Histology for robot engineers

nick.hockings@gmail.com

About me:

Vet, 8 years of emergency surgery practice.

Engineer by nature, became a surgeon by accident

Came to robotics via medical diagnostics

=> the need for embodiment to ground semantic concepts.

This seminar :

A synthesis of medical & engineering knowledge

Histology = the study of living tissue

Oscar the bionic cat

Acknowledgements

Evolutionary and Adaptive Systems group, University of Sussex

Prof Owen Holland, ECCE Robot Project,

Prof Ezequiel di Paolo, University of the Basque Country

Prof Inman Harvey, EASY group

Dr Luc Berthouze, Centre for Computational Neuroscience and Robotics

Dr Anil Seth, Sackler Centre for Consciousness Science

Dr Xabier Barandarian, CCNR

Dr Tom Frose, Philosophy of AI and Cognitive Science

Matthew Egbert, CCNR

and many others whose brains I have picked over the last two years.

(Any errors are mine alone.)

Aim

Show :

- Possible to make robots that truly reproduce the material behaviour of living bodies.

- Why it is necessary that we make this change.

Assume know of : composites, elastomers, & gels.

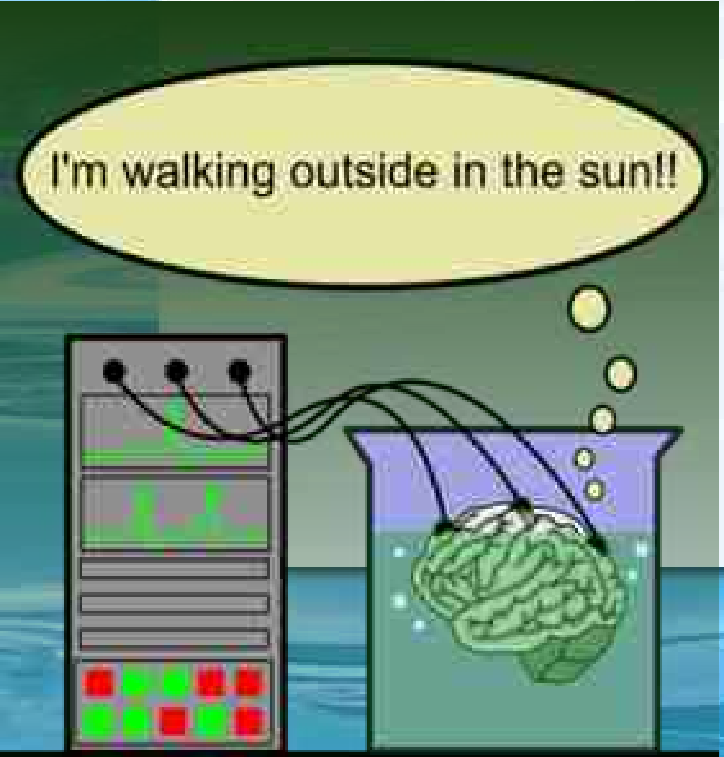
Sections

What we must emulate:

1. Embodiment
2. The basic tissue types
3. Joints
4. Musculo-skeletal system
5. Biomechanics

Doing it:

6. Building a materially biomimetic robot



Bigdog, Bionic cat, & natural cats

Pathology of embodimemt

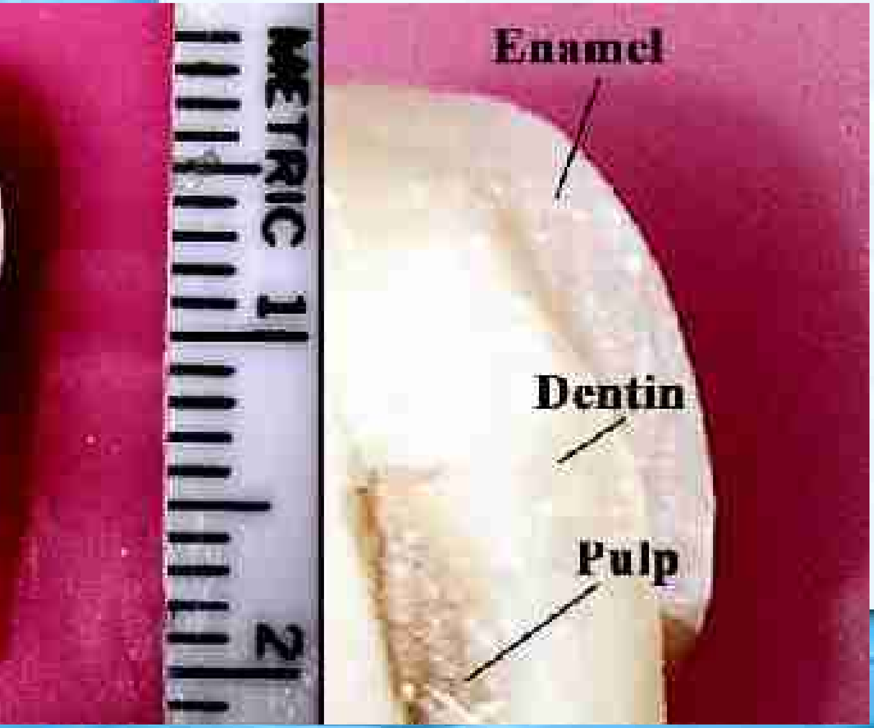
David Vetter, suffered developmentally in later childhood due to his confinement.

Analyze robot anatomy as human/animal pathology, “how would this form affect the function of a natural body”?

Robot bodies do not need to be identical to humans.

Is the robot “sufficiently humanoid” that a human child with this pathology would still develop healthily/normally ?

Material embodiment



Role of the materials from which living organisms are made.

Life is capable of producing very hard materials such as the enamel of teeth, and of armouring the body with dermal bone and horn as we see in turtles, and crustaceans,

BUT, in most niches vertebrates have evolved soft bodies.

We need to pay attention to how they are built and why this is more successful.

Functional biomimetics

soft, vulnerable, sensitive and reactive

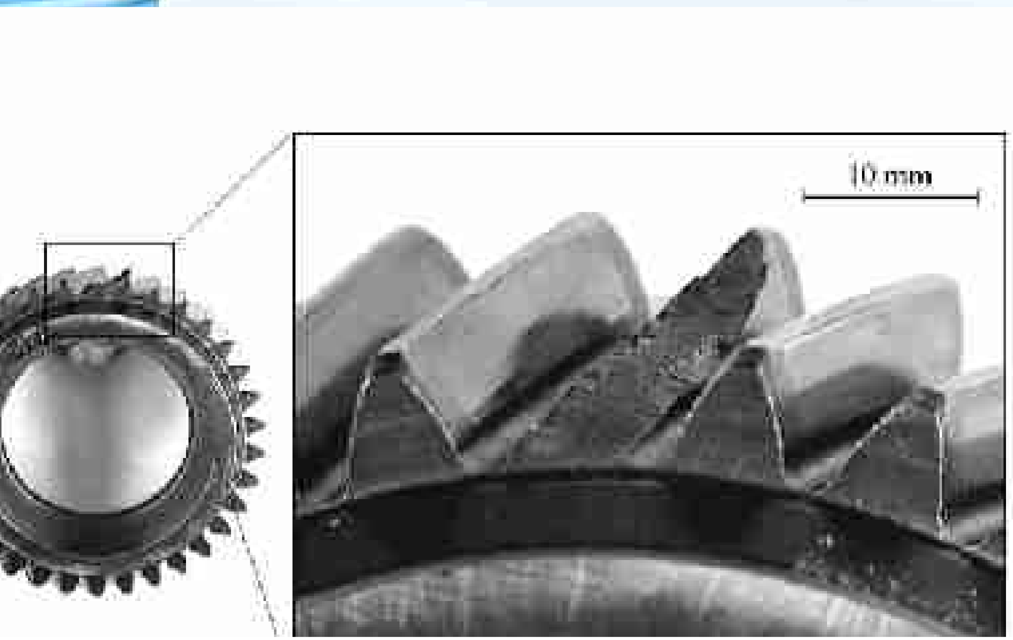
The behaviour of living animals is closely entwined with the materials the materials they are made from.

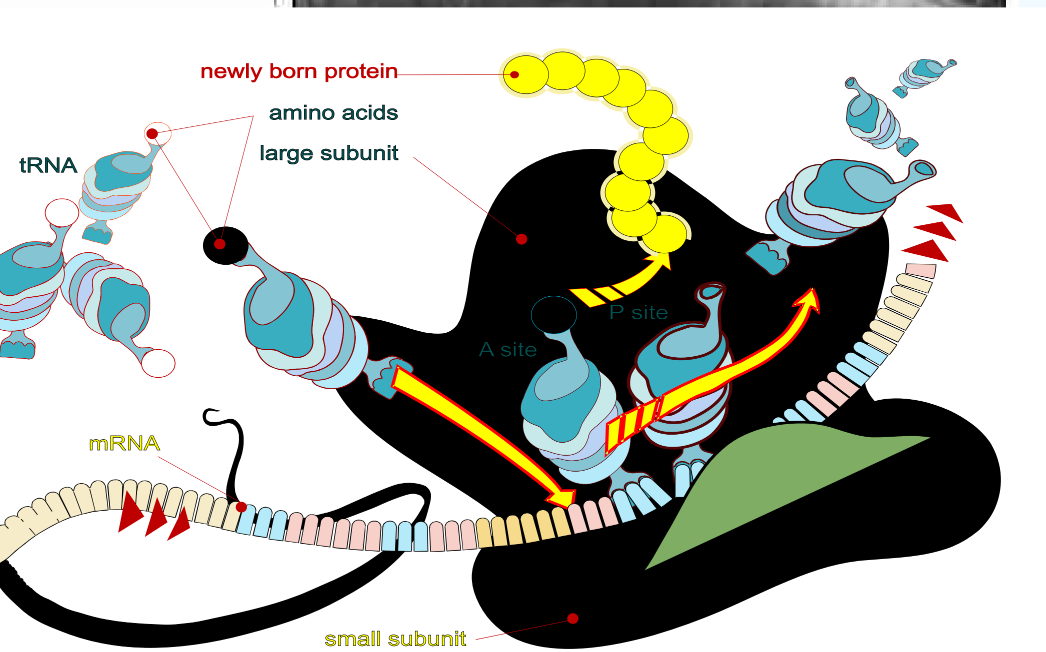
It defines the behaviour of their bodies without the input of nerves, and it defines the problems which the nervous system must solve.

What we observe is that living things are "soft, vulnerable, sensitive and reactive".

There is a reason for this.

The needs of autopoiesis



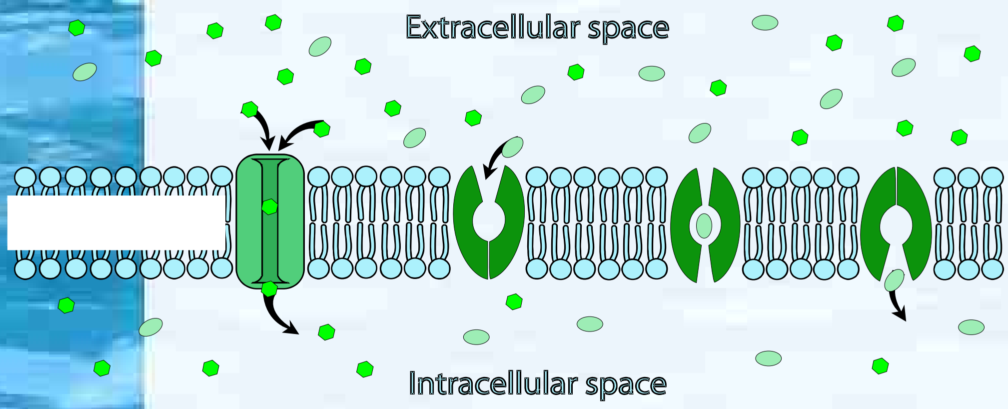


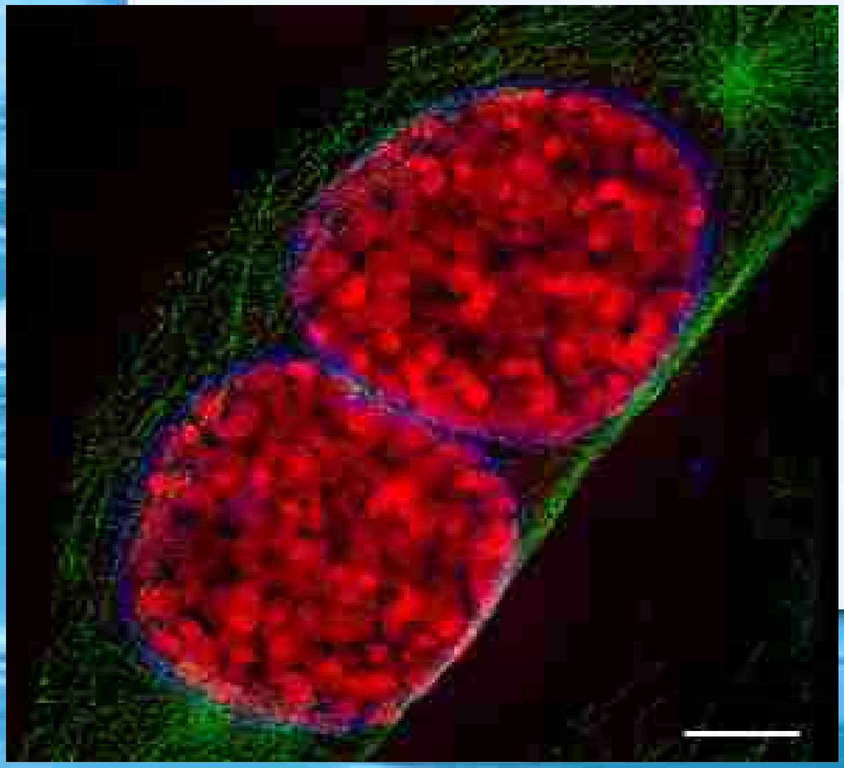
Living things must organize & build themselves from below the scale of entropy -

that is they must manipulate and assemble physical quanta (atoms & molecules) to build themselves upwards from that level.

This is necessary for living organisms because if entropy wore out the components they were made from, how would they replace them ?

Life occurs as a fibro-gel-emulsion





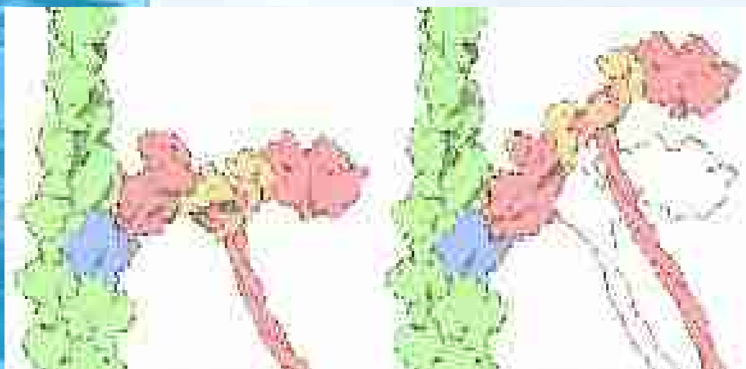
The need to manipulate individual molecules means that life must occur in solution.

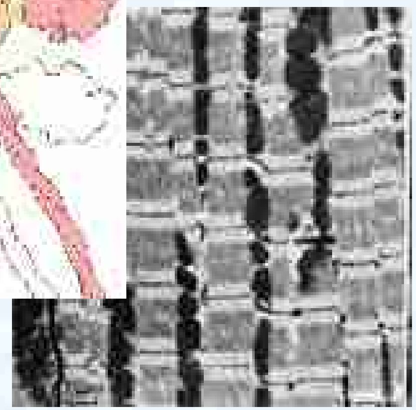
… & limits materials to enzymatic synthesis, which in turn makes heat + temperature crucial

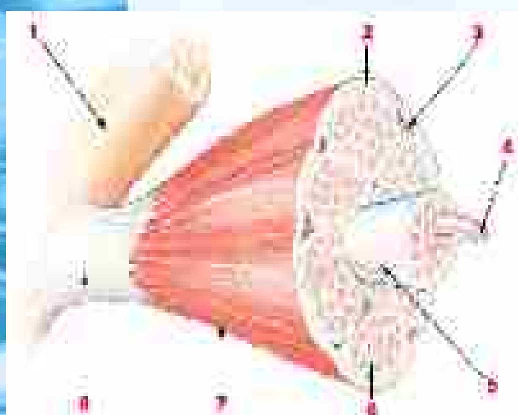
The need to prevent that solution from diffusing away, necessitates cell membranes ,

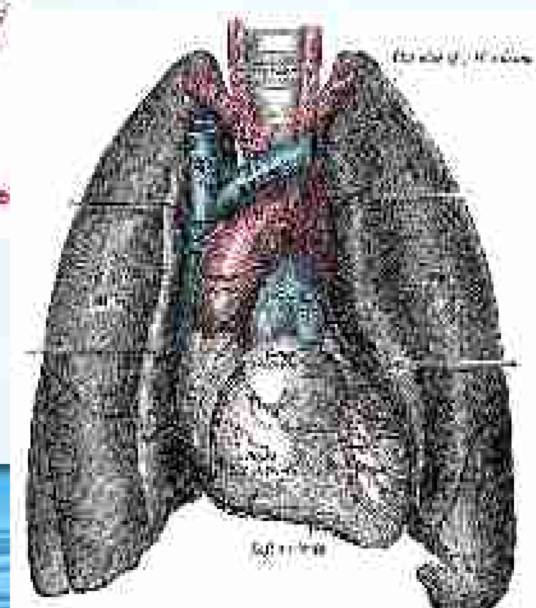
and the need to hold cells together individually and in multi-cellular structures, necessitates polymer fibres which make the gel both within and between cells.

Non-fractal complexity









The problems to be solved at each physical scale change with the relative effects of intermolecular forces, gravity, inertia and diffusion.

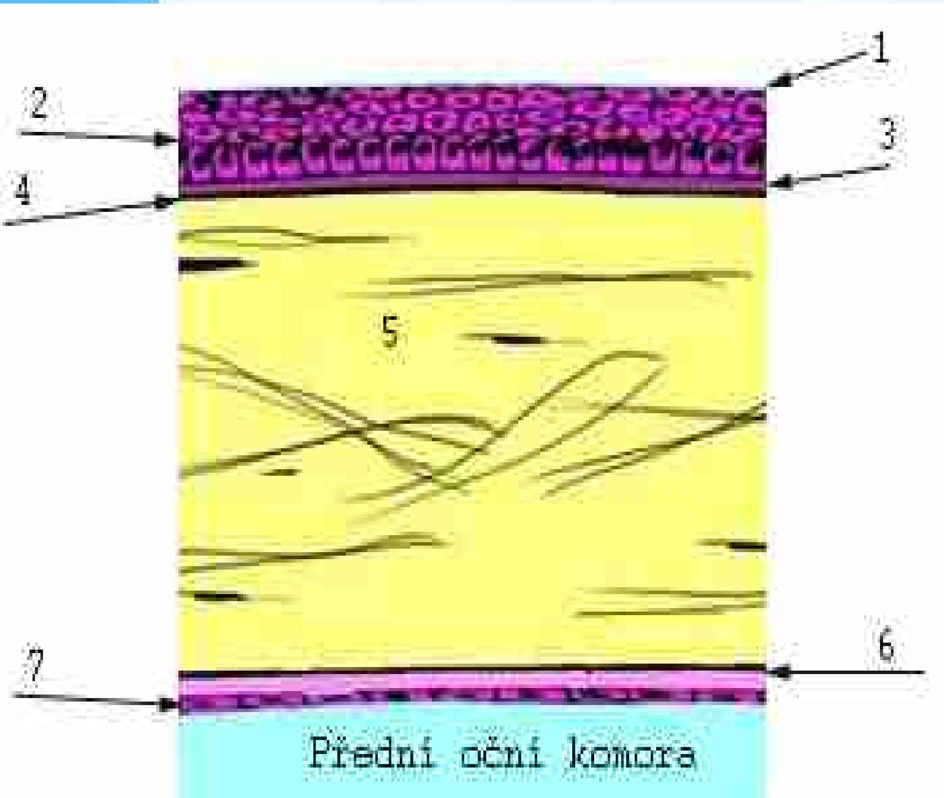
A characteristic feature of life is non-fractal complexity

- Rock looks similar at scales from micrometers to tens of meters,
- Life shows different patters at every scale.

Below a millimetre, diffusion and molecular pumping at membranes are sufficient for transport,

At larger scales bulk flow and specialist pumping organs & systems are essential.

Section 2 : The basic types of tissue



All tissues are composites with task-specific material behaviours.

There are two fundamental tissue types

- epithelia
- connective tissue.

They are defined by the relation of cells to the extra-cellular fibre-gel.

Epithelia

Multi-cellular equivalent of the cell membrane.

Essential to the chemical physiology of the body and dominate the visceral organs.

Fundamentally 2D, topologically continuous barrier separating two extra-cellular fluid compartments.

Entropy of basement membrane irreversible process of aging.

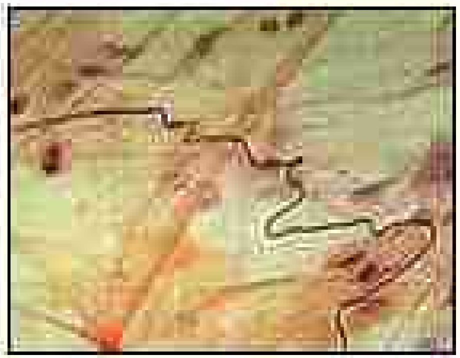
Basement membranes get their structure from plastic expansion during growth.

Cannot be repeated without increasing the size of the organism.

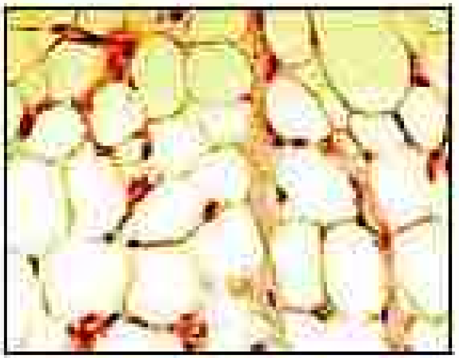
Connective tissues

Most important for robotics,

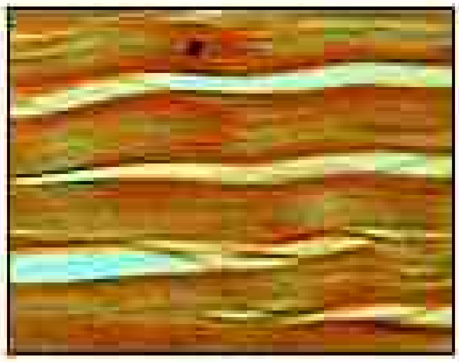
- Dominate the musculo-skeletal system,
- Connective tissues are fundamentally 3D.
- Cells dispersed individually throughout an extra cellular gel,
- Composed of fibers and matrix.



Areolar connective tissue

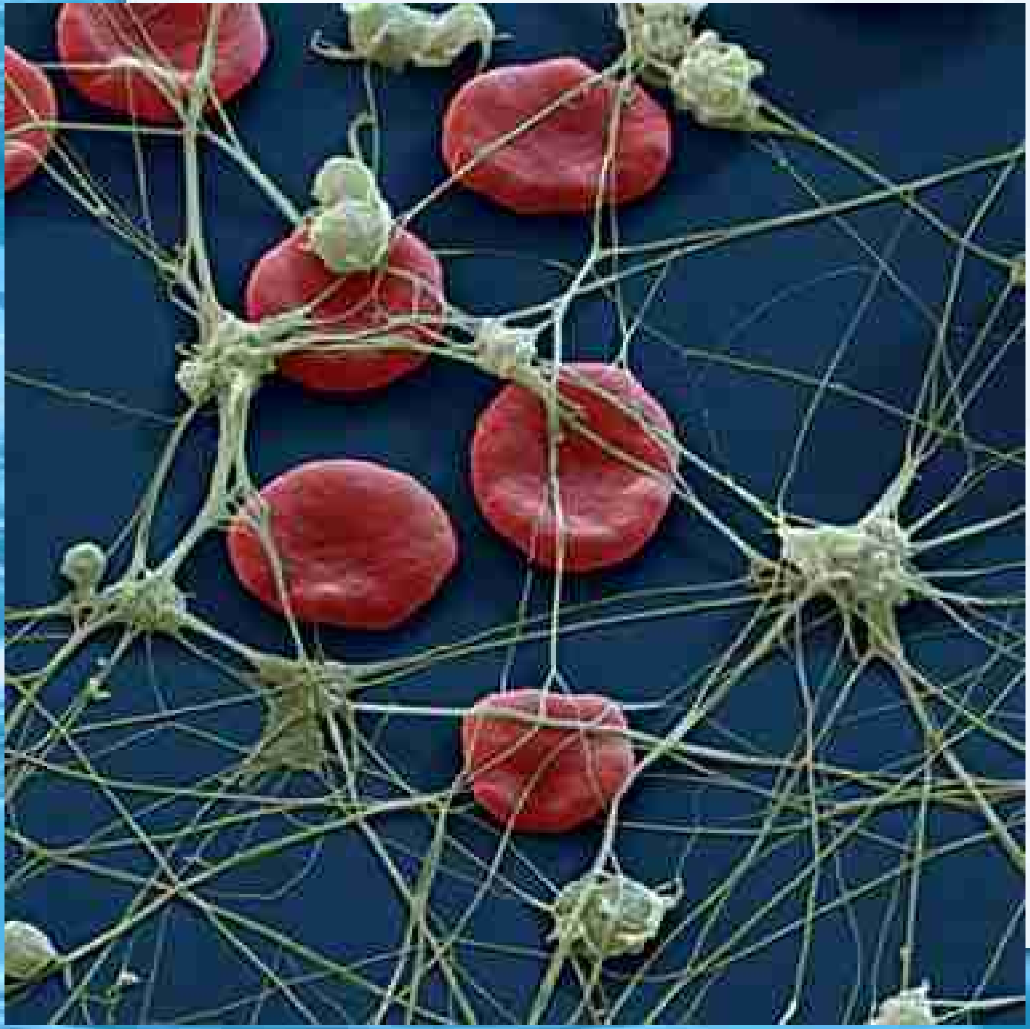


Adipose tissue



Fibrous connective tissue

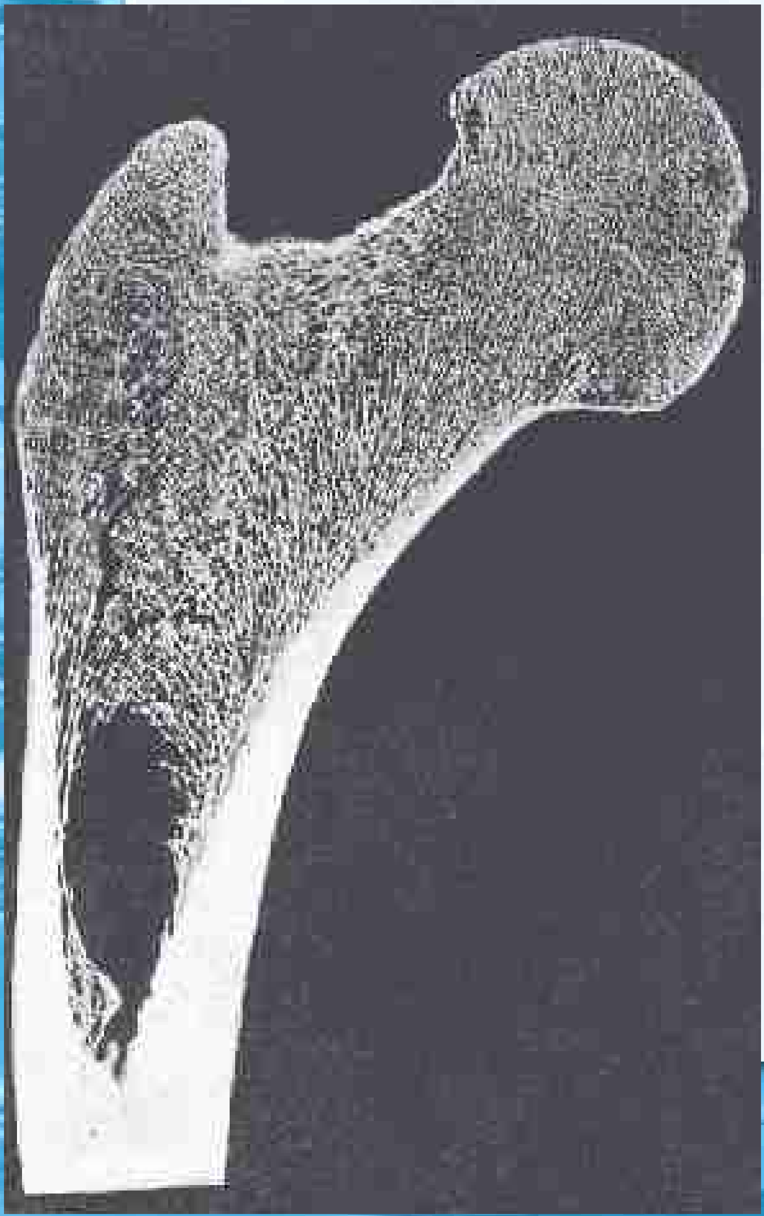
Connective tissue : Blood



Blood is a connective tissue.

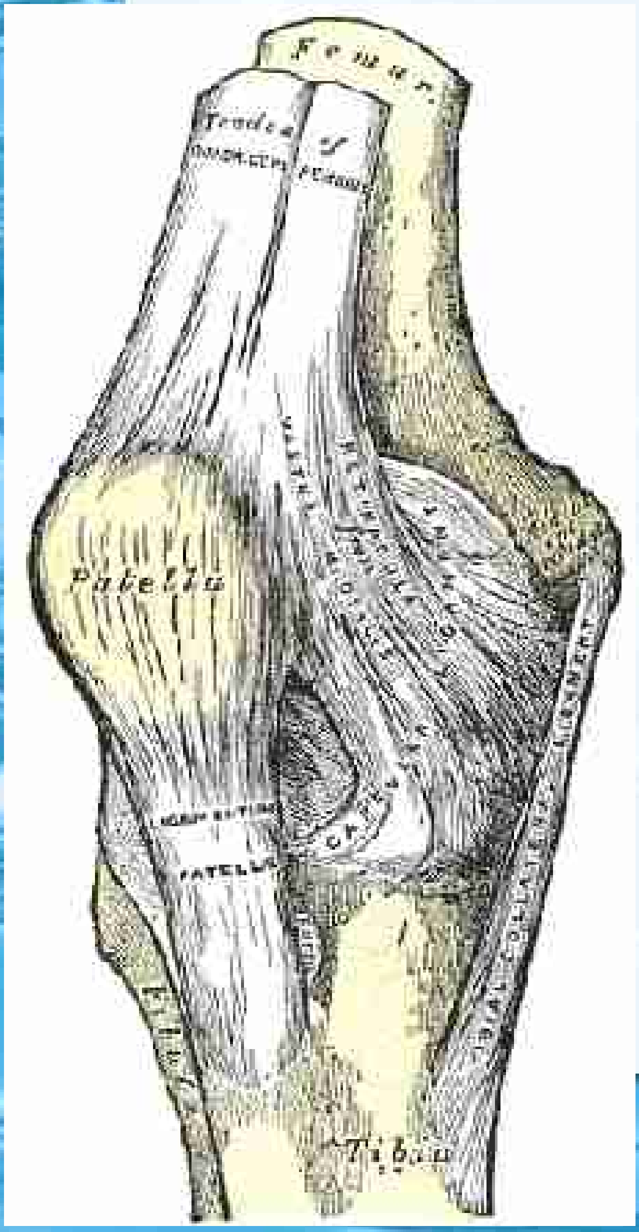
- Fibers are in solution as fibrinogen,
- Precipitates to form fibrin when clotting is triggered.

Connective tissue : Bone



Bone is a connective tissue whose matrix is dominated by calcium phosphate crystals, hence it is rigid.

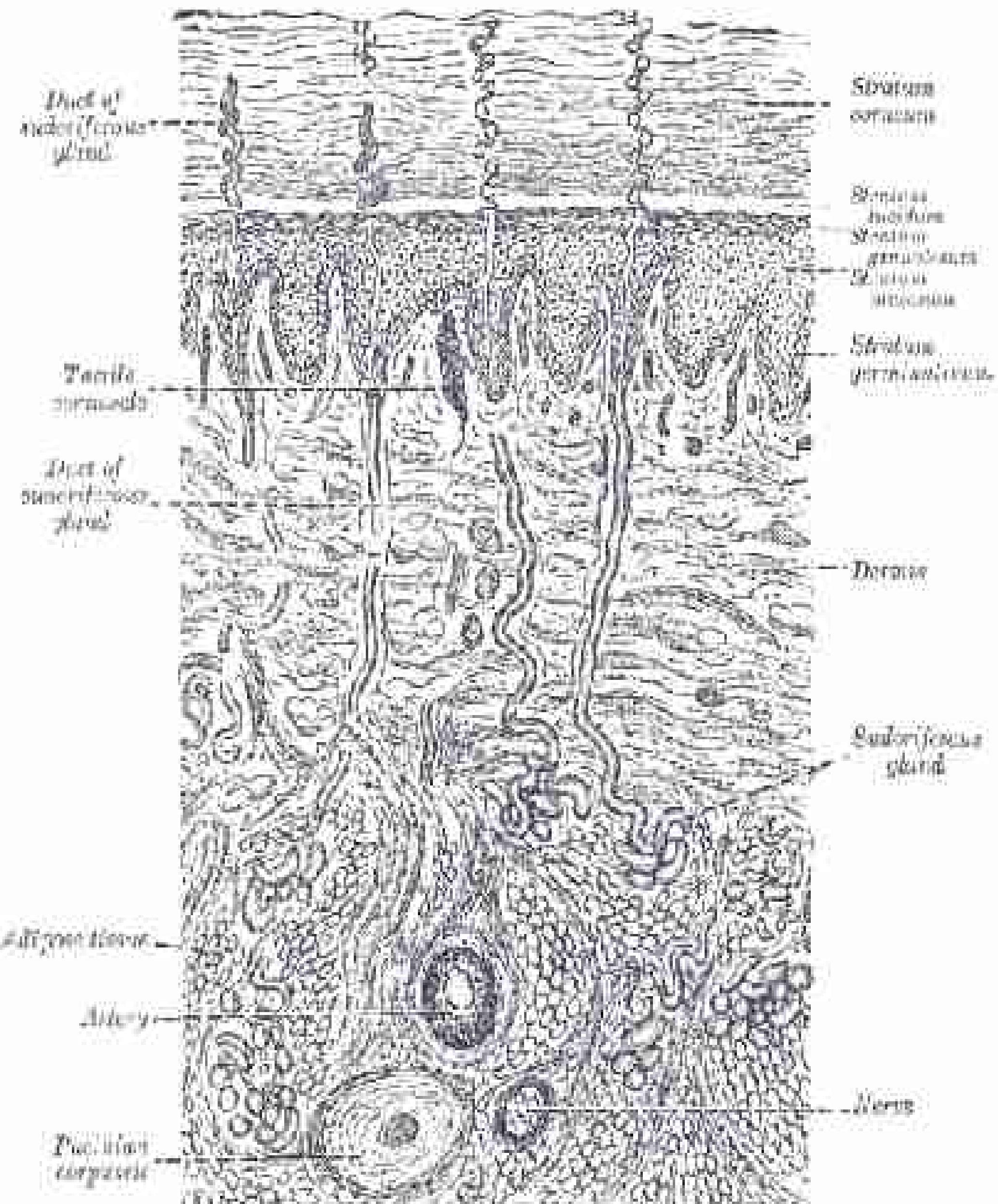
Connective tissue : Ligaments, Tendons...



Ligaments, tendons, joint capsules, tendon sheaths, fascia …

- Dominated by their fibrous component
- Varying coherence of orientation of their fibers,
- Varying elastic modulus.

Connective tissue : Dermis



Dermis has a fluid matrix, with a high fiber density, random fiber orientation.

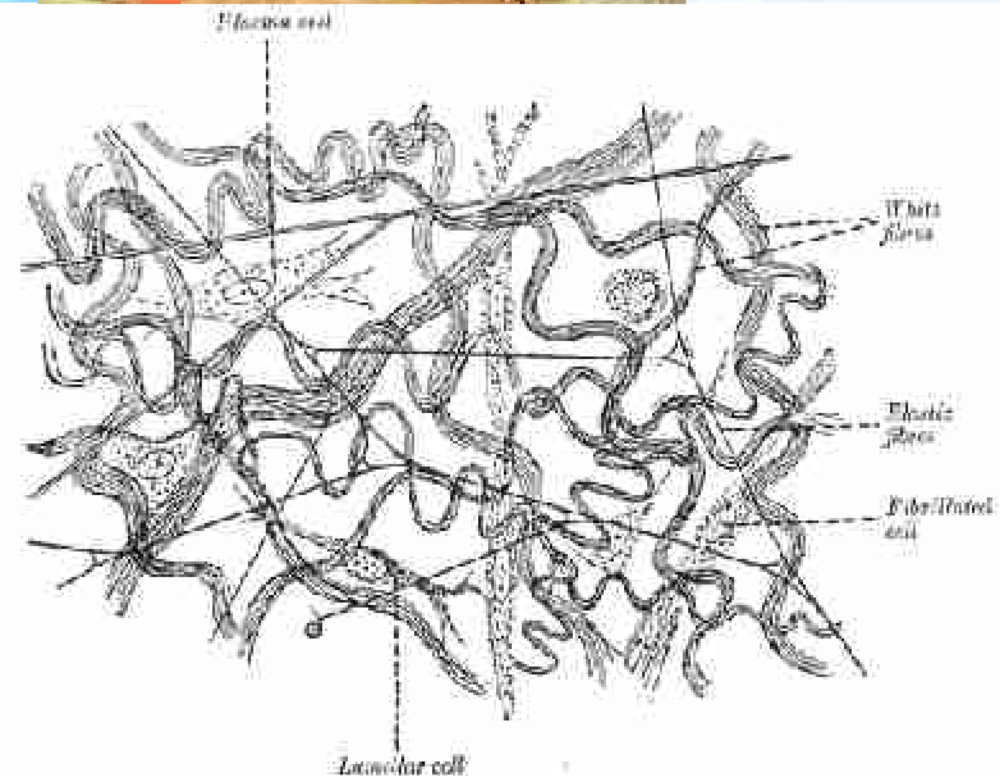
The fibers are a mix of

- hyper-elastic (elastin)
- high-strength low-elasticity (collagen)

Macroscopically

- Connective tissue support for the exterior epidermis.
- Shares the 2D continuous envelope properties of the epidermis.

Connective tissue : Areolar



Areolar "loose" connective tissue is the fundamental connective tissue from which all others develop.

- Topologically continuous throughout the body,
- Envelopes all other tissues.
- Dominated by hyper-elastic fibers and fluid matrix
- Allows & lubricates the movement of other tissues relative to each other.

Connective tissue : Areolar -ve pressure

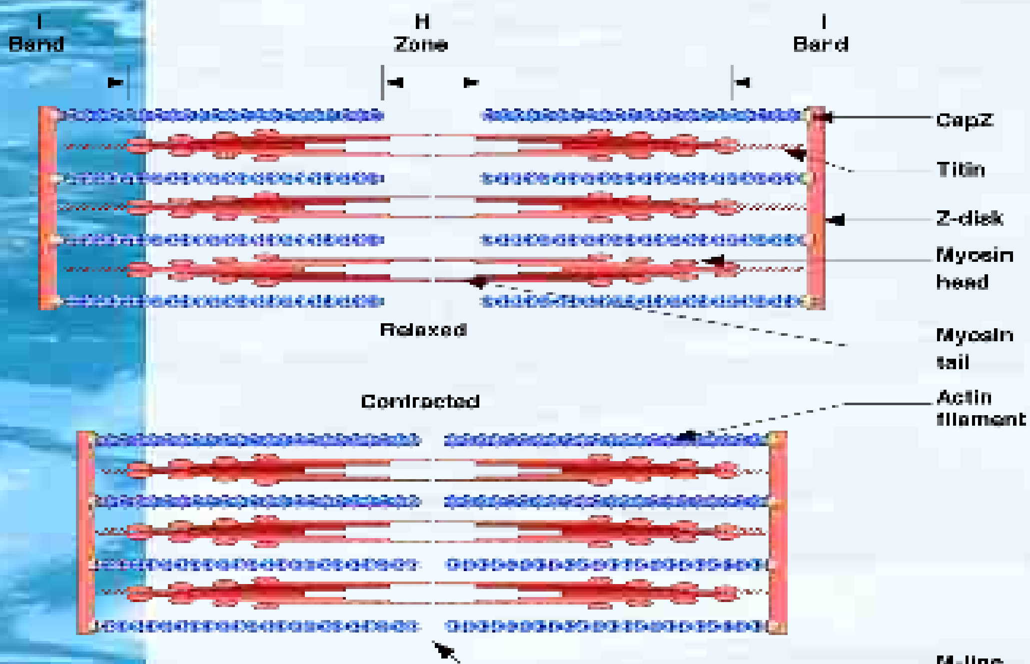
Crucially areolar connective tissue is under negative pressure –

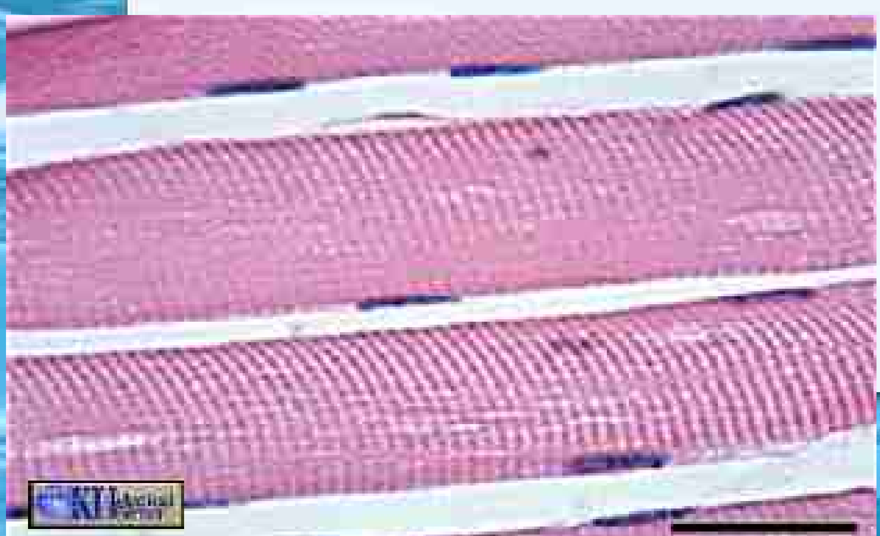
evidenced by the tendency of air to infiltrate it when the skin or trachea are perforated.

Areolar connective tissue's most limiting dimension is its volume, rather than its fibres.

It behaves like a sealed plastic bag with a small amount of water lubricating its movement.

Connective tissue : Muscle – motor & fuel cell





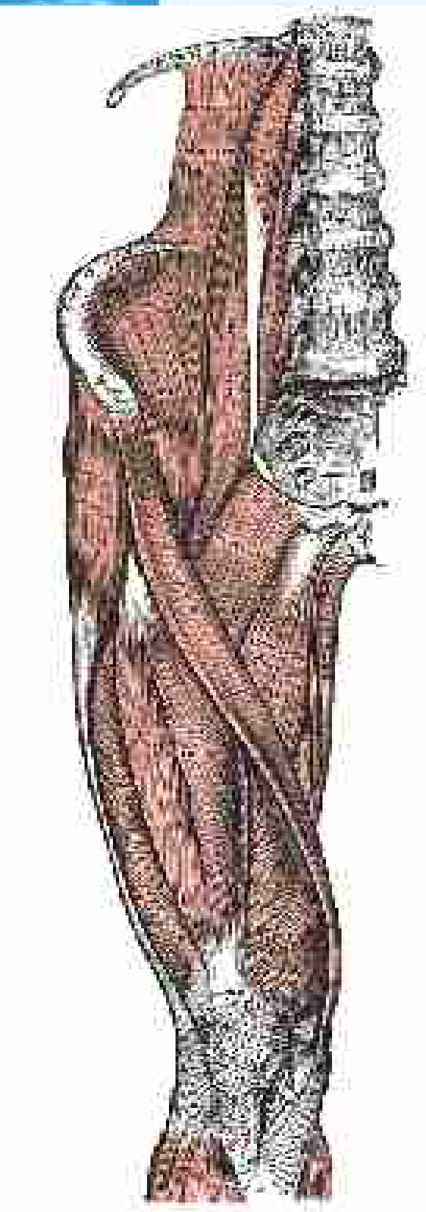
Muscles are connective tissue dominated by metabolically active, intra-cellular, contractile fibers.

These are the same actin & myosin fibers that are responsible for ameboid movement of white blood cells and protozoa.

A muscle cell is both a **linear electrostatic motor** and a **fuel cell**.

Essentially nil friction when relaxed because the sliding distance is microscopic and repeated in series at every sarcomere.

Connective tissue : Muscle – compact power



Because muscles are a bundle of fibers, they can be packed around bones & other muscles to produce impact absorbing padding.

The force density of muscles is hard to match eg:

20kg child hopping on one leg.

Quadriceps of one leg must exert 2x body weight

With a 10:1 leverage disadvantage :- aprox 4000N

And muscle cross section area of 100cm2 = 0.01m2

400KPa or 60psi of tension,

with **<u>no gaps</u>** between actuators.

Connective tissue : Cartilage

Cartilage is a fibrous tissue with a turgid matrix that allows it to resist compression, and retain its shape.

There are three types

Elastic, Fibrous, Hyaline.

Hyaline cartilage - forms the load bearing surface of synovial joints.

Fibers parallel to the surface to resist deformation by friction.

Under pressure it weeps synovial fluid – hydrocolloid lubricant

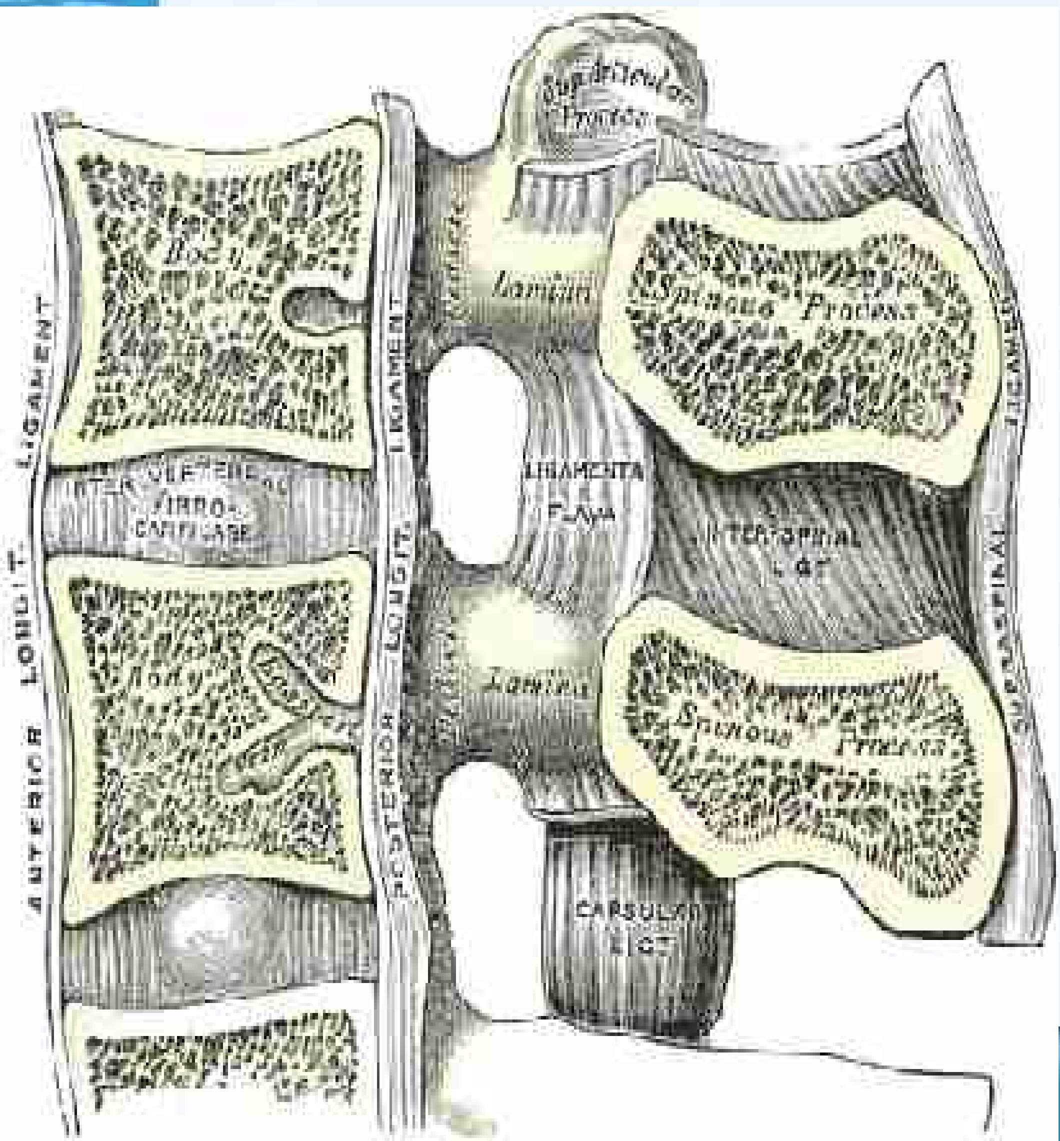
Section 3 - Joints : cartilaginous

pro-chordates and cartilaginous fish (sharks, eels, rays)

Notochord stiff cartilaginous rod, flexed by contraction of muscles either side.

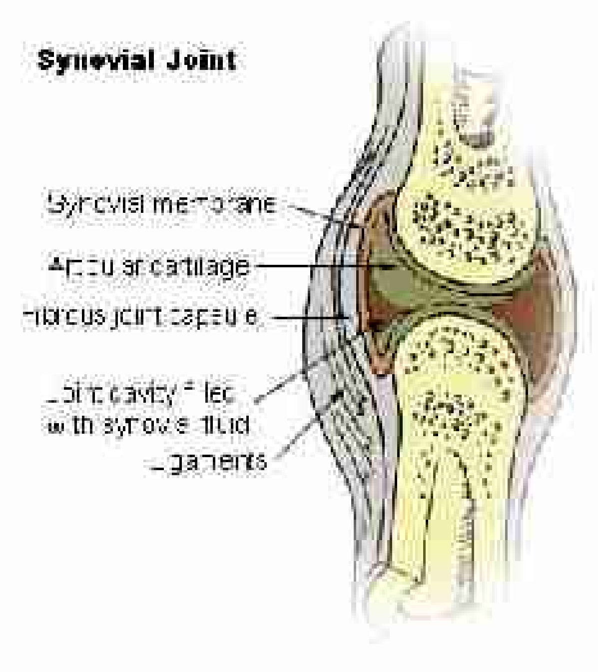
Cartilaginous joints – eg sternum & ribs

Joints : vertebral disks



Vertebral disks – anulus fibrosus + nucleus pulposus

compare with cartilaginous spine

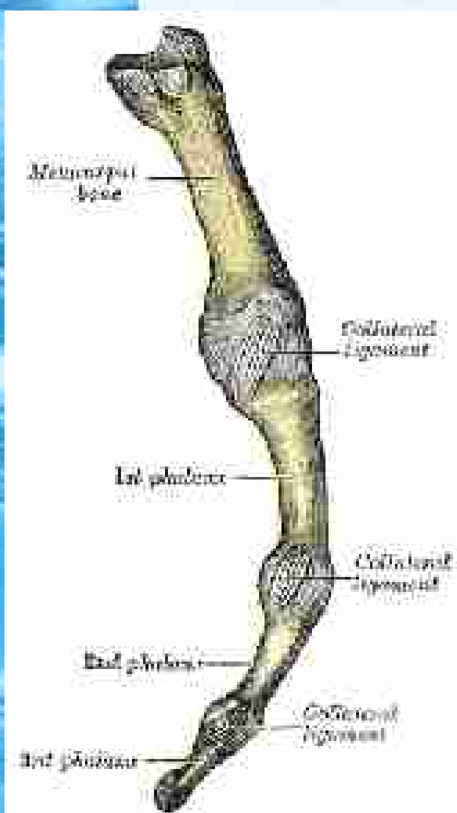


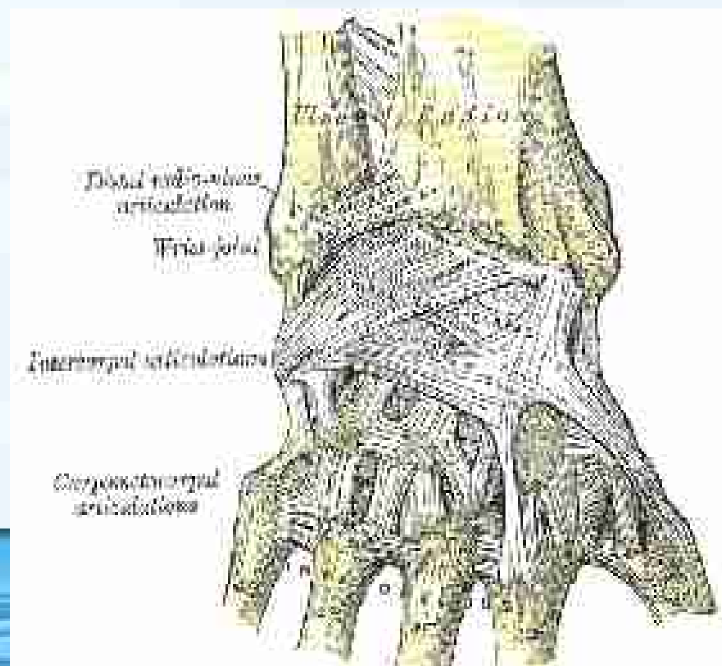
Synovial Joints

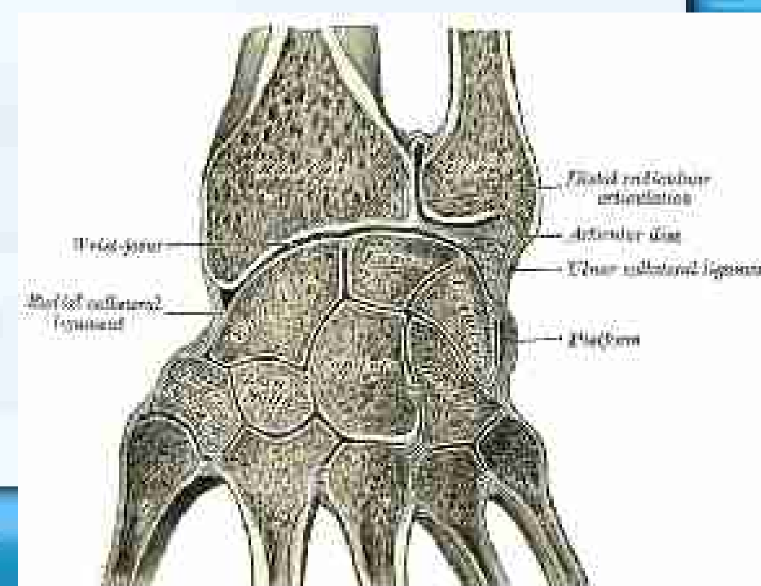
synovial fluid, articular cartilage, joint capsule, ligaments, tendons, spongy bone, lamellar bone

=> engineered stiffness.

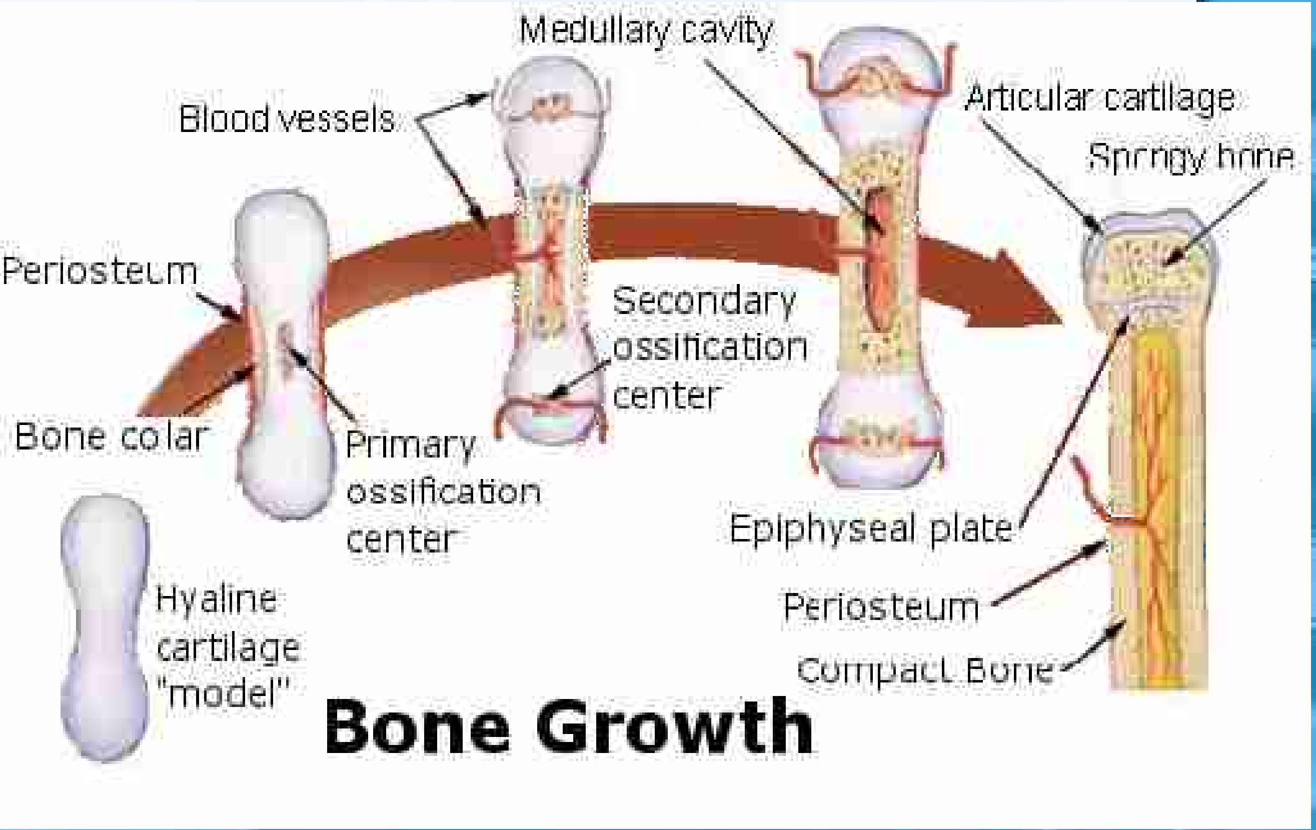
NB continuity of fibres across tendons/ligaments/bones







Section 4 - Musculo-skeletal system : Formation



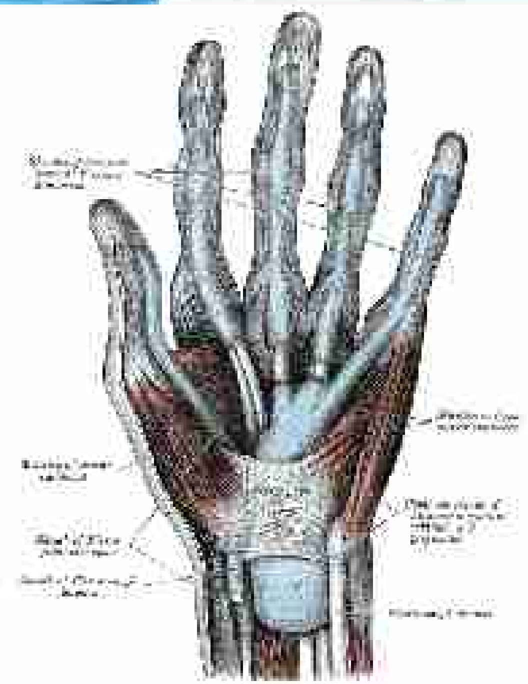
Musculo-skeletal system : Remodelling

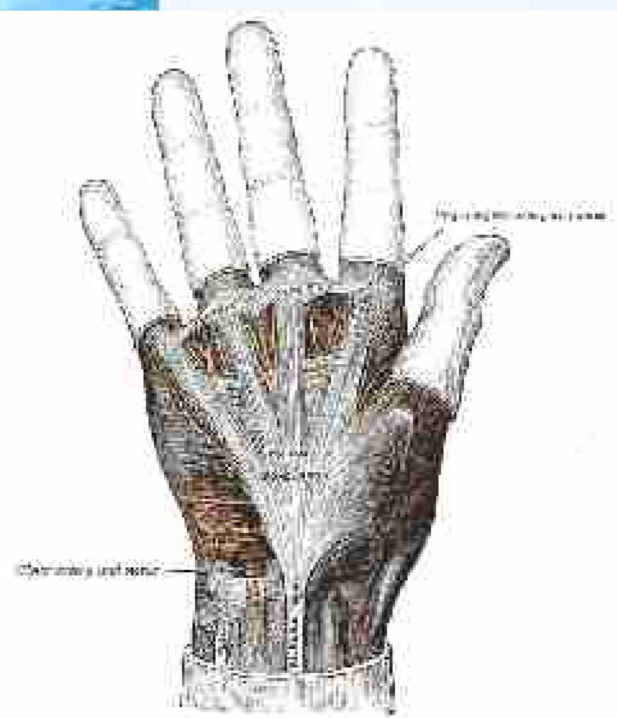
Both fibrous and bony connective tissue continuously remodel & adapt to loads.

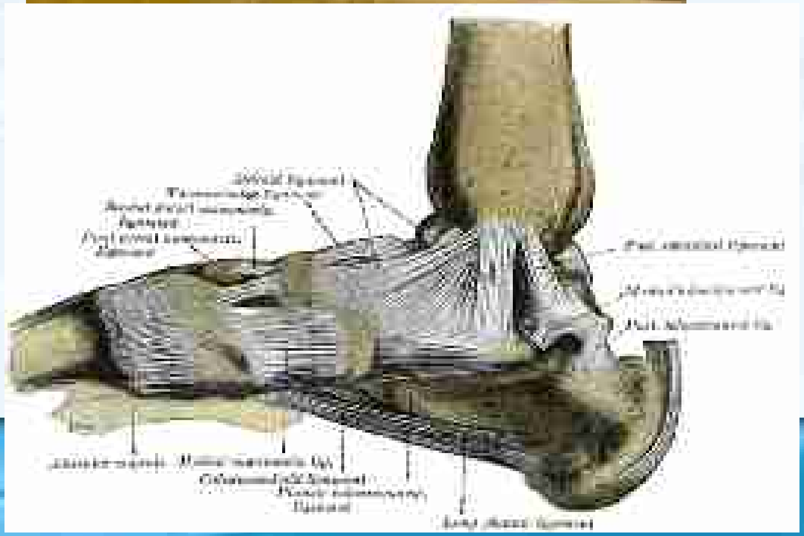
Thus shape is evidence of forces on anatomy.

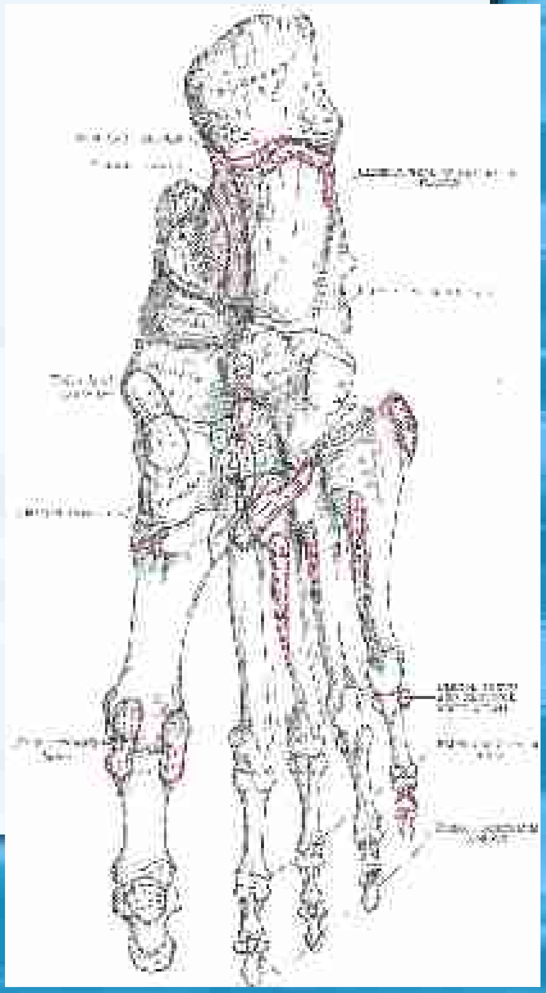
Musculo-skeletal system : Function

A muscle is a ligament with variable length & elasticity

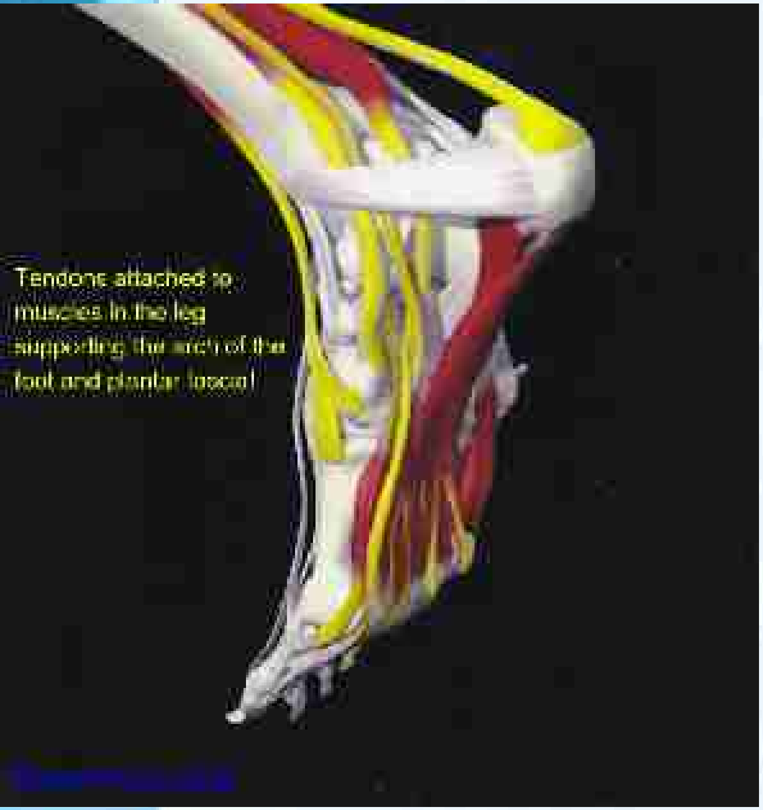








Human feet

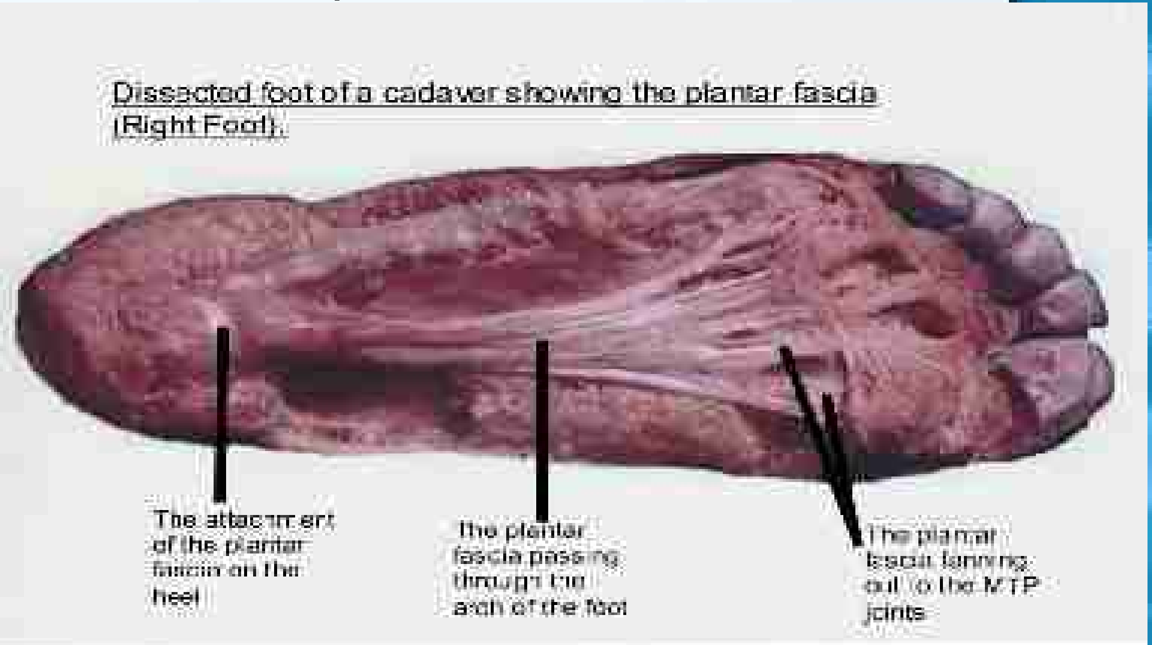


Human plantar digits are short, but important for balance. Most hand structures have analogues in the foot

Muscles modify compliance.

The foot bears load either plantigrade (energy saving), or digigrade when running and jumping.

Primate ankle movement is under-constrained by ligaments, hence requires muscular effort.



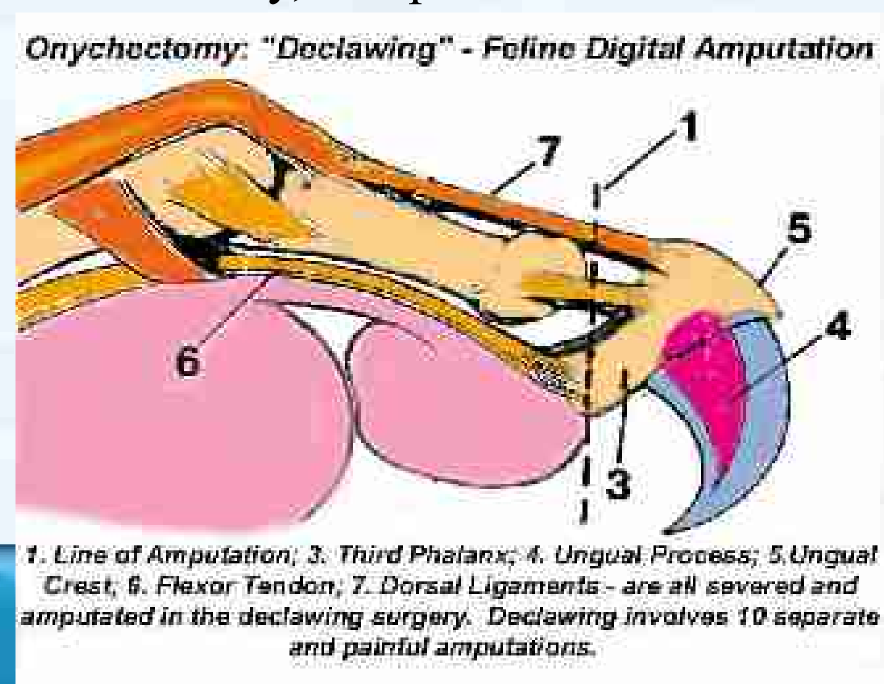
Section 5 -Biomechanics : Comparative anatomy

Finger nails are a higher primate feature, but hands are ancient.

The basic design has been adapted to different loads.

The compliance of the carpus/tarsus is a consistent feature.

Digital pads allow sensitivity, compliance & control.

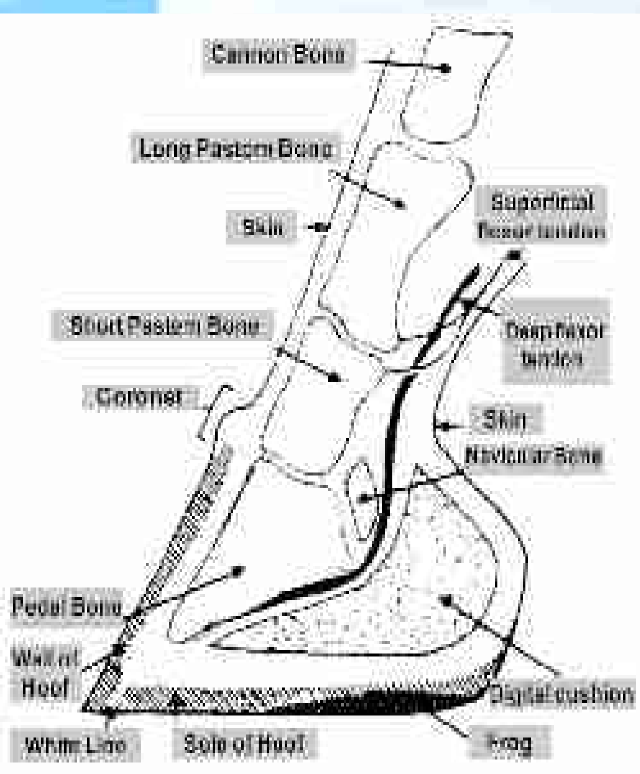


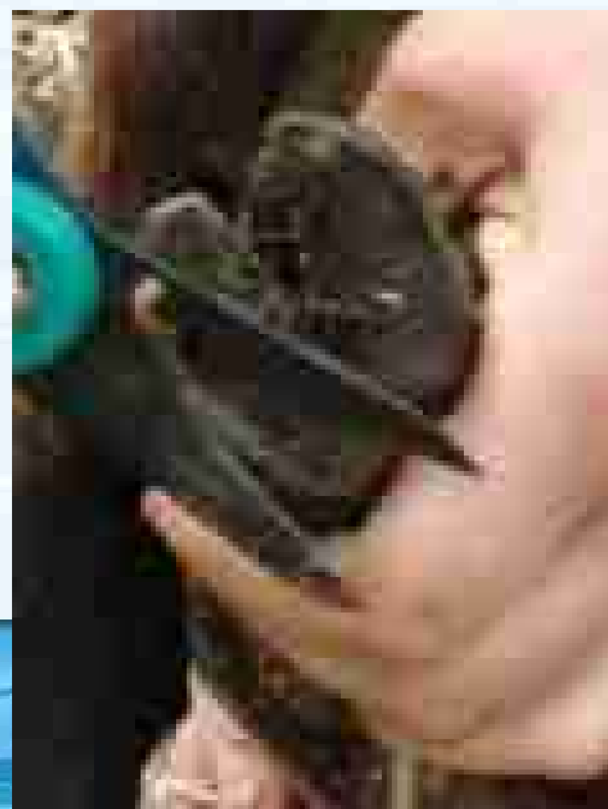
Comparative anatomy : Hooves

Proportion and hardness are optimized

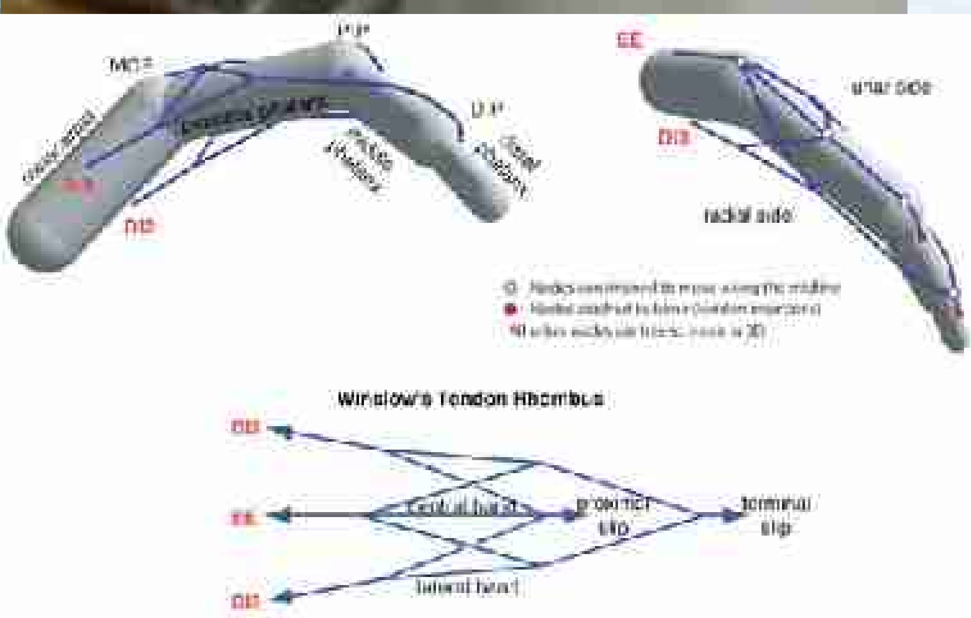
Horses are native to grassy plains. They rely on compliant soil under foot.

Sheep are native to mountains, with stony soil. Their hoof horn resembles vulcanized rubber.





Biomechanics of hands



Tendon networks –

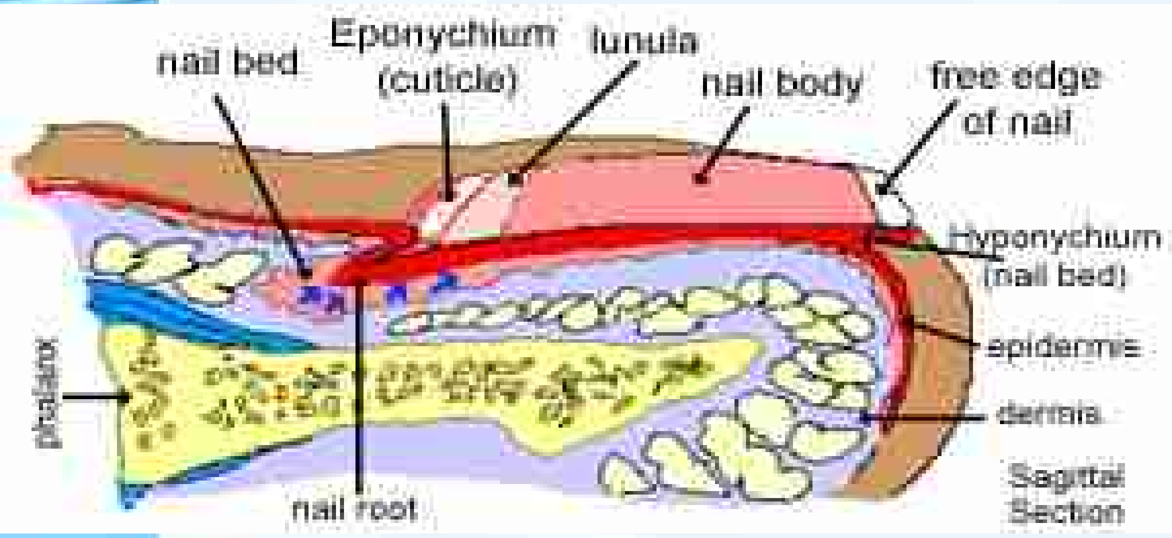
preflexes : passive pure mechanical, faster than reflexes, load balancing,

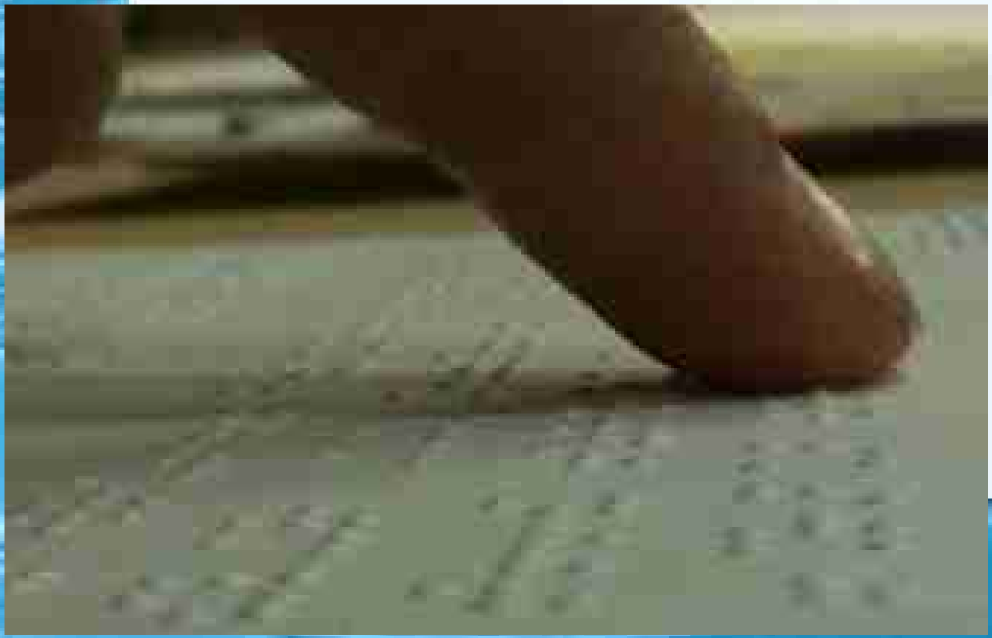
F.J.Valero-Cuevas 2007

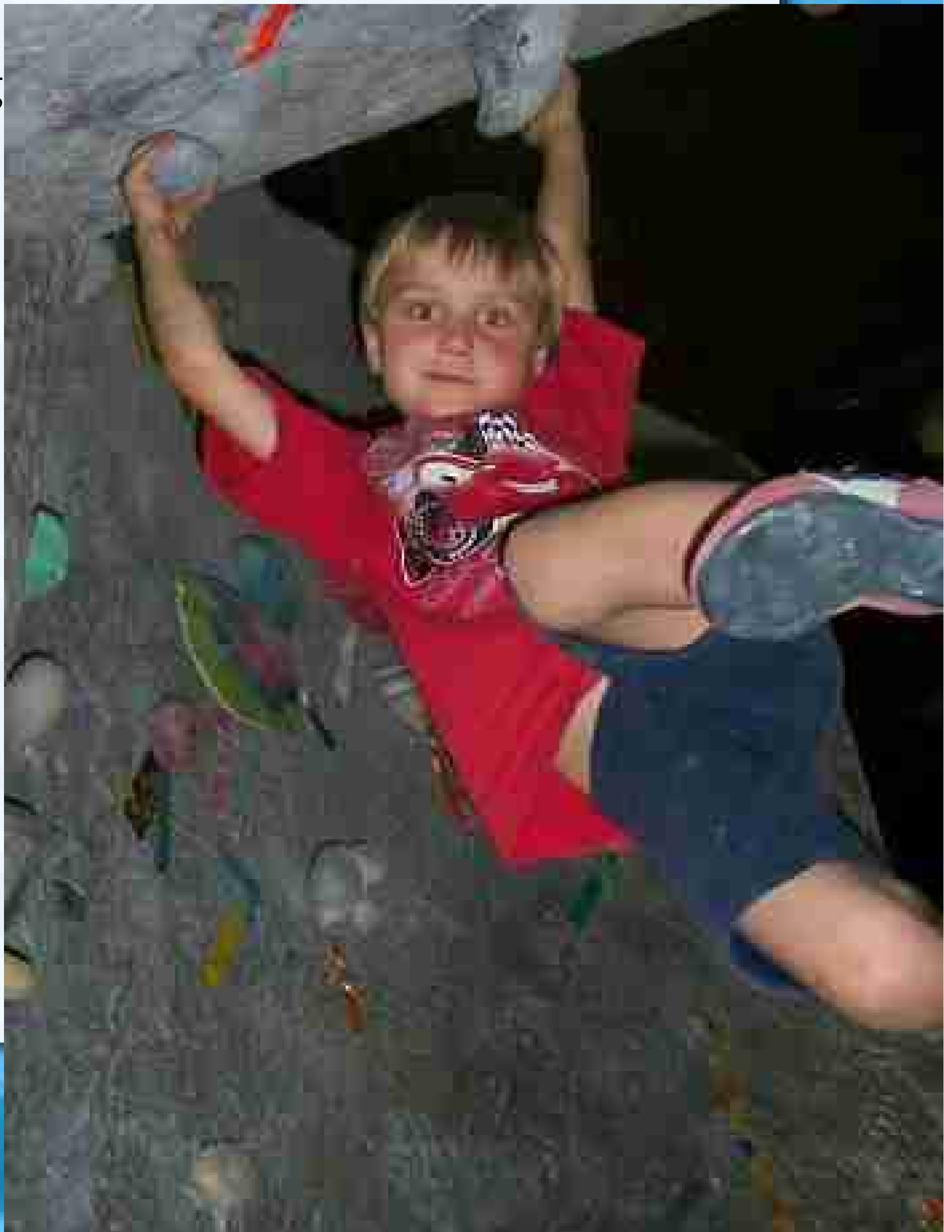
hand closing : birds feet, primates hands, amphibians, reptiles

Passive stay : hanging grip

Materials of fingers







Geometry of fingernails

Compliance with support gives greater precision.

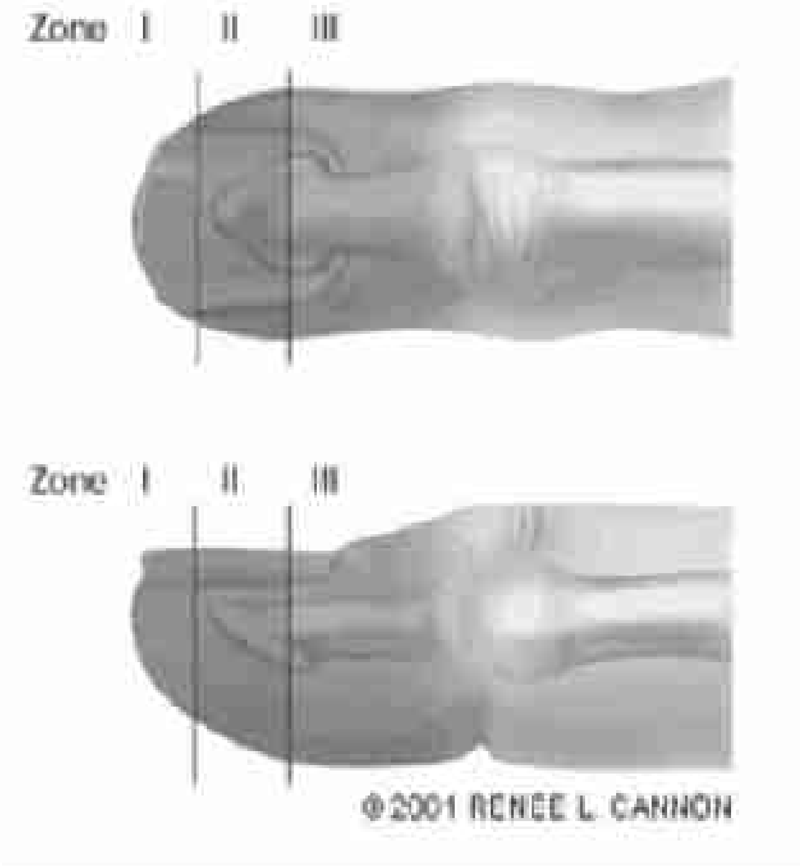
- small radius of curvature of dermis at the end of the finger nail.
- importance of fingerprints and balance of skin humidity for stiction.

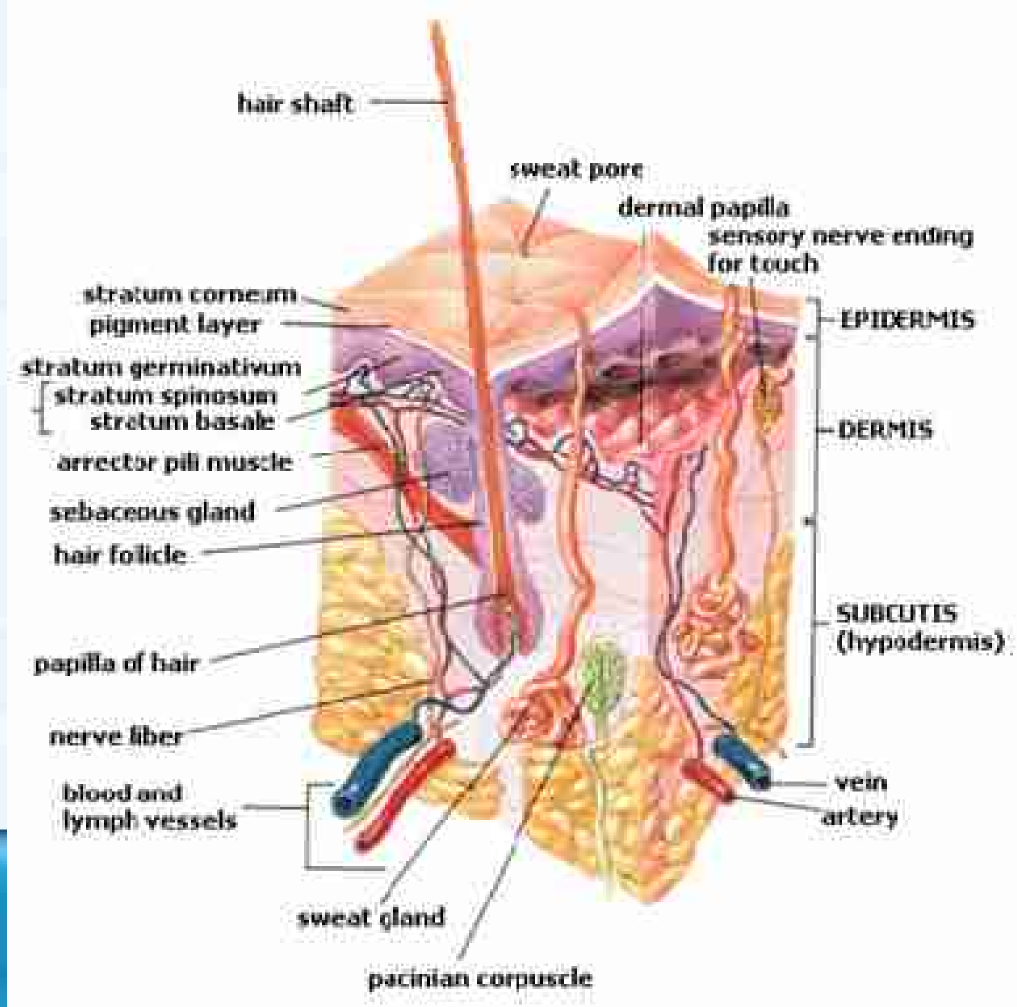
Sensitive & robust

Tactile sensation & robustness : finger pad, finger tip, finger nail, palmar vs dorsal sensitivities.

Note : scale and location of receptors in tissue.

Figure 10a. Fingertip amputation zones.





Section - 6 : Building a materially biomimetic robot

Don't

When we build a robot it is not a living organism.

It does not need to build itself, hence we are not bound by the physiological demands of autopoiesis.

We do not need to use only materials that are enzymatically synthesized.

We do not need to reproduce the visceral organs and entire physiology of the organism.

Do

We need to produce the material embodiment.

The musclo skeletal system and organs of sensation, especially the skin.

Our robot can have different physiology, BUT

it should still look after itself in terms of avoiding injury, regulating body heat & energy reserves, and other self maintenance .

Building biomimetic anatomy : Skeletal system

Propose :

Resin transfer moulding + vacuum bagging

Moulds 3D printed from meshes adapted from medical imaging

– especially the CT, MRI & photo sections from the visible human project.

NB continuous fibers are essential to prevent avulsion

Building biomimetic anatomy : Skeletal system

Use either UHMWPE or high temperature nylon depending on elasticity required.

Use Polycaprolactone – low temp crystalline thermoplastic eg ECCE Robot.

Good – non-toxic, no fumes, good lamellar bone imitator.

Use open cell phenolic foam – spongy bone & lumen => forms frame on which to pin the fibers before closing the mould.

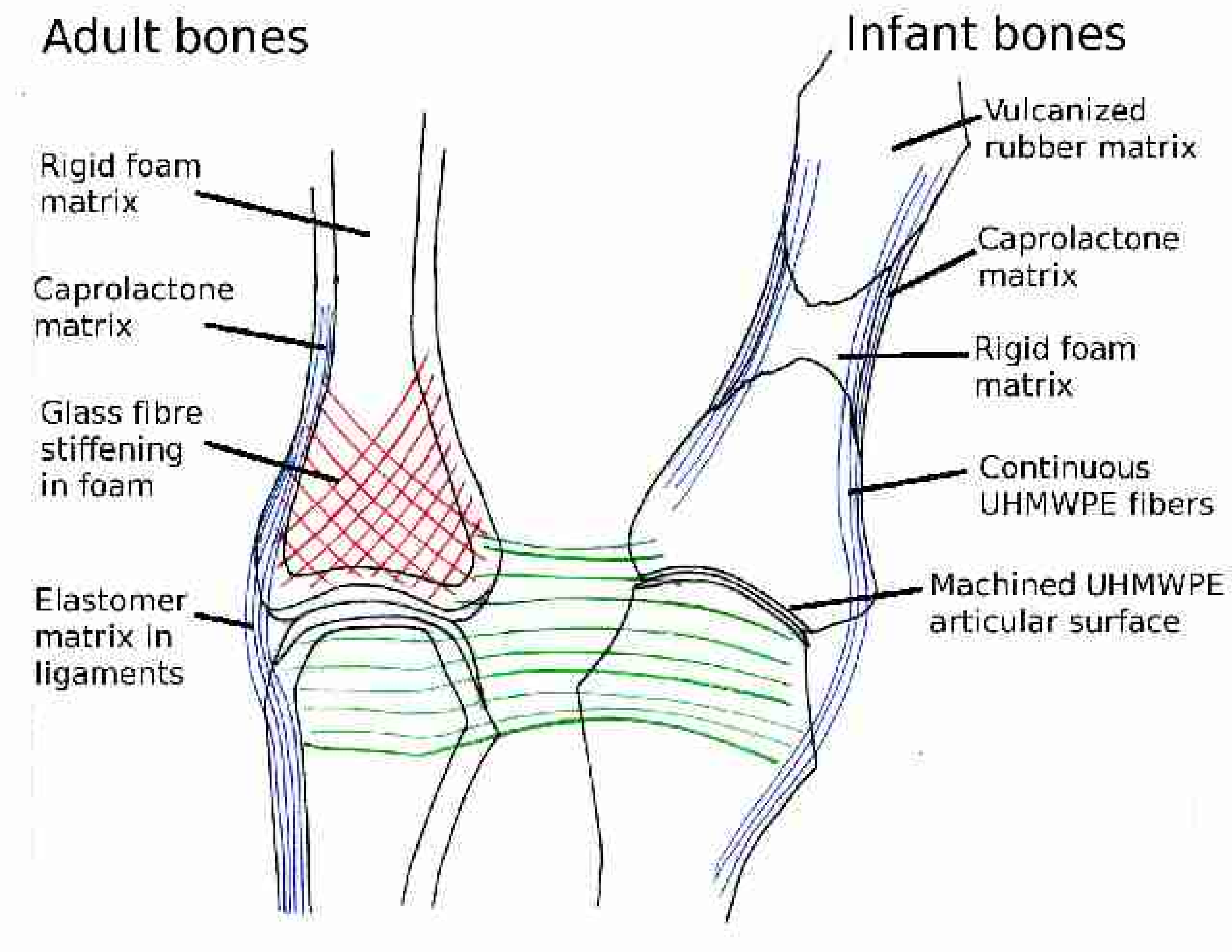
Building biomimetic anatomy : Skeletal system

Use solid block UHMWPE carved & polished for articular cartilage

Use thin flexible tubes of UHMWPE for tendon sheaths.

Use water for lubrication.

Skeletal system lay-up



Building Skin & Subcutis

Use soft silicone gel for areolar tissue : finger pads – tactile flexibility

Use silicone impregnated knitted nylon elastane (lycra) for dermis

Use thin coat of vinyl for epidermis NB fingerprints embossed in dermis

Keratin lacquer for stratum corneum

Dehydrated jelly for Areolar tissue

Areolar tissue is a gel whose fibers are longer than the tissue.

This can be made by polymerizing the gel in an over hydrated state, then dehydrating it dow to the final volume.

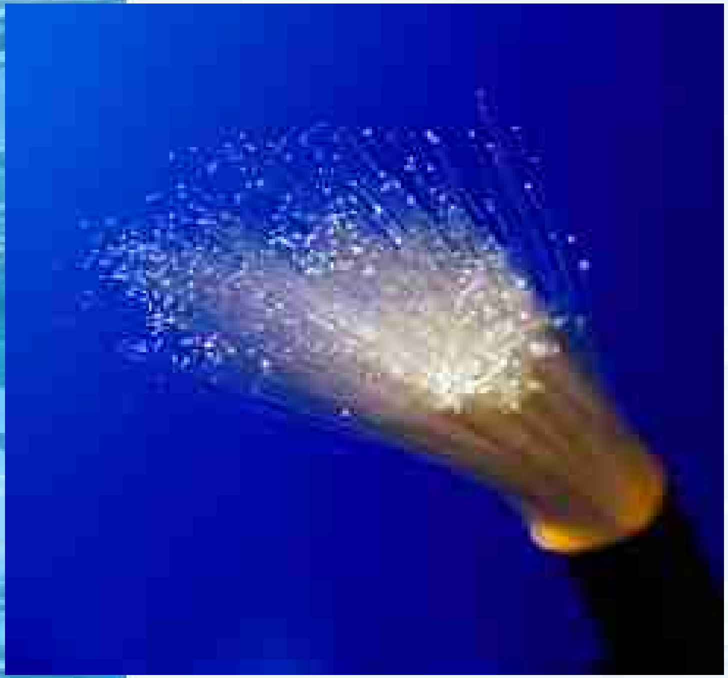
Use an air conditioner to extract vapor from the air.

NB the polymer must be a chemo-set that does not form new linkages after the initial curing.

Dry the skin + sub-cutis separately from muscles + fascia.

Spray the interface with mist of polyurethane, then fit skin like a glove, & vacuum bag to bond them together.

Building nerves



Use ultra fine optical image fibres for nerves

Fibre diameter 12 microns

Bending radius 10mm

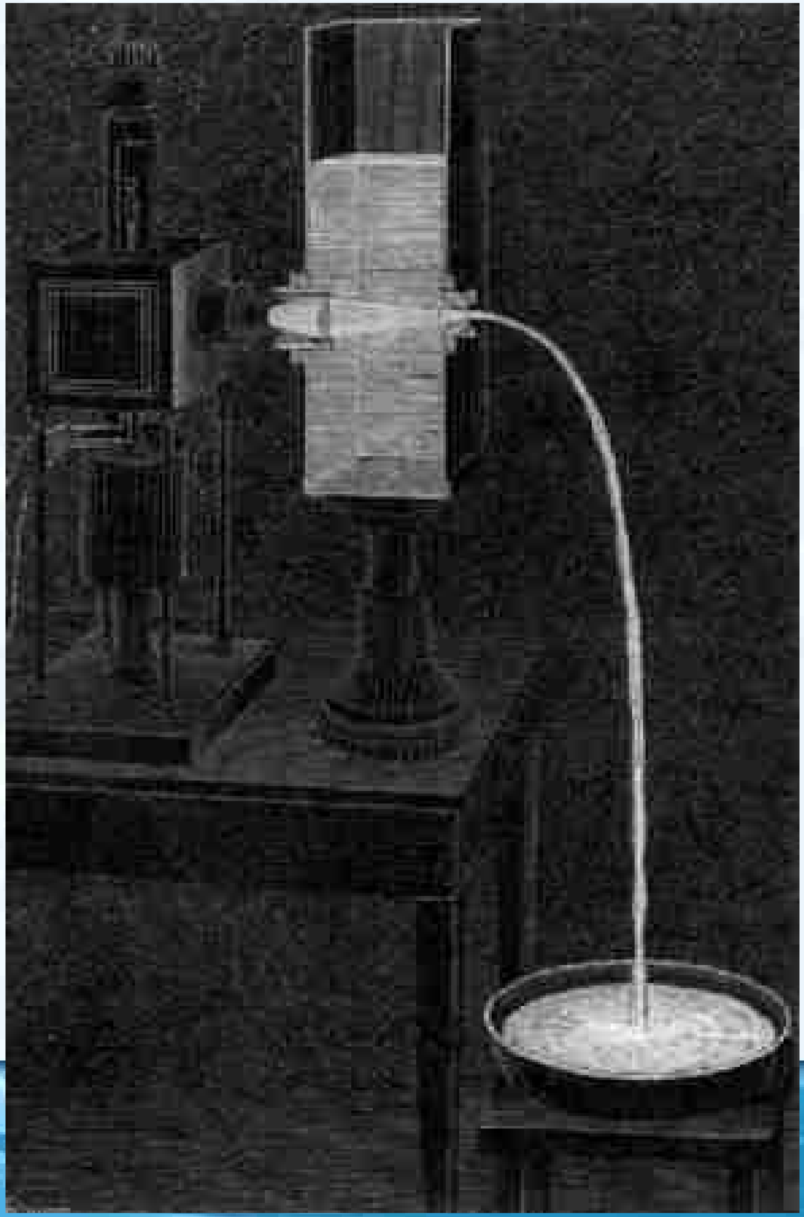
Free from electrical interference.

Aneal & stretch the last 10cm for finer, more flexible fiber in the fingers.

Bundle of 3000 fibres, diameter 0.2mm

Capture data on CMOS chips.

A more flexible nerve



3D inkjet printed silicone gel pipe

High refractive index oil printed into the pipe.

Gel stretched to reduce diameter.

Cured to convert gel to elastomer.

Provides an optic fiber that will not crack.

Fine enough to allow free movement of subcutis.

Power LED for sensor via 'wires' with saline hydrogel.

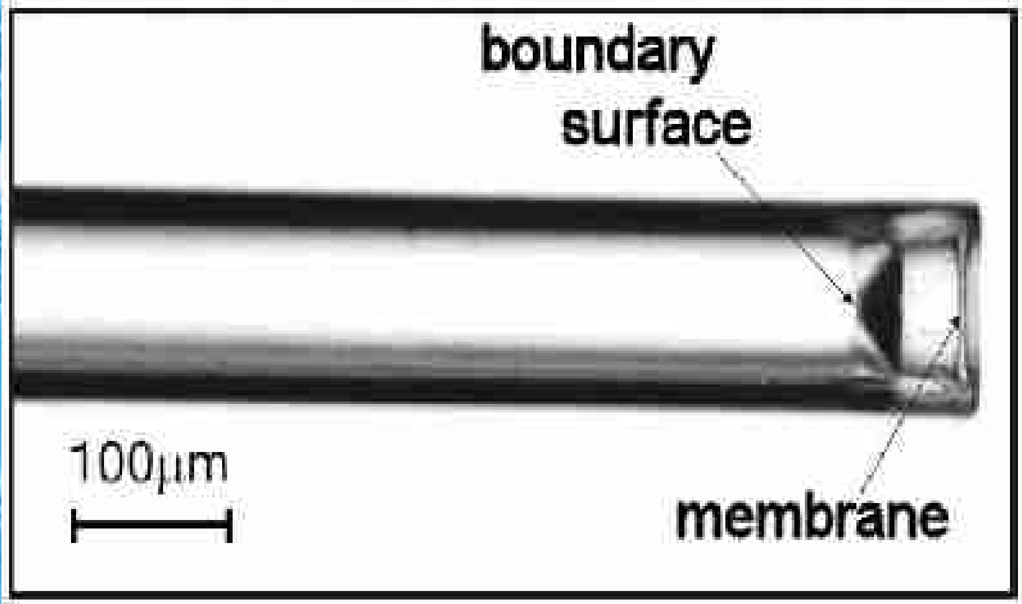
Nerve endings

Need to measure vibration, fine resolution touch, deep pressure, skin temperature, tension in skin/tendon/ligaments.

0.125mm diameter optical pressure sensors developed by University of Maribor, Slovenia. Manufactured by Fiso in Canada as FOP-F125.

Pressure range +/-300mgHg

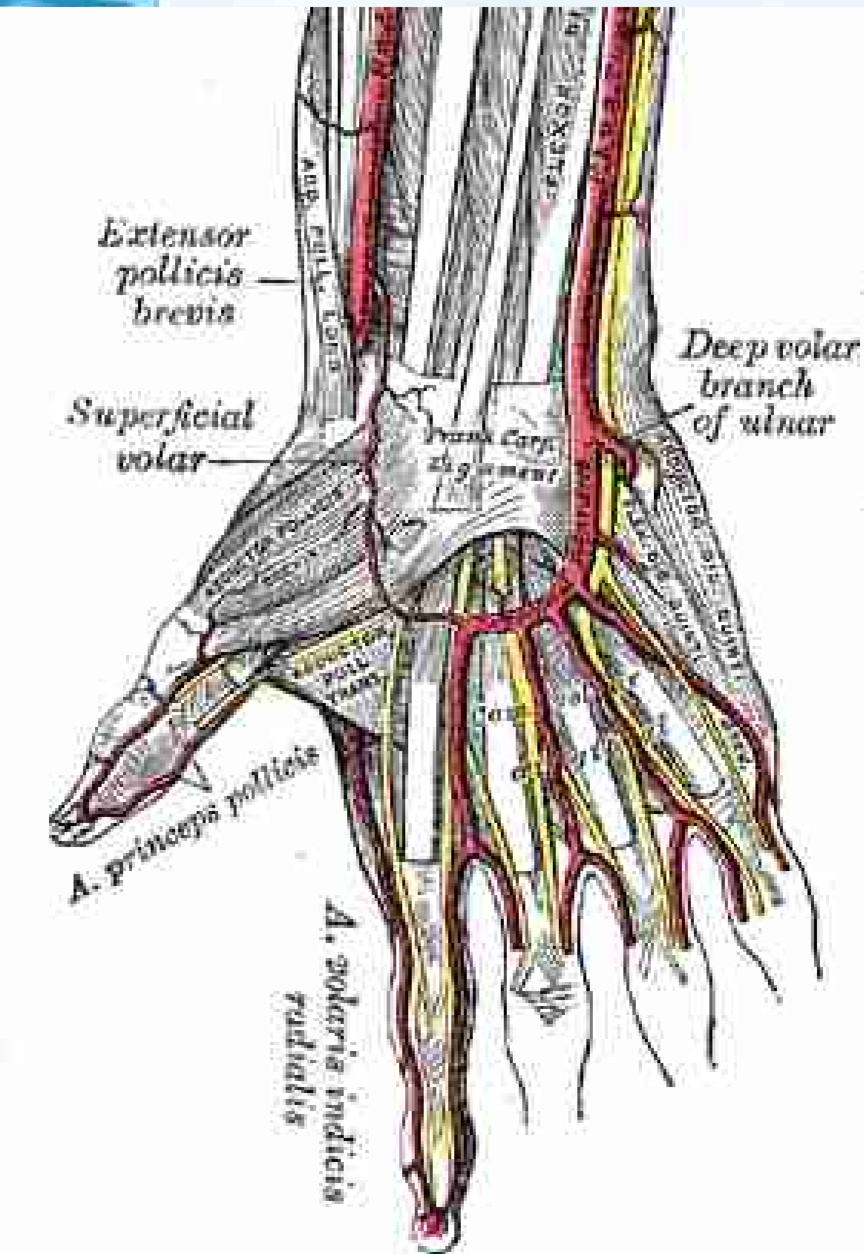
Accuracy 5mmHg



Use 1 sensor per mm @ finger tips, 1 per 5mm elsewhere

embed in dermal ridges of fingerprint, ligaments, tendons, nailbeds.

Protecting nerves



- Make them longer than the tissue around them
- Run them in protected locations : diagrams of anatomy
- NB minimum radius of curvature for optic fibers
- NB stiffening effect of fibers in tissue

Muscles

Danfloss Polypower lifting 10kg

Need force density, dynamic range, elasticity, soft fiber bundle, very low resistance.

Hard to match muscle, BUT

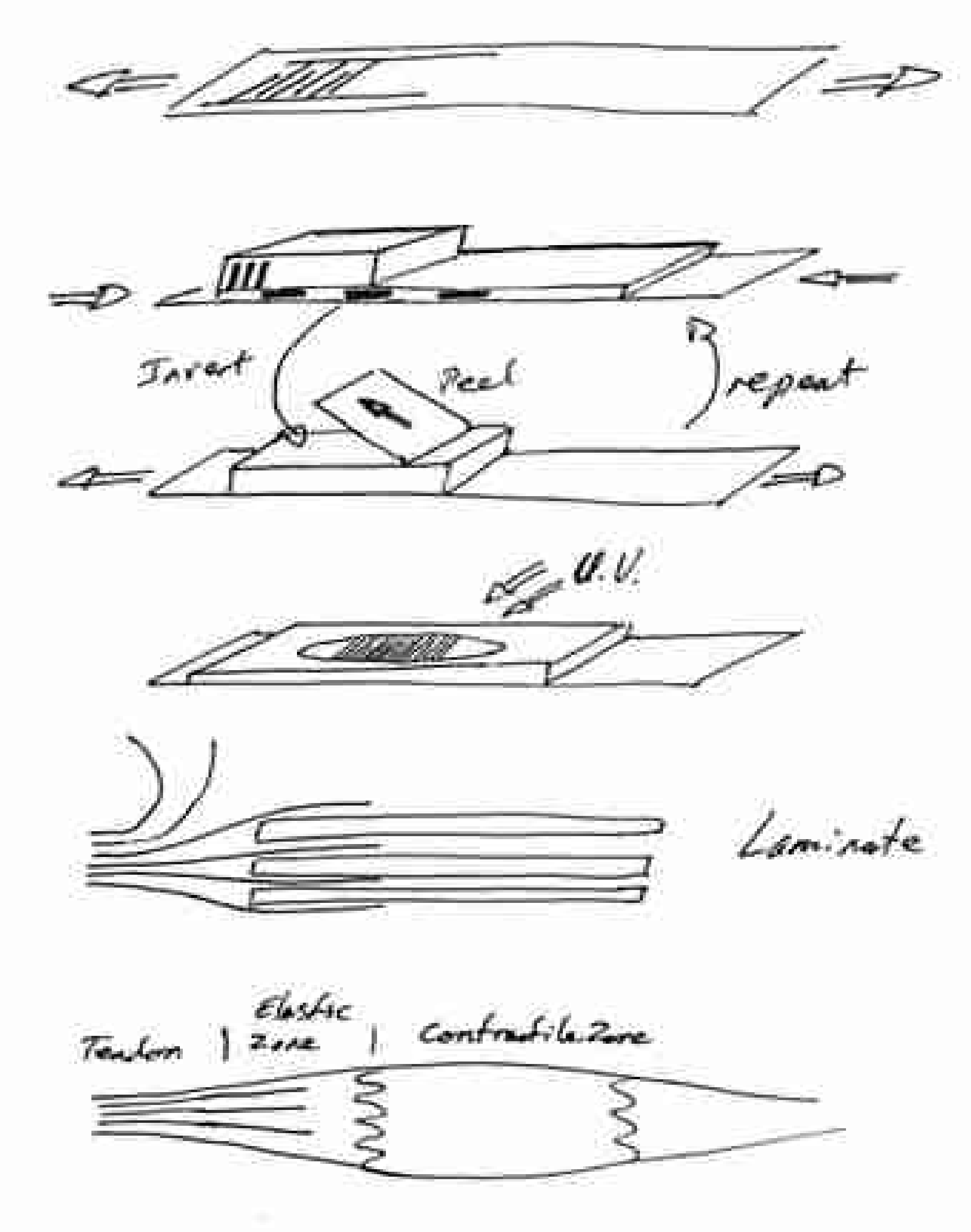
We can use different actuators for different purposes.

Dielectric gel stack actuators may be useable.

1 MPa contraction matches muscle

High voltage requires insulation.

Printable gel dielectric stack



Non-polar dielectric gel : eg Hexane, Carotene, Silicone

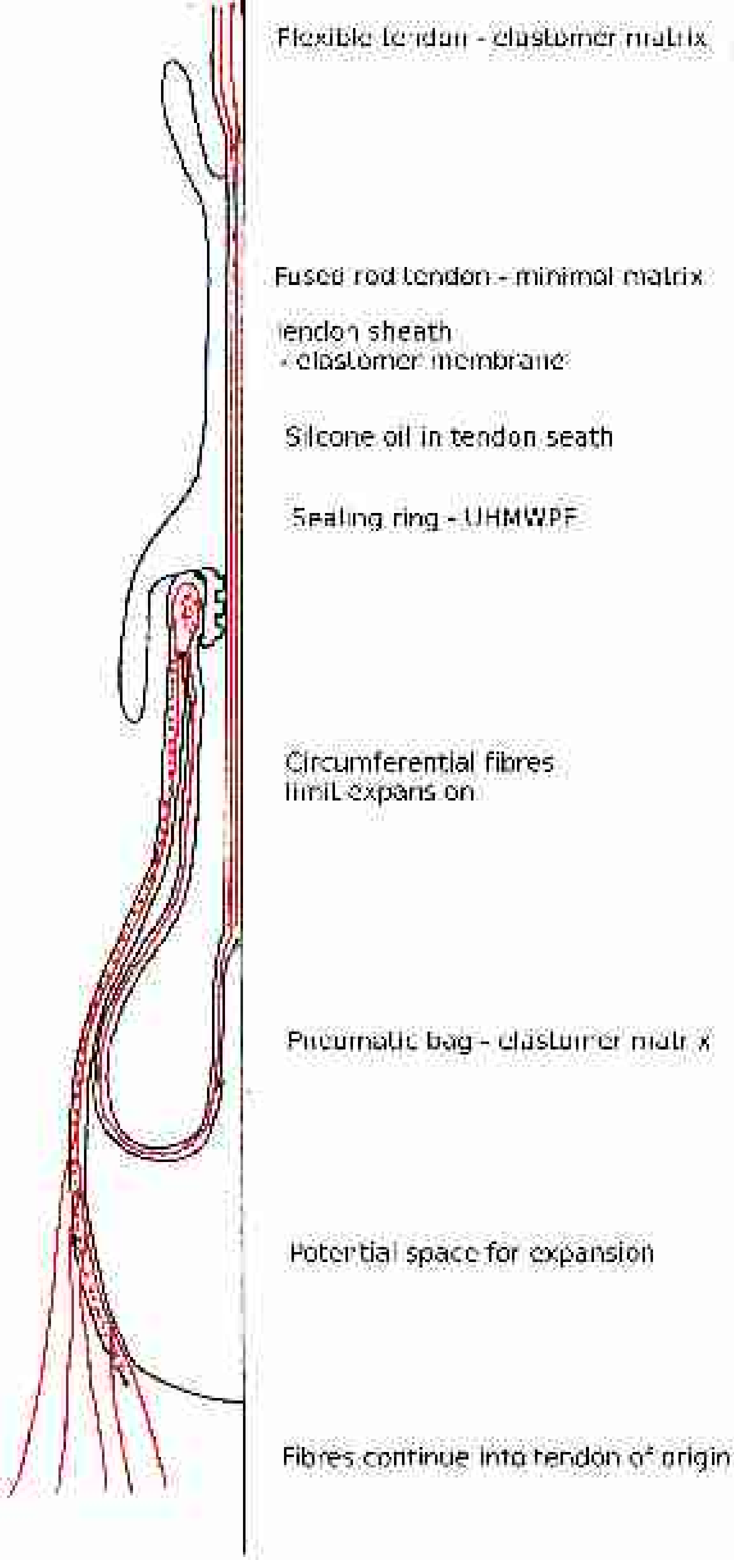
Saline hydrogel gel for plates

Print sheets of muscles hyper extended in pseudo-plastic fluid state.

Compress longitudinally then cure to form permanent gel shape, and laminate to tendon fibers.

Allows structure much finer than the resolution of the printer.

Hyperelastic gel spliced with tough fibres resembles the relaxed state of muscle

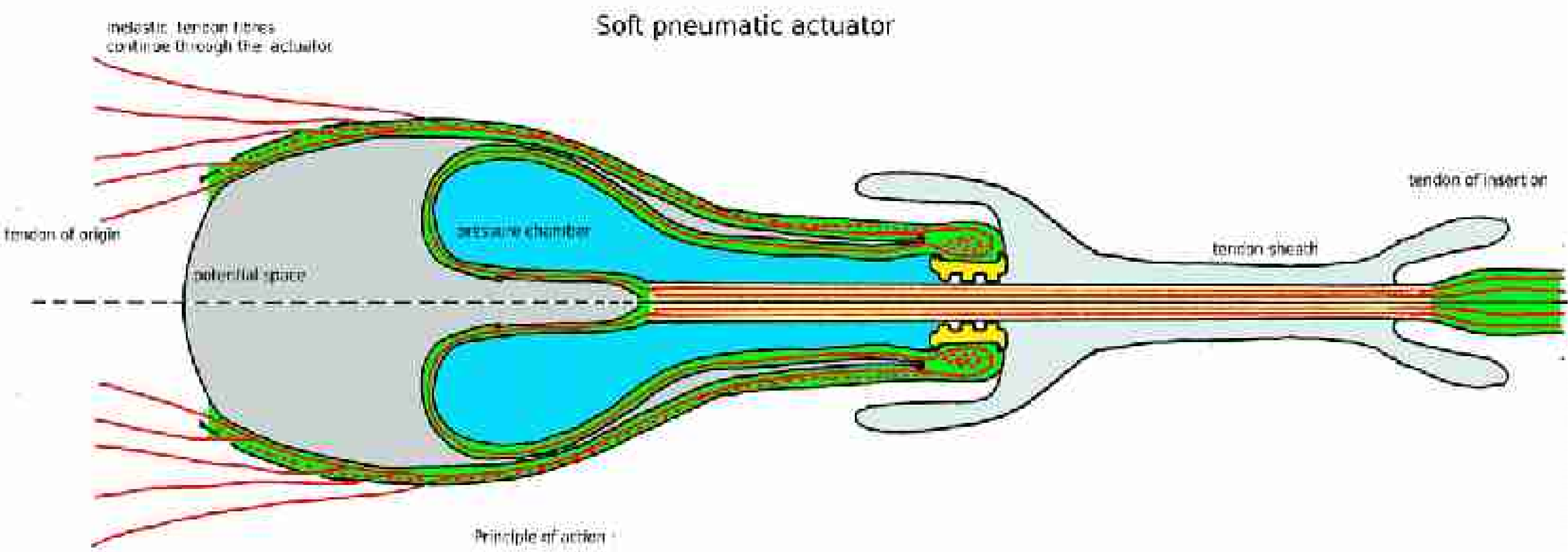


A Pneumatic muscle

- Fully flexible
- Integrates with skeletal system
- Continuous tendon fibers
- Varying matrix and geometry
- Long stroke and high pressure
- Low friction – anisotropic elastomer composite
- Better shape & more compact than pleated or woven air muscles.

Soft pneumatic actuator - detail

Stress:strain curve - designed by varying circumference along length



- elastomer matrix
- fused rod, with uhmw-pe sheath
- uhmw-pe dynamic seal

Principle of action :

Tendon fibres (red) run through the length of the actuator, preventing longitudinal stretching.

The bag of the pressure chamber can expand perpendicular to the tendon fibres.

The outer bag is constrained by circumferential fibres, limiting the expansion of the pressure bag.

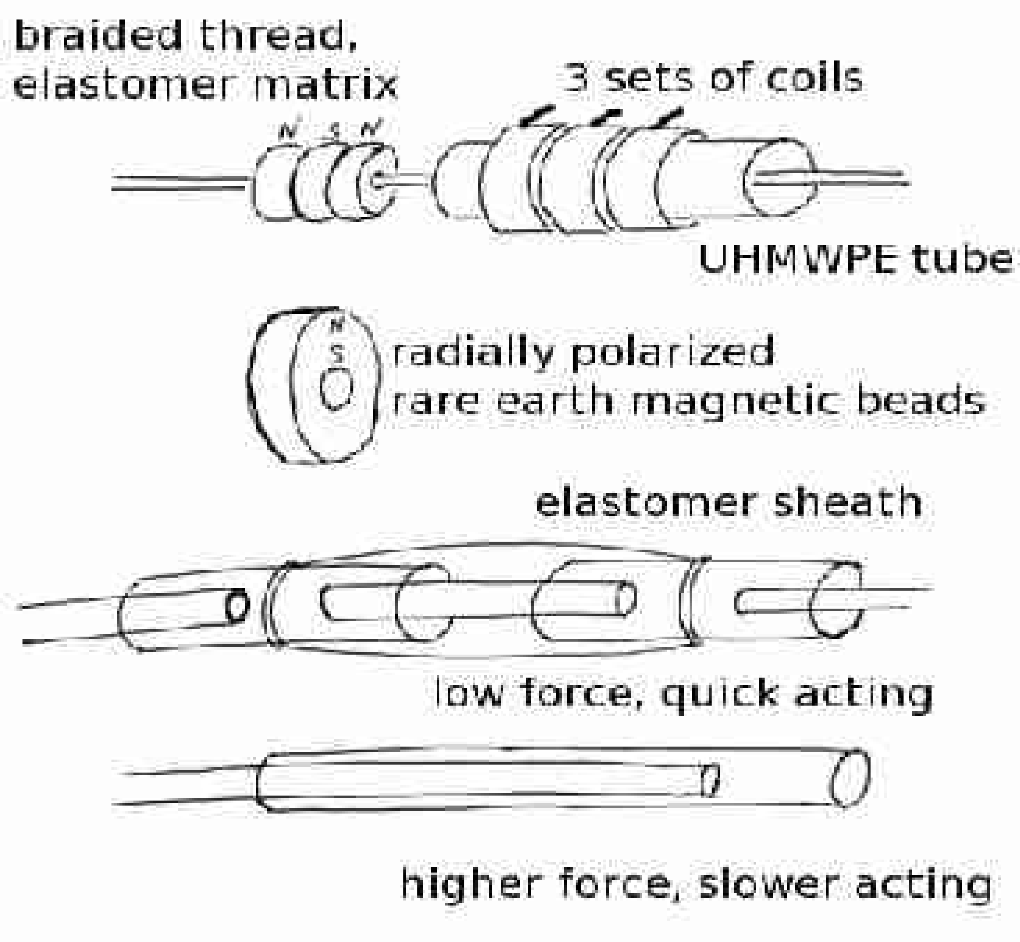
Thus the pressure bag forms a cylinder, whose expansion depends on pulling the fused region of the tendon through the dynamic seal.

Most of the thrust of the pressure chamber is born on the conical shoulders of the outer bag.

Maximum pressure is limited by the density of circumfrential fibres in the outer bag, and the number of fibres in the tendon.

Any leaked air is scavenged from the tendon sheath.

A fibrous electric motor



Millimeter diameter, indefinite length, “Force Tube”.

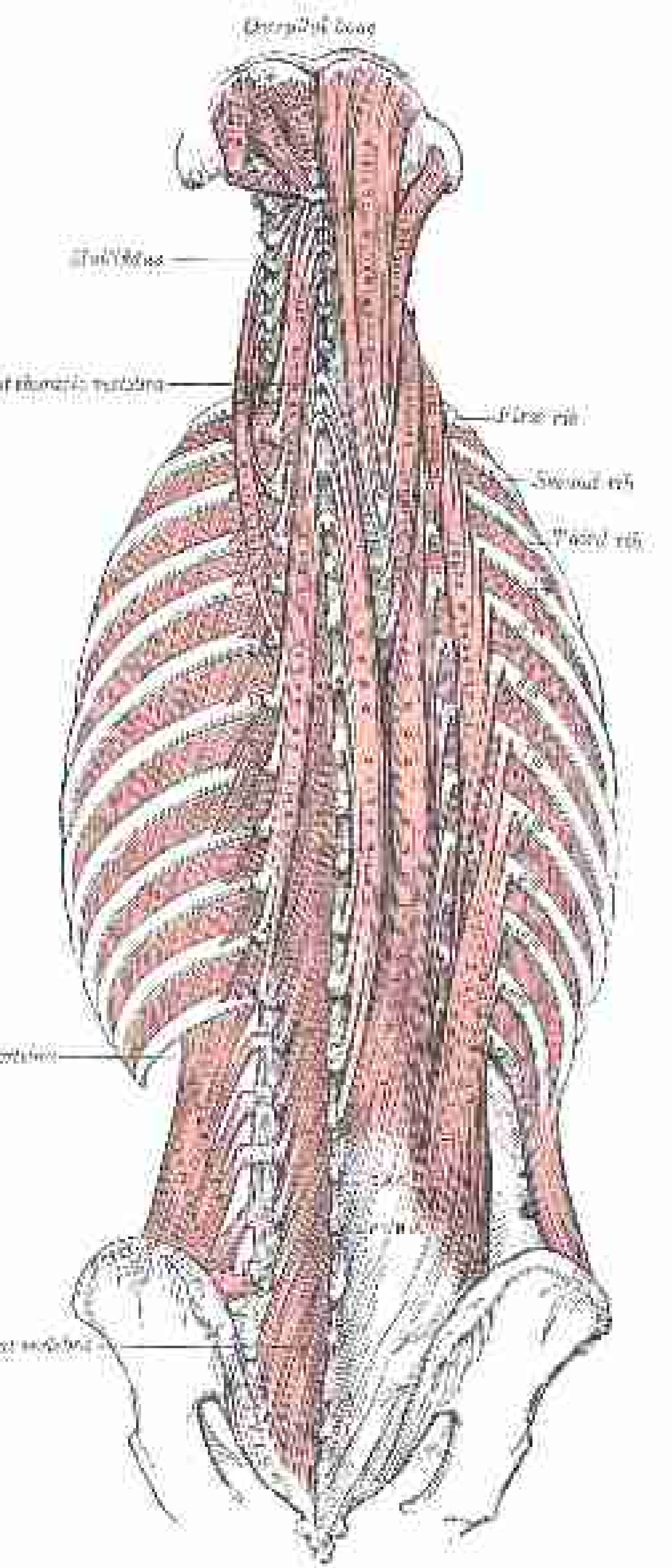
Low force

Very compact, and precise.

No bulging inflation

Muscles of facial expression

Fine control of fingers for delicate tasks



Elastic in place of muscle

Fascia, sheet muscles of abdominal wall, deep muscles of spine

Can be replaced with elastic – nylon-lycra sheets passing into bones, elastomer matrix in muscle.

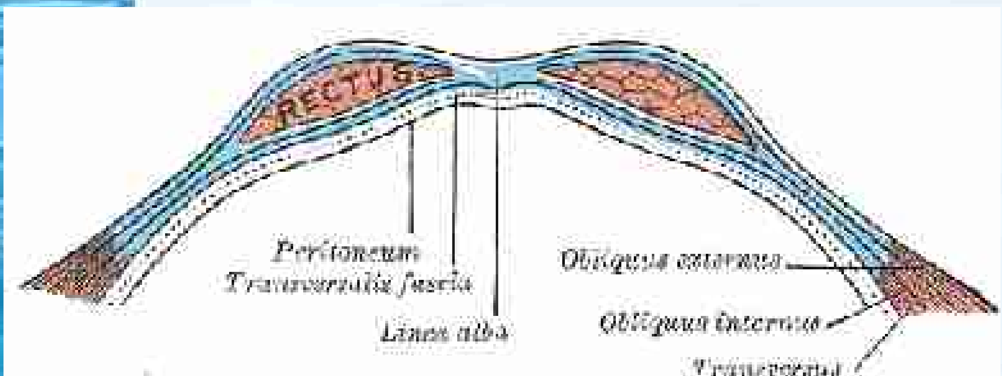
NB gel between muscle sheets.

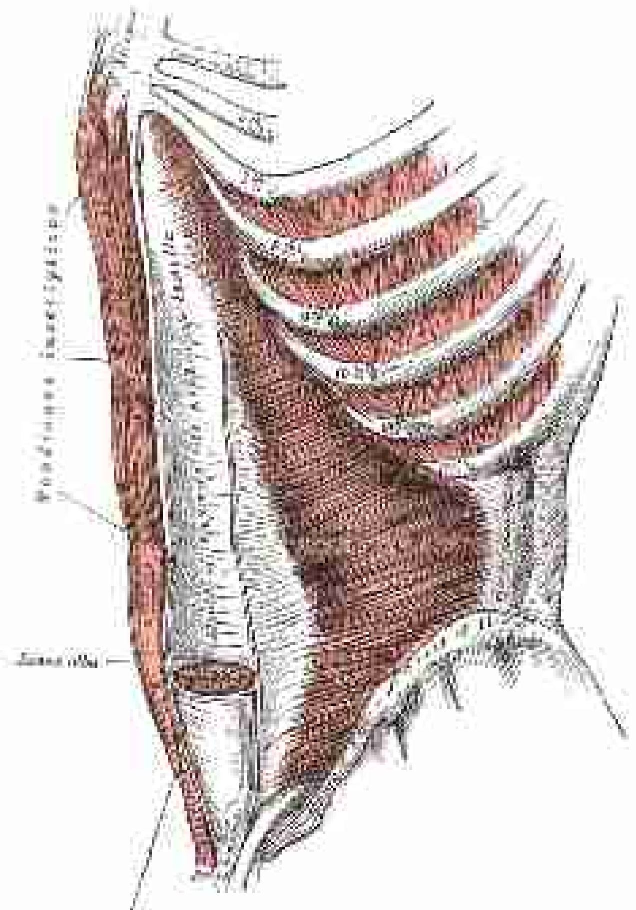
Redundant level of control that is not essential for normal movement.

The cost :

- cannot be tensed for extra rigidity - anticipating impacts and heavy loads.
- Reduced agility

Making elastic muscles





Knitted nylon-lycra sheets that pass through the bones of ribs and spinal processes,

THEN impregnated with an elastic matrix

NB direction of abd muscles + place of actuators between the sheets.

Vary elastic modulus & bulk of material to vary the athletic character of the robot.

Need gel = areolar tissue, between the layers to eliminate friction.

Single fibro-elastic continuum

Think of the body as a **single fibro-elastic continuum.** Cavities only exist if the shear strains necessitate it, ie tendon sheaths and synovial joints

Muscular energy is expensive.

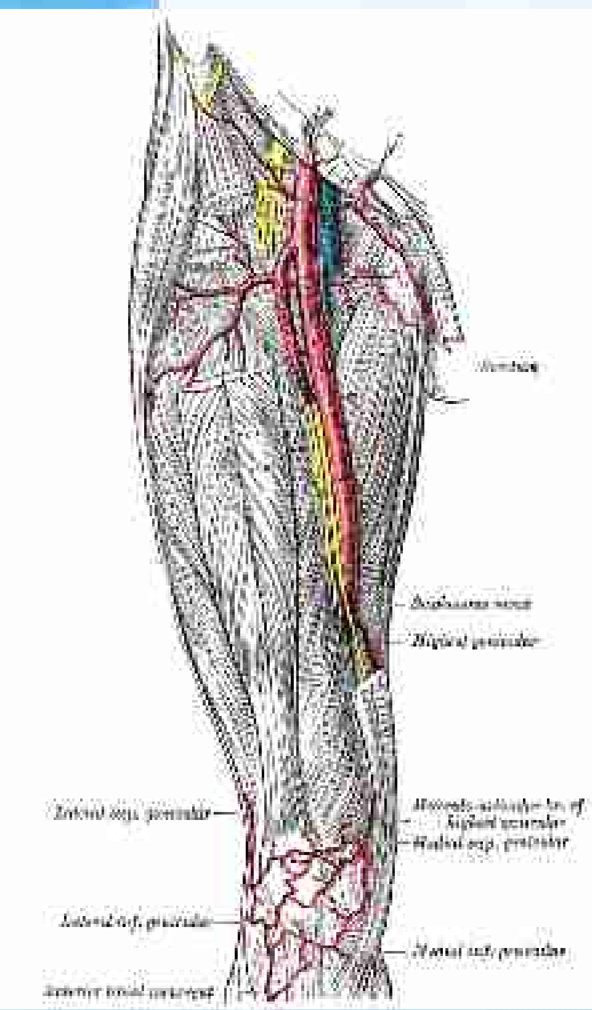
The body moves harmonically, transferring energy between limbs. Areolar tissue provides low resistance, elastic lubrication of relative movement.

Work-done is stored as inertia & elastic energy NOT dissipated as friction/hysteresis.

There are multiple levels of tuned compliance, achieved through variation of matrix, fibers, and geometry.

Any object that does not share its elastic moduli, anisotropies, geometry, and mass distribution cannot have the same dynamics.

Body layout - adapt the natural solution

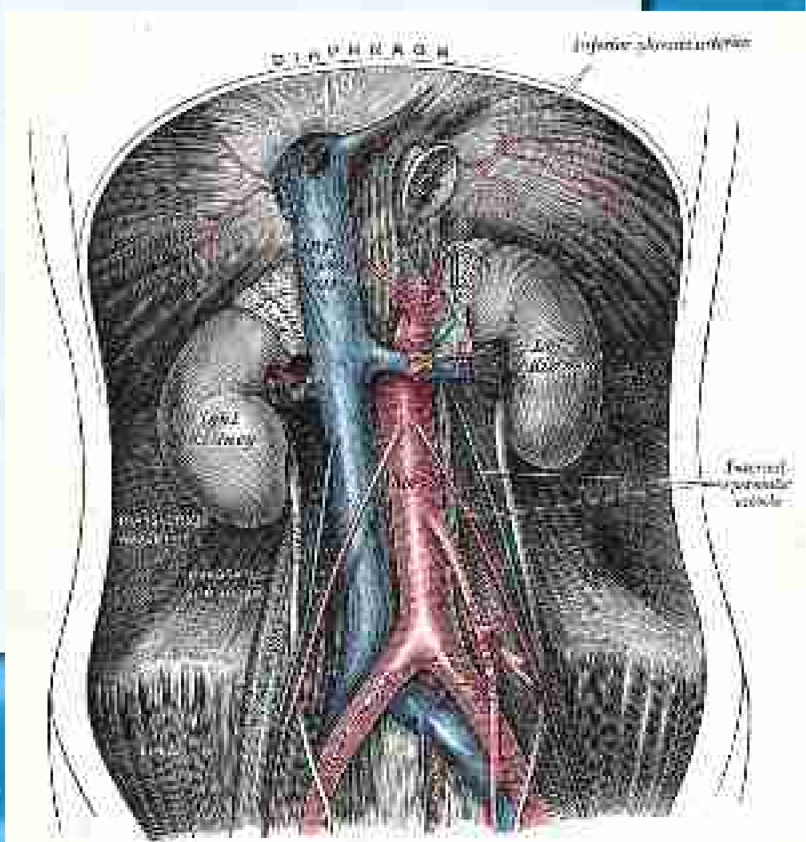


Put pipes & cables along routes of major blood vessels & reserves. These areas have the least risk of damage.

Abdomen bears load like a spinal disk. The lumbar spine and fluid filled, muscle walled abdomen work together for locomotion and balance.

Things that need protection can be fixed to the spine, like the kidneys, or the inside of the pelvis.

Unzip the mid-line for access, + unbolt sternum



Power & Robot Physiology

Simple version 1, use umbilicus for indoor activity & knapsack power unit for out door activity.

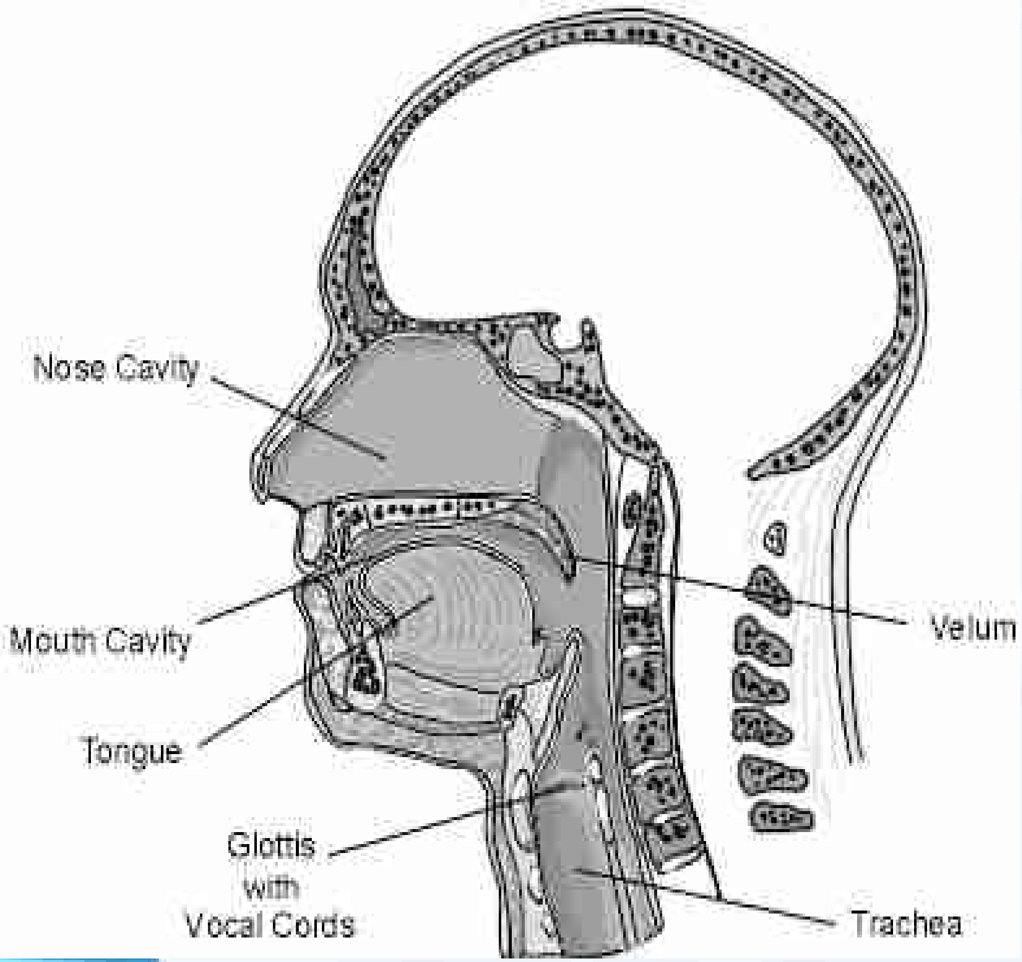
Free play – climbing & running & jumping may make internal power & wifi worth the trouble.

On board power is not just about freedom, and weight.

Heat, and energy metabolism are essential functions that define basic motivations.

Balancing learning with meeting essential needs and avoiding harm define the problem that emotion and intelligence exist to solve.

Senses of taste & smell

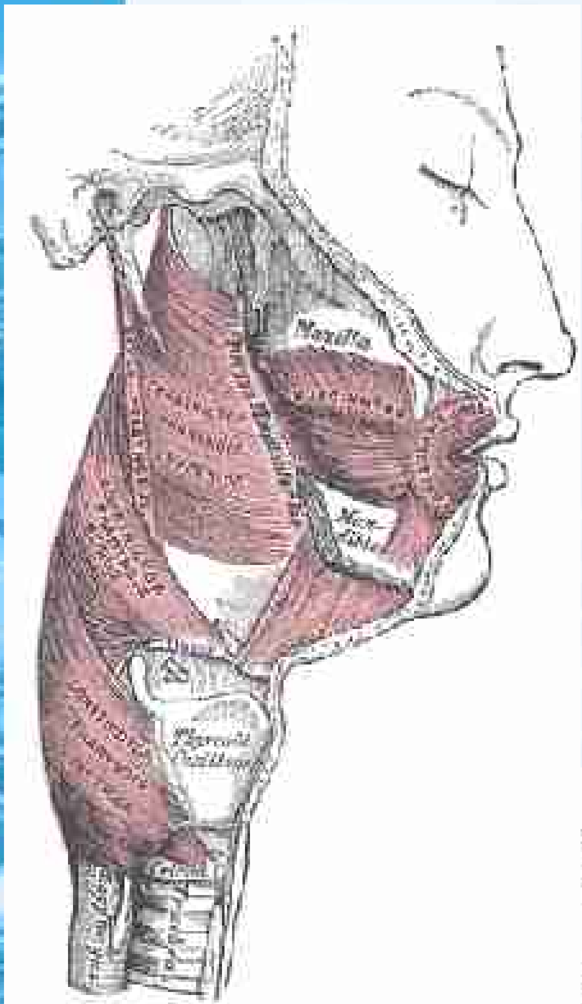


olfaction & eating are very important.

Wet phase chemical sensors require salivation & swallowing.

Tongue, cheeks, pharynx, oesophagus would be buildable with resin transfer and printed muscles.

Oral & vocal tracts

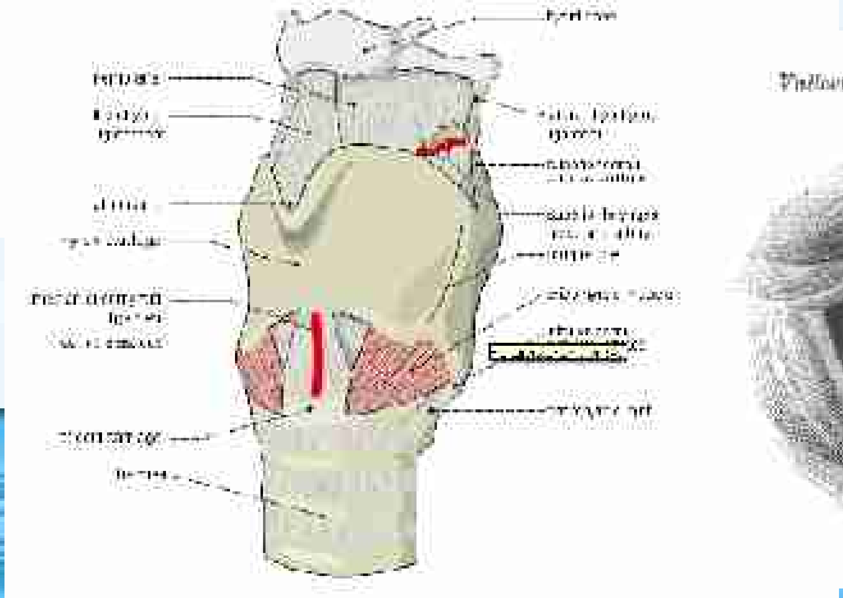


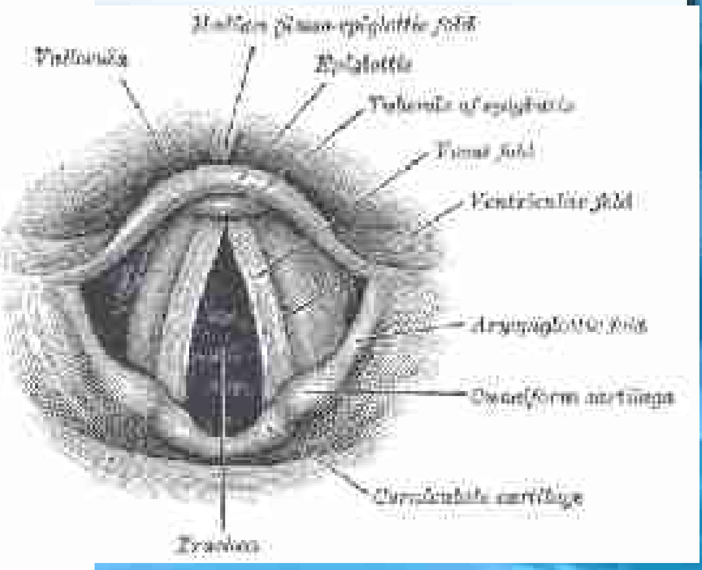
feasible goals with fibro-elastic tissues

very important for :

- social interaction
- infant exploration.

Should at minimum have lip-speaking and lip sensitivity.





Expressive eyes, Binaural hearing

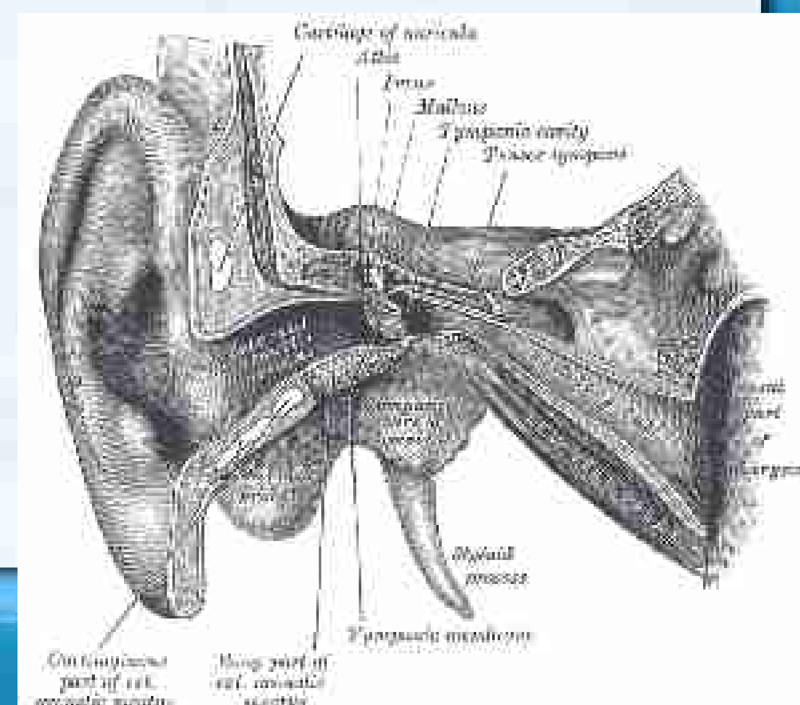
Depth of field focusing,

Iris, foveated retina,

wide peripheral vision,

peri-ocular facial muscles.

Pinae & canals have substantial tuning effect, relevant to direction finding due to changing the frequency spectrum.

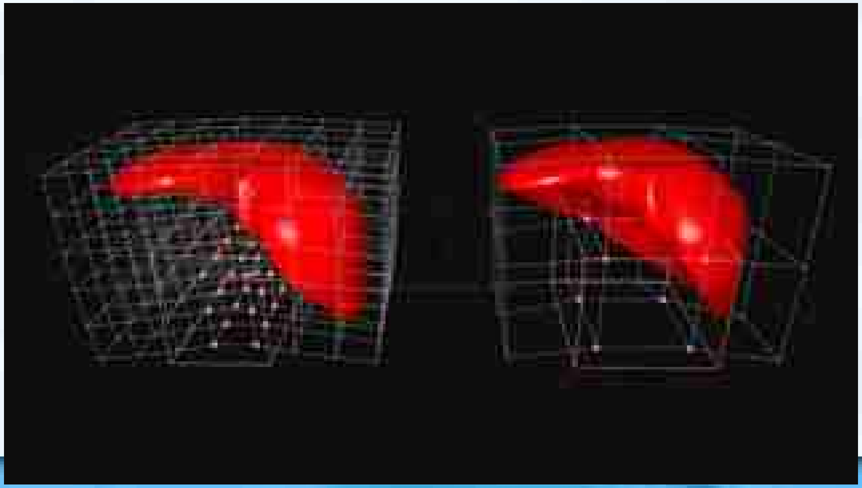


Simulation of soft bodied robots

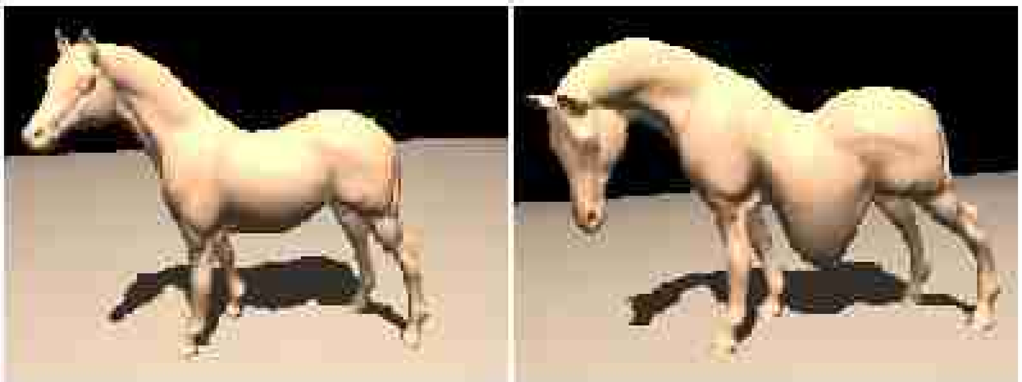
Sofa-framework for surgical simulation coordinates FEM, collision and other solvers.

Design/grow/evolve body + train nervous system.

LGPL license, from INRIA, France.



FEM for anisotropic, hyper-elastic



"A Real-Time Multigrid Finite Hexahedra Method for Elasticity Simulation using CUDA"
(C. Dick, J. Georgii, R. Westermann
Technical Report, July 2010)
Graphics & Visualization,
Technical University Munich

GPU accelerated FEM

for anisotropic, hyper-elastic materials including co-rotation.

physics-based simulation at an object resolution of 64x64x64 is achieved at interactive rates.

Conclusions

Functional biomimetics

=> understanding the body

Vs

=> imitating outward appearance

Doable now

- Existing materials
- Existing tools
- Established techniques
- New combinations

Bibliography

“Biological actuators are not just springs” Buehrmann, T., and Di Paolo, E. A., (2006).

“The organ of form: towards a theory of biological shape” Francisco J. Varela and Samy Frenk (1987)