ran, as opposed to the anatomical sagittal bands which adhere to the tendon and slide with it over the dorsal aspect of the metacarpal condyles. The use of polyamide tendon slips with PCL matrix allowed repeated adjustment of the relative lengths of the extensor tendon network, until a functional network was achieved. Notably the branches of the extrinsic extensor tendon to the distal extensor slip were located more dorsally at the proximal interphalangeal joint than they are often portrayed in anatomy texts, and stabilized in that position by the transverse retinacular ligament.

3) *Performance of finger without soft tissue:* (See video clip) The completed finger skeleton and tendon network was compact, being nearly as slender as the musculoskeletal system of the human finger on which it was based. Despite the low friction of PCL and HD-PE surfaces, the finger required lubricating with paraffin oil in the joints and tendon apparatus to achieve smooth actuation.

The range of motion and of the finger joints and excursion of the tendons matched the normal human range. The mechanism demonstrated that both interosseous muscles and the extrinsic extensor are required to fully extend all the joints of the finger.

C. Finger with soft tissue

A finger tendon network including soft tissues (fig.6b-6e) was laid up on bones and ligamentous joints described in [10]. These joints differed from those in the paw, in that they used immiscible thermoplastics to prevent fusion of the joints during the layup of the tendon network, (method two in [10]). A membrane of SEBS-paraffin gel blended with PCL was wrapped over the ligaments and bones and thermally bonded to them, making the surface adhesive to SEBS (fig.6c).

1) *Flexor apparatus:* Polyamide tows were tied with clove-hitches to the distal and middle phalanges, then infused with SEBS-paraffin gel matrix (fig.6d). The radial and ulnar branches of the superficial flexor tendon were fused together above the deep flexor tendon as before.

The sheath for the flexor tendons (fig.6c) was made from Surlyn 9320 (random copolymer ionomer of poly-ethylene-acrylic-acid-acrylate-Zinc) blended with paraffin to soften it. This produced a soft tough elastomeric thermoplastic membrane that could bond to polyamides, but not to SEBS. This membrane was then wrapped around the flexor tendons and welded closed. The distal end of the sheath was tied to the distal phalanx by the insertion of the distal extensor slip, and welded to it. Paraffin was infused down the sheath to lubricate the tendons.

The annular ligaments were formed by wrapping Kevlar polyamide tows around the phalanges the flexor sheath, (fig.6c). The weld flange of the sheath was folded to the palmar face of the sheath and used to weld the sheath to the annular ligaments. Between annular ligaments the weld

flange was trimmed away to facilitate flexion. The palmar pulley and digital annular ligaments were made in this way.

2) *Extensor apparatus:* The extensor tendons (fig.6d) and associated retinacular ligaments were made from Kevlar tows. The Distal extensor slip was tied with a clove hitch to the distal phalanx and welded to the flexor tendon sheath (see above). The proximal and distal extensor slips were welded to the patellae of the DIP and PIP. The tendon slips were infused with a Dryflex 5000 SEBS oil-gel matrix and pressed flat into ribbons. The bones, joints and flexor apparatus were then wrapped in a membrane of SEBS-paraffin gel, excluding the extensor tendons, to serve as the lubricant layer under the extensor apparatus. This arrangement provided the tendons with a flexible matrix that bound their fibres to each other while allowing them to slide over the underlying bones and joints.

Tendon sheaths for the interosseous tendons at the MCP joints were made with Surlyn-paraffin blend as for the flexor tendon sheath. The sagittal bands were then wrapped around the MCP joint and welded to the first annular ligament, the interosseous sheaths, and the extrinsic extensor tendon, thus stabilising both the interosseous sheaths and the extrinsic extensor, (fig.6e).

The transverse retinacular ligament was laid under the branches of the distal extensor slip, and over the proximal extensor slip at the level of the PIP. The ends of the transverse retinacular ligament were welded to the palmar side of the second annular ligament. The relative lengths of the branches of the interosseous and extrinsic extensor tendons to the proximal and distal extensor slips were then adjusted, before welding the branches to each other and the transverse retinacular ligament to fix their lengths.

Testing the extensor mechanism then showed that the tendon slips were falling too far palmarly on the sides of the flexed finger and failing to extend it. The interosseous hood and triangular ligament of the distal extensor slip were then constructed to correct this, (visible in fig.7g).

A membrane of SEBS-paraffin gel was laid over the branches of the extrinsic extensor, and a second membrane of Dryflex 880101 was laid over this such that the branches of the interosseous tendons to the distal extensor slip lay along the margins of the Dryflex membrane. Polyamide pseudo-monofilament thread was then repeatedly looped around the interosseous slips and dorsally over and through the margins of the Dryflex membrane. This formed an interosseous hood with a smooth stiff Dryflex 880101 face sliding over the underlying extrinsic extensor slips. The triangular ligament of the distal extensor slip was formed in a similar way supporting branches of the distal extensor slip from its insertion to the transverse retinacular ligament.

3) *Dermal structures attached to the flexor apparatus:* The ability to securely attach a structured fibre-gel dermis to the musculoskeletal core of the finger would be essential for producing a functional emulation of a human finger. An initial demonstration of materials was made by constructing simplified digital pads on the palmar side of the finger, (Fig 7a).

The pads were cut from a solid block of SEBS-paraffin gel and positioned on the palmar face of the flexor apparatus over each of the phalanges, and the MCP joint. These were then covered with a membrane of Dryflex 5000 (Shore A 0 hardness). This membrane was then welded to the sides of the finger immediately palmar to the extensor apparatus. The palmar creases were then formed by laying strips of Dryflex 5000 membrane over the palmar faces of the joints, so as to separate the digital pads, and welding these 'crease ligaments' to the lateral faces of the joints.

4) *Performance of soft tissue finger:* (See video clip) The range of motion of the finger for each tendon's actuation is shown by (fig.7).

The finger as built is nearly twice the thickness of the human finger on which it was based. Several faults contribute to this. The gel blocks used for the pads are twice the thickness of the anatomical pads, too soft and lack fibrous septae (Grayson's ligaments). The retrofitted interosseous hood and triangular ligament of the extensor apparatus are too thick, and need to be constructed with thinner membranes and welding instead of sewing. The flexor tendons have too many tows and are twice the diameter of the anatomical tendons. The flexor sheath is thicker than ideal and the weld flange adds to its bulk. The lubricant gel layers of the extensor apparatus were thicker than they need to be.

The finger does not flex as tightly as it should. This is mostly due to errors manufacturing the joints of the finger used for the last iteration of soft tissue tendons.

IV. DISCUSSION

The demonstration pieces were hand built without special tools, consequently the quality control was poor and the build process variable. However they serve their purpose in that they demonstrate a suite of base materials, composites and layup techniques that allow emulation of the mechanical composition and behaviour of vertebrate soft tissue tendon networks and dermal structures. The demonstration pieces have also shown the critical role of hyper-elastic tissues, and precise geometry of ligaments and tendon networks. SEBS-paraffin oil-gels were shown to meet and exceed the softness and hyper-elasticity required to emulate loose connective tissues.

Much better quality control could be achieved with mechanical mixers and rollers for blending thermoplastics and producing thin membranes. Special tools for laying, pressing, fusing membranes would potentially improve build quality and provide the possibility of automating the layup. Automated layup would provide CNC control and repeatability. This however would require a CAD-CAM system capable of modelling very soft hyper-elastic and highly anisotropic materials, and some means of monitoring the build process. This work is in progress and will allow more rigorous testing of mechanisms built with these materials.

V. CONCLUSIONS

The method described provides a way to build known anatomical tendon mechanisms on ligamentous joints. Much scope remains to refine the materials and layup techniques.

The technique is likely to be most competitive versus other robot architectures for complex compact structures such as hands and feet. Here the reproduction of joint and tendon path geometry allows advantageous anatomical kinematics to be exploited, such as the reflexes of the hand. It would also be applicable for building humanoid faces and vocal tracts.

VI. FURTHER WORK

A. Materials

Further development of the materials would include varying co-block-polymers' monomers, side groups and block lengths to facilitate controlled elasticity and adhesion or immiscibility.

B. Actuators

To be useful robot hands built in this way require actuators that would fit into the muscle spaces, and provide substantially similar actuation. This would imply a soft linear actuator, with a fast clutch-release behaviour and low modulus in the relaxed (floppy) state. Alternatively new tendon routes would need to be designed that allowed all the actuators to be extrinsic. For pawed and hooved feet this is not a problem because the anatomical tendons are extrinsic.

Work is in progress on a bulk MEMS fibrous iterative linear electrostatic actuator set in SEBS-gel that would be suitable for the intrinsic muscles of the hand.

C. Sensors

Hands and feet also require tactile sensitivity. The reproduction of soft tissues provides the possibility of sampling mechanical strain as somatosensory mechanoreceptors do. This would require sub-millimetre sized MEMS strain sensors, connected by soft wires that can tolerate the strain of the tissues through which they must pass.

A hyper-elastic parallel pair wire of SEBS and Gallium-Indium amalgam has been made for this purpose and will be the subject of another paper.

REFERENCES

- [1] Arvind Ananthanarayanan, Mojtaba Azadi, and Sangbae Kim. Towards a bio-inspired leg design for high-speed running. *Bioinspiration & Biomimetics*, 7(4):046005, 2012.
- [2] Karl K Bilderback and Ghazi M Rayan. The septa of legueu and juvara: an anatomic study. *The Journal of hand surgery*, 29(3):494–499, 2004.
- [3] MANUEL GIUSEPPE CATALANO. *Soft Robotics: Design for Simplicity, Performance, and Robustness of Robots for Interaction with Humans*. PhD thesis, Universit degli Studi di Pisa, Italy, 2013.
- [4] A.D. Deshpande, Zhe Xu, M.J.V. Weghe, B.H. Brown, J. Ko, D.D. Chang, L.Y.; Wilkinson, S.M. Bidic, and Y. Matsuoka. Mechanisms of the anatomically correct testbed hand. *Mechatronics, IEEE/ASME Transactions on*, pages 238–250, Feb 2013.
- [5] Alan Diamond, Rob Knight, David Devereux, and Owen Holland. Anthropomimetic robots: concept, construction and modelling. *Int J Adv Robotic Sy*, 9(209), 2012.
- [6] Aaron M Dollar and Robert D Howe. The highly adaptive sdm hand: Design and performance evaluation. *The international journal of robotics research*, 29(5):585–597, 2010.
- [7] James R Doyle. Palmar and digital flexor tendon pulleys. *Clinical orthopaedics and related research*, 383:84–96, 2001.

- [8] Jonathan Mark Fussey, KF Chin, N Gogi, S Gella, and SC Deshmukh. An anatomic study of flexor tendon sheaths: a cadaveric study. Journal of Hand Surgery (European Volume), 34(6):762–765, 2009.
- [9] Markus Grebenstein, Maxime Chalon, Werner Friedl, Sami Haddadin, Thomas Wimbck, Gerd Hirzinger, and Roland Siegart. The hand of the dlr hand arm system: Designed for interaction. Int J Robotics Research, 31(13):1531–1555, 2012.
- [10] Nick Hockings, Pejman Irvani, and Chris R. Bowen. Artificial ligamentous joints : methods, materials and characteristics. Accepted to IEEE Humanoids 2014, preprint available at <http://people.bath.ac.uk/nch28/pdfs/Artificial%20Ligamentous%20Joints%20-%20Methods%20Materials%20and%20Characteristics.pdf>, 2014.
- [11] WARREN H. LEWIS, editor. Grays Anatomy of the Human Body. LEA & FEBIGER : BARTLEBY.COM, 2000, 20 edition, 1918.
- [12] GE Loeb. Control implications of musculoskeletal mechanics. In Engineering in Medicine and Biology Society, 1995., IEEE 17th Annual Conference, volume 2, pages 1393–1394. IEEE, 1995.
- [13] Robert J Schultz, James Furlong II, and Anthony Storace. Detailed anatomy of the extensor mechanism at the proximal aspect of the finger. The Journal of hand surgery, 6(5):493–498, 1981.
- [14] Timothy P Schweitzer and Ghazi M Rayan. The terminal tendon of the digital extensor mechanism: Part i, anatomic study. The Journal of hand surgery, 29(5):898–902, 2004.
- [15] Carla Stecco, Veronica Macchi, Luca Lancerotto, Cesare Tiengo, Andrea Porzionato, and Raffaele De Caro. Comparison of transverse carpal ligament and flexor retinaculum terminology for the wrist. The Journal of hand surgery, 35(5):746–753, 2010.
- [16] Julio Taleisnik, Richard H Gelberman, Brent W Miller, and Robert M Szabo. The extensor retinaculum of the wrist. The Journal of hand surgery, 9(4):495–501, 1984.
- [17] James S Thompson, J William Littler, and Joseph Upton. The spiral oblique retinacular ligament (sorl). The Journal of hand surgery, 3(5):482–487, 1978.
- [18] Francisco J Valero-Cuevas, Jae-Woong Yi, Daniel Brown, Robert V McNamara, Chandana Paul, and Hod Lipson. The tendon network of the fingers performs anatomical computation at a macroscopic scale. Biomedical Engineering, IEEE Transactions on, 54(6):1161–1166, 2007.
- [19] RL Zwanenburg, PMN Werker, and DA McGrouther. The anatomy and function of clelands ligaments. Journal of Hand Surgery (European Volume), 39(5):482–490, 2014.