Grundlagen der Biomechanik – 719.009
Sommersemester 2016, TU Graz

Vortragende:	**Gerhard A. Holzapfel** **Justyna A. Niestrawska**
Studienassistentin:	Julia Branstetter

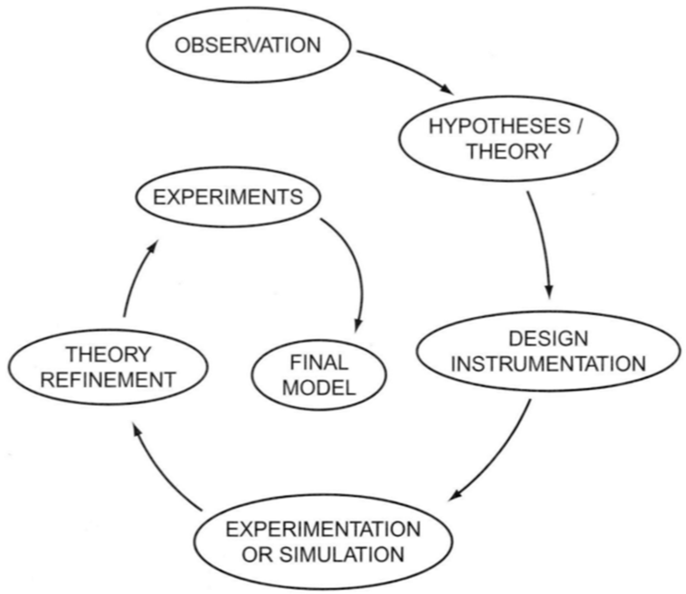
Institut für Biomechanik
Stremayrgasse 16/2, TU-Graz

Vorlesung –19 :

Experiments in Biomechanics

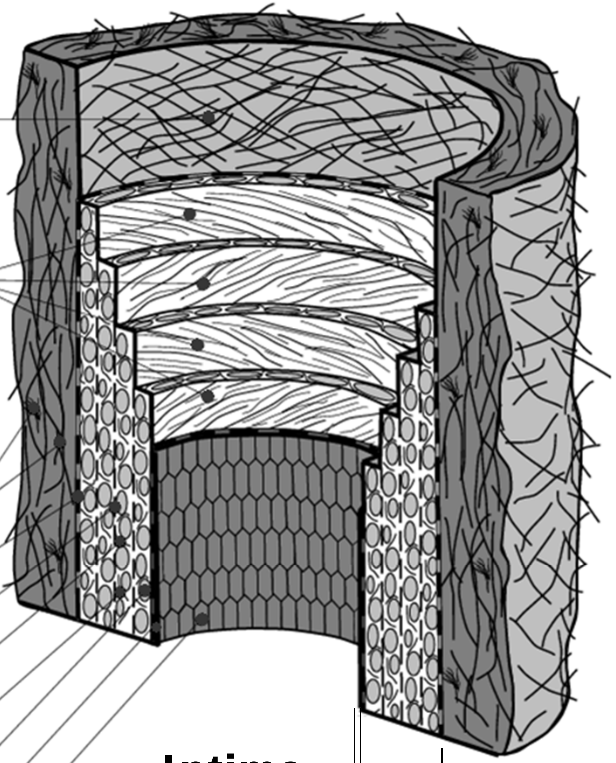
- **Uniaxial Tensile Test**
- **Biaxial Tensile Test**
- **Extension-Inflation Test**
- **Shear Test**

Experiments in Biomechanics



Arterial Histology

Major components of a healthy *elastic* artery



Composite reinforced by collagen fibers arranged in helical structures

Circumferentially arranged fiber-reinforced medial layers

Bundles of collagen fibrils

External elastic lamina

Elastic lamina

Elastic fibrils

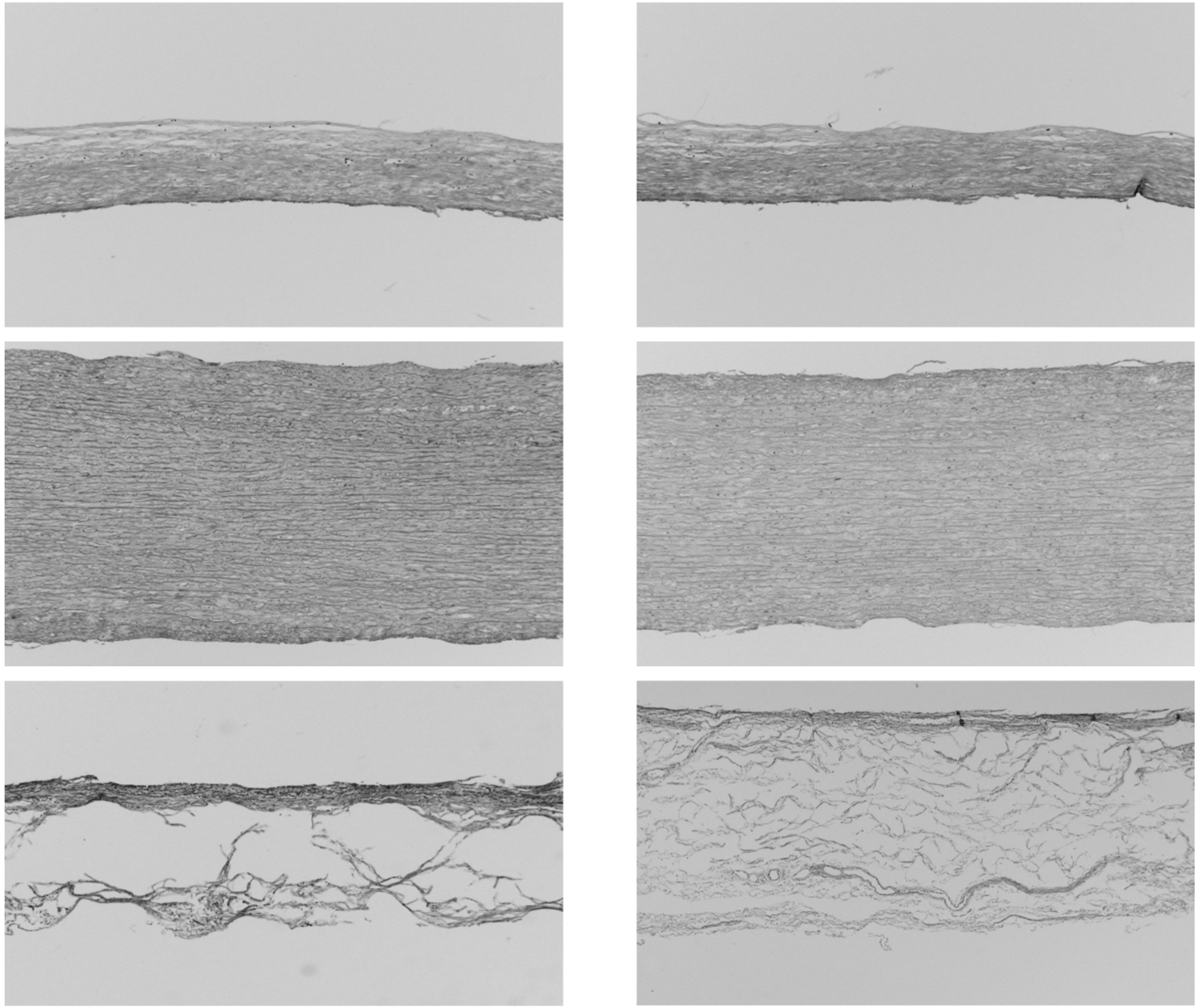
Collagen fibrils

Smooth muscle cell

Internal elastic lamina

Endothelial cell

Aorta abdominalis after layer-separation

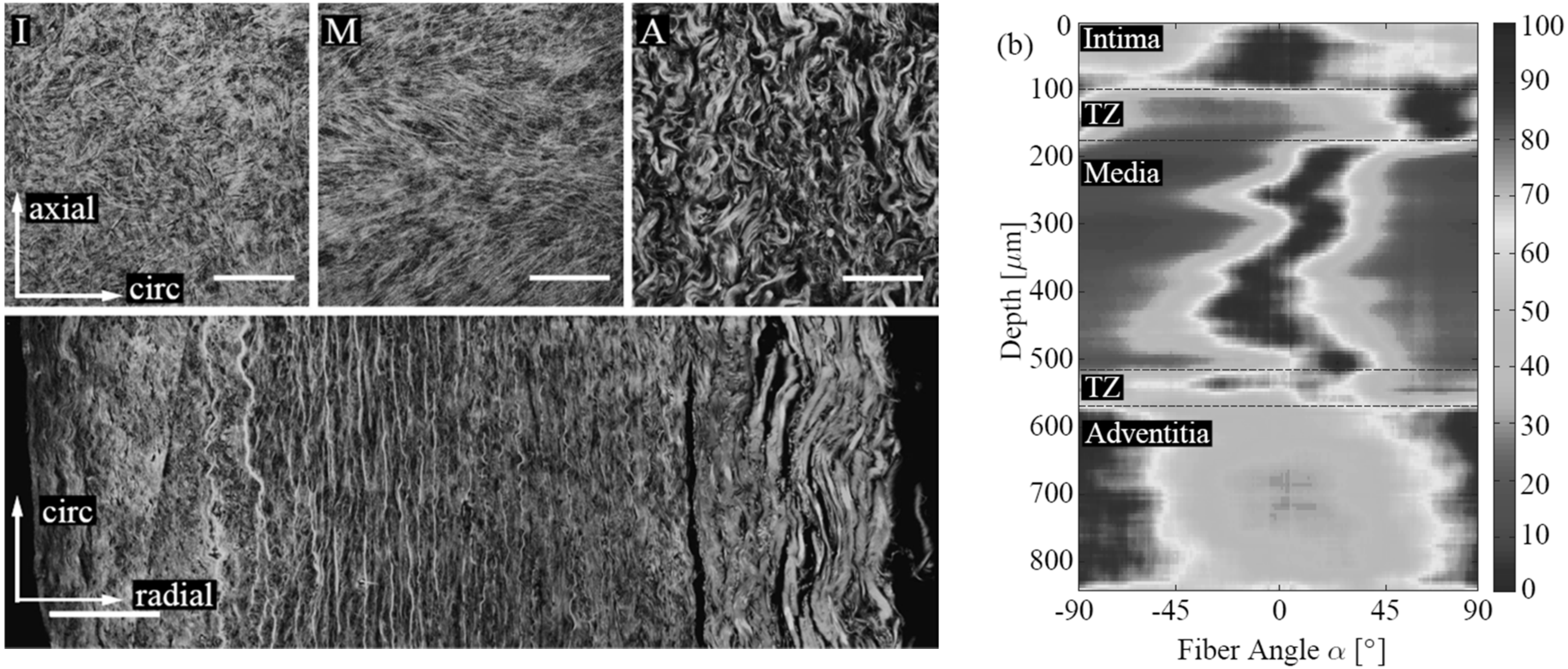


250 μm

Figure: Photomicrographs of 3-μm-thick Elastica Van Gieson - stained sections from wall layers in circumferential direction stemming from aorta abdominalis after anatomic separation and mechanical testing. *A*: intima. Note homogeneous thickening due to diffuse intimal fibrous hyperplasia in an aged patient. The outer part (lowest part in image) carries elastic fibers from the membrana elastica interna. *B*: media. Note irregularities in the surface are caused by histological processing during embedding. *C*: adventitia. Note tendency to separate and stretching after microtome cutting, because of loose collagen fibers in the outer part (histologic artefact). Original magnification 40x.

Aorta abdominalis

a)



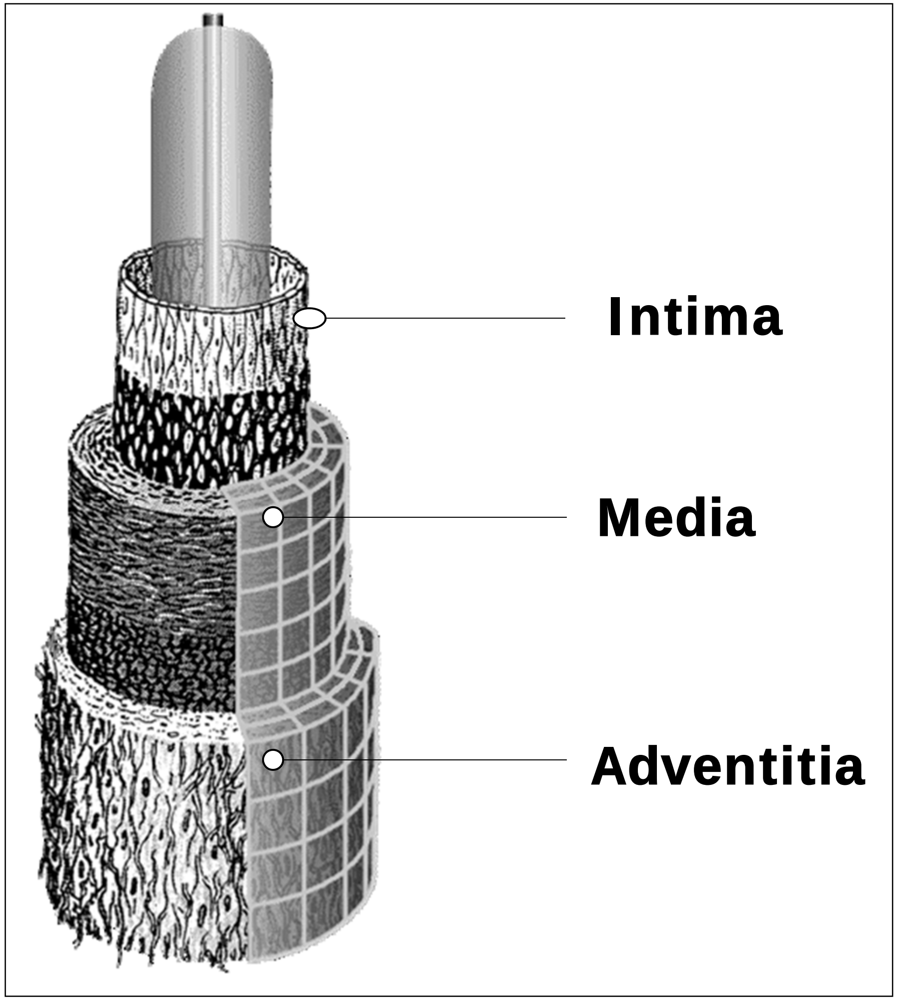
a) Second Harmonic Generation (SHG) images throughout the depth of the abdominal aorta (top) and a side view of the radial direction. Note the distinct layers, the highly aligned fibers in the media and the axially aligned, very wavy fibers of the adventitia.
b) Intensity plot of fiber angle distribution throughout the depth of the same specimen

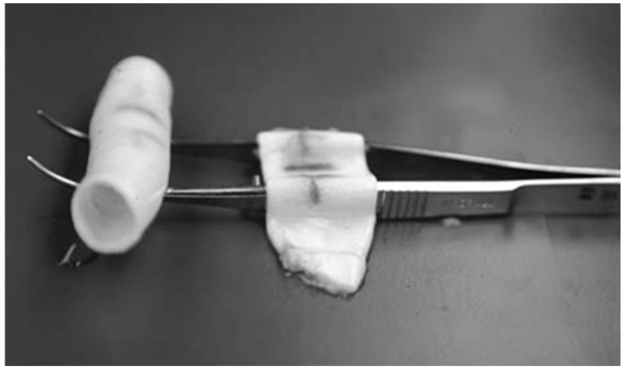
General mechanical characteristics of soft tissues

- **Anisotropic (fibers have preferred directions)**
- **Incompressible**
- **Non-homogeneous (in a microscopic sense)**
- **Large deformations, viscoelastic (viscoplastic) behavior**
- **Pre-strained**
- **Material response is nonlinear stiffening**

Material properties depend on

Topographical site and respective function in the organism





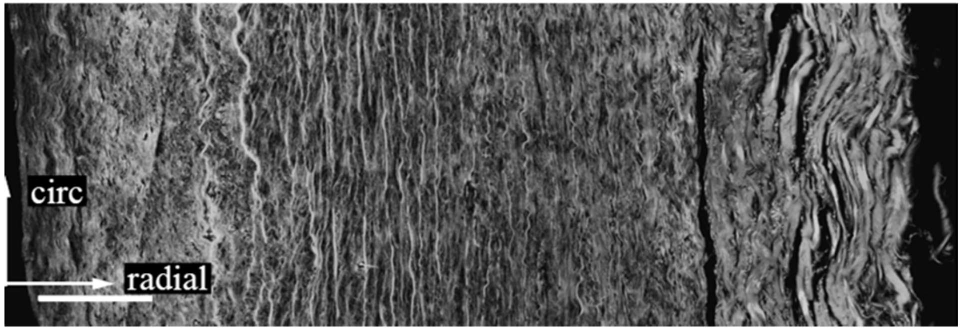
Material properties depend on

- Topographical site and respective function in the organism
- Concentration and structural arrangement of constituents collagen, elastin, hydrated matrix of proteoglycans

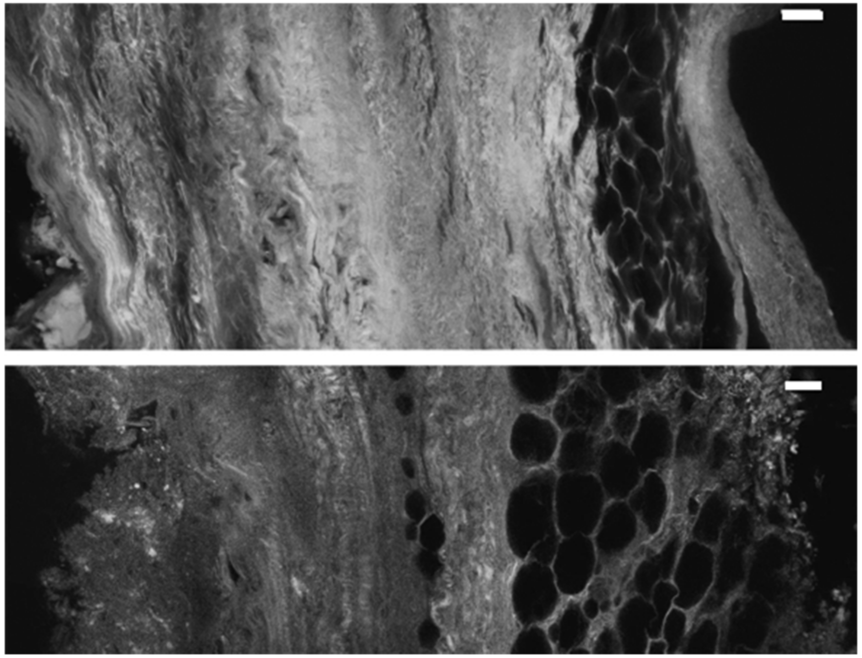
Material	Ultimate tensile strength (MPa)	Ultimate tensile strain (%)	Collagen (% dry weight)	Elastin (% dry weight)
Tendon	50-100	10-15	75-85	<3
Ligament	50-100	10-15	70-80	10-15
Aorta	0.3-0.8	50-100	25-35	40-50
Skin	1-20	30-70	60-80	5-10
Articular Cartilage	9-40	60-120	40-70	-

Material properties depend on

- Topographical site and respective function in the organism
- Concentration and structural arrangement of constituents collagen, elastin, hydrated matrix of proteoglycans
- Species
- Age
- (Vascular) risk factors
- Diseases



SHG image of the circumferential – radial plane of a healthy abdominal aorta



SHG images of the circumferential – radial planes of two abdominal aortic aneurysms

Experimental biomechanics is a challenging and important discipline itself.

Experiments provide information that is essential:

- **for formulating constitutive relations**
- **for proposing and evaluating broader theoretical concepts as well as for solving many boundary value and initial value problems of importance.**

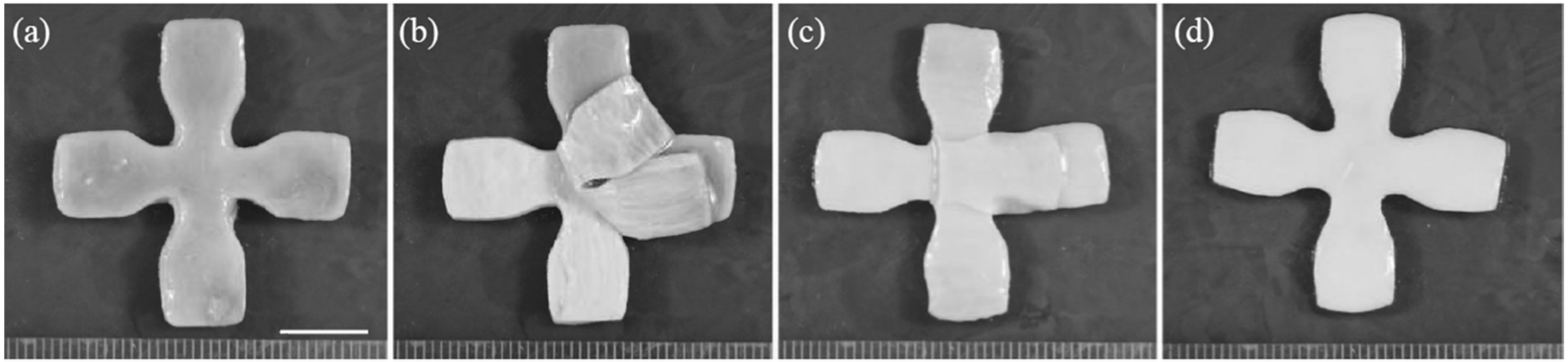
Sample preparation and procedures

Various conditions influencing the results need to be considered:

- Preparation and shape of the sample
- Clamping
- Tissue Integrity
- Time between death and test
- Liquid bath
- Temperature
- Biochemical equilibrium
- Preconditioning

Sample preparation and procedures

Preparation and shape of the sample: e.g. abdominal aorta

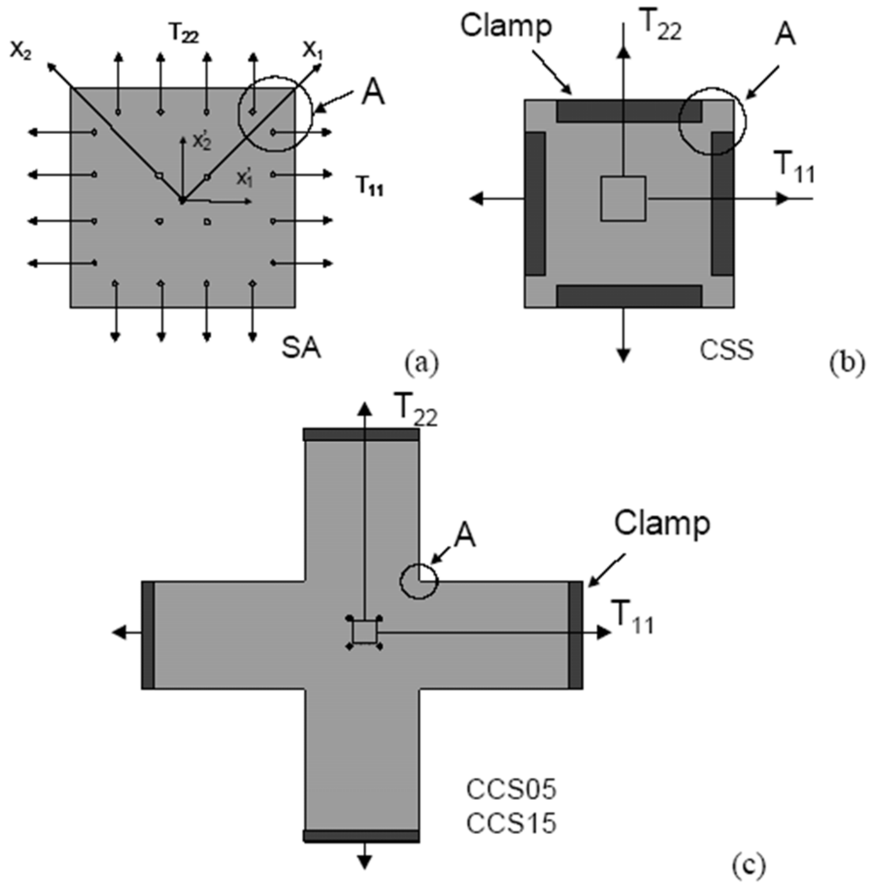


a) Sample which was punched out of the intact abdominal aorta
b) Adventitial layer during peeling off – note some media attached to it
c) Removal of the intimal layer from the media
d) Sample of medial layer after preparation

Sample preparation and procedures

Clamping

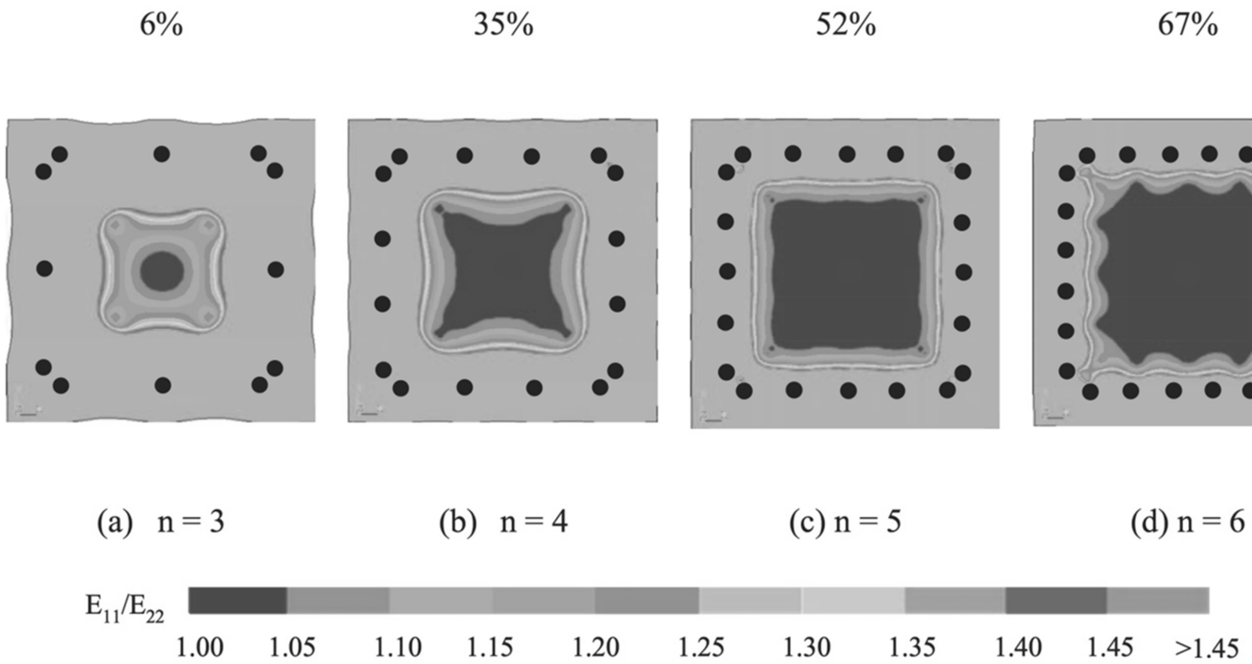
Different gripping methods for biaxial testing (Sun et al 2005) result in different boundary conditions for the sample.



Sample preparation and procedures

Clamping

Number of attachement points changes strain field inside the region they define, as indicated by the color-plots.



A. Eilaghi et al., Journal of biomechanical engineering, 2009.

Sample preparation and procedures

Tissue Integrity

The specimen may not be damaged by

- pathological processes in the body (e.g. inflammations, tumors)
- autopsy (e.g. tear trauma during disembowelling)
- excision (e.g. superficial cuts)
- storage (e.g. to high temperatures, to long storage)

Sample preparation and procedures

Time between Death and Test

It appears that active and passive behaviour are both relatively insensitive to storage at 5°C for up to 48 hours (Cox 1978)

There is no universally prescribed method for storage.

In the literature there are also reports of storage for up to 5 days at 4°C (e.g., von Maltzahn et al 1984), or 1 month at -20°C (Carmines et al 1991).

Sample preparation and procedures

Liquid bath

Soft tissues are usually tested within a Physiologic Salt Solution (PSS), also called Krebs-Ringer solution consisting of water with:

- NaCl
- Na_2HCO_3,
- NaH_2PO_4
- $NaSO_4$
- KCl
- $MgSO_4$
- CaCl
- dextrose

To ensure, that only the passive behavior of muscle tissue is measured, metabolic poisons may be added.

Sample preparation and procedures

Temperature

The body typically maintains its temperature within a narrow range near 37°C.

If this normal range is exceeded, physiologic functions may cease, and thermally induced cell death and tissue degradation may occur.

The rate at which the latter occurs depends strongly on small changes in temperature above 41°C (Chen et al 1998).

For this reasons, measurement and control of temperature is very important in biomechanical testing (Humphrey 2002).

Sample preparation and procedures

Biochemical equilibrium

Related to the bath temperature and chemical composition is the time required for an immersed artery to come to biochemical equilibrium.

Due to the lack of a rigorous analysis of ionic transport across soft tissues as a function of temperature and bath composition, most studies are based on empirical criteria.

Not surprisingly, there are variations in the literature, but **about 1 hour** of initial equilibration time appears to be preferred for arteries (Humphrey 2002).

Sample preparation and procedures

Preconditioning

Arterial behaviour depends on the strain history. Soft tissues tend to soften in multiple cycles; this was observed before in rubber.

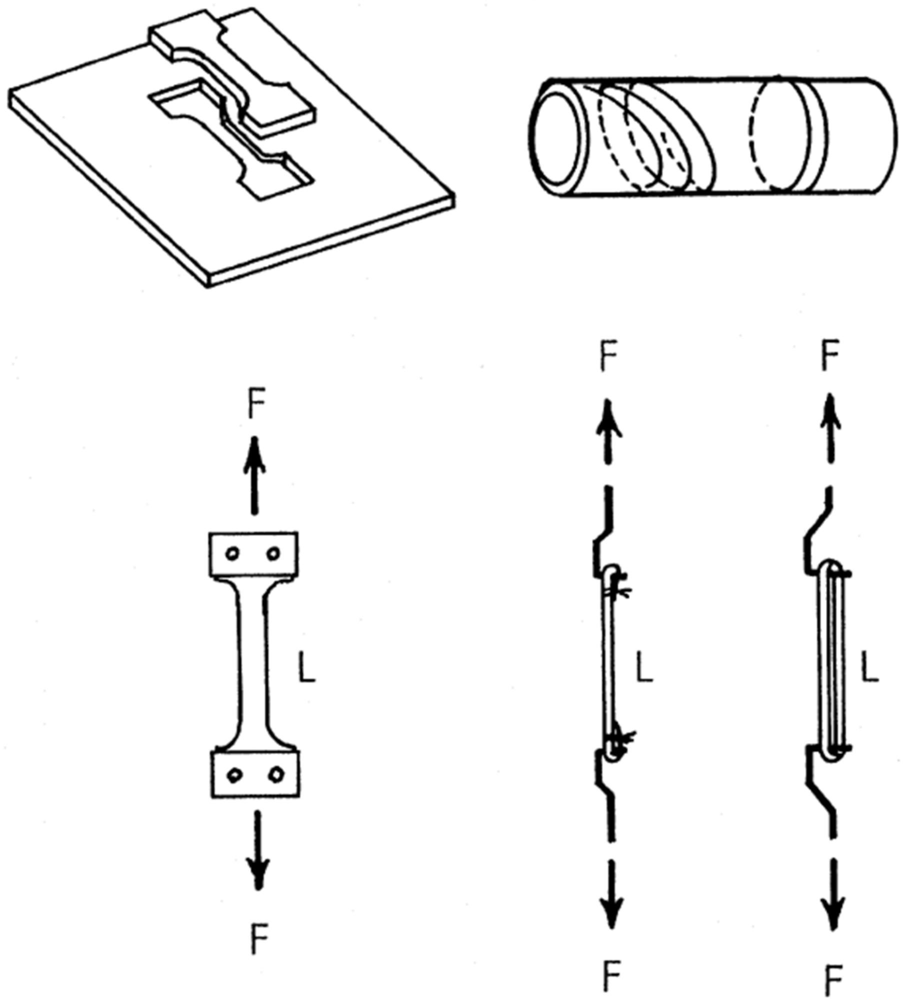
After a number of loading-unloading-cycles, the stress-strain results become repeatable. This procedure is called preconditioning.

The mechanisms which cause this behaviour are unknown.

Uniaxial Tensile Test

Uniaxial Tensile Test

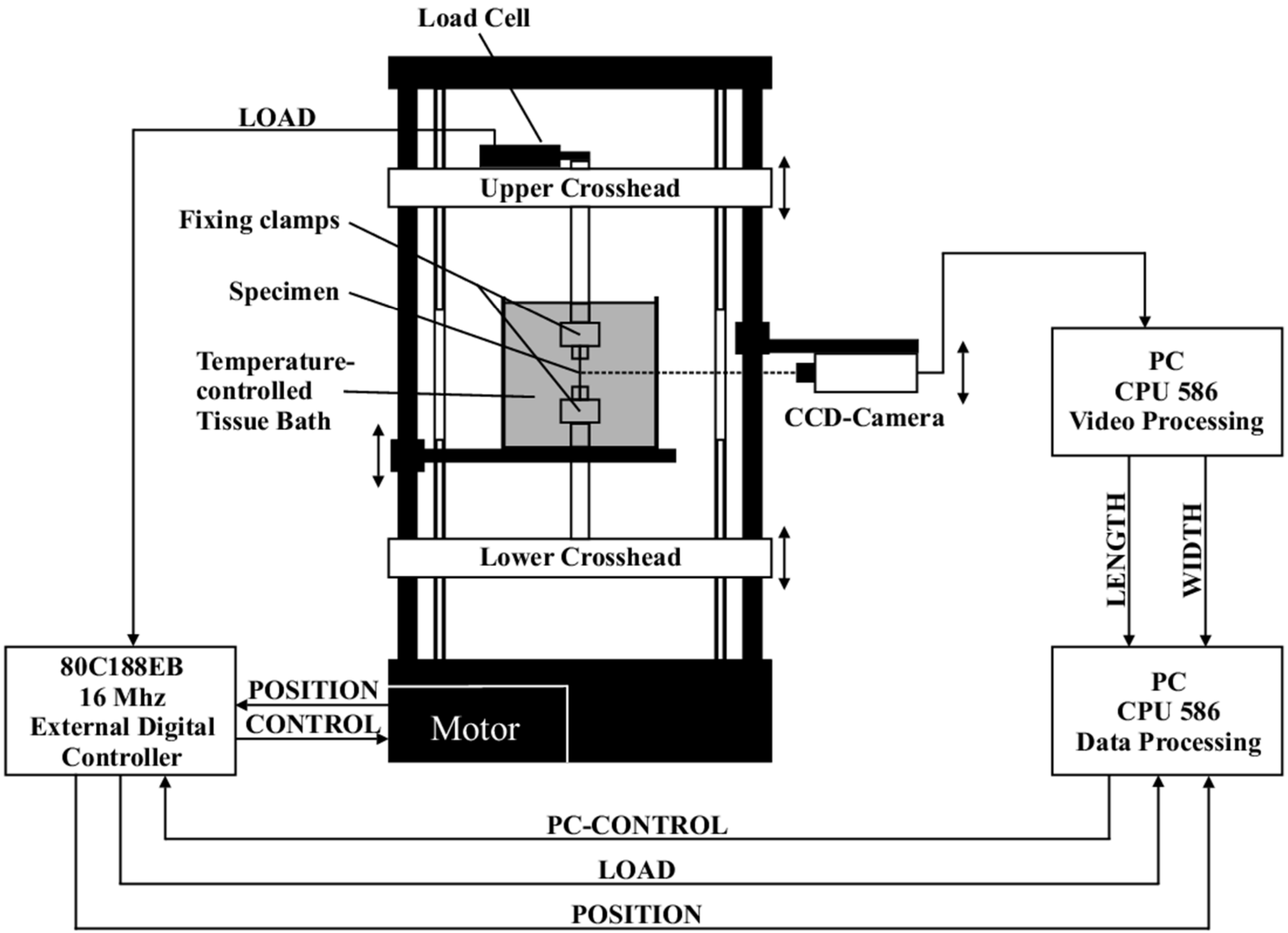
Shape of strips



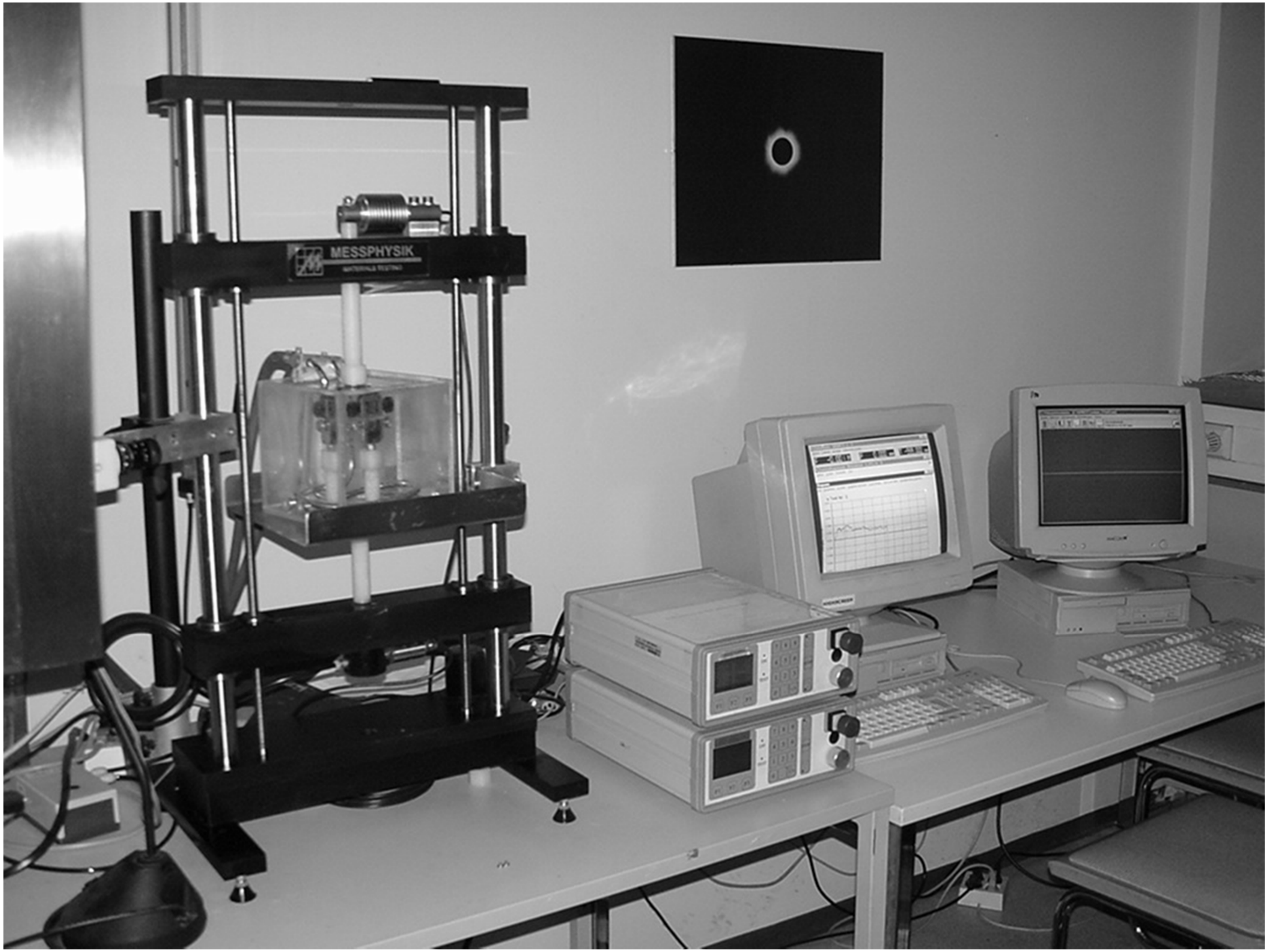
Dumbbell-shape,
helical strip,
ring specimen
(Hayashi 2000)

Schematic experimental setup

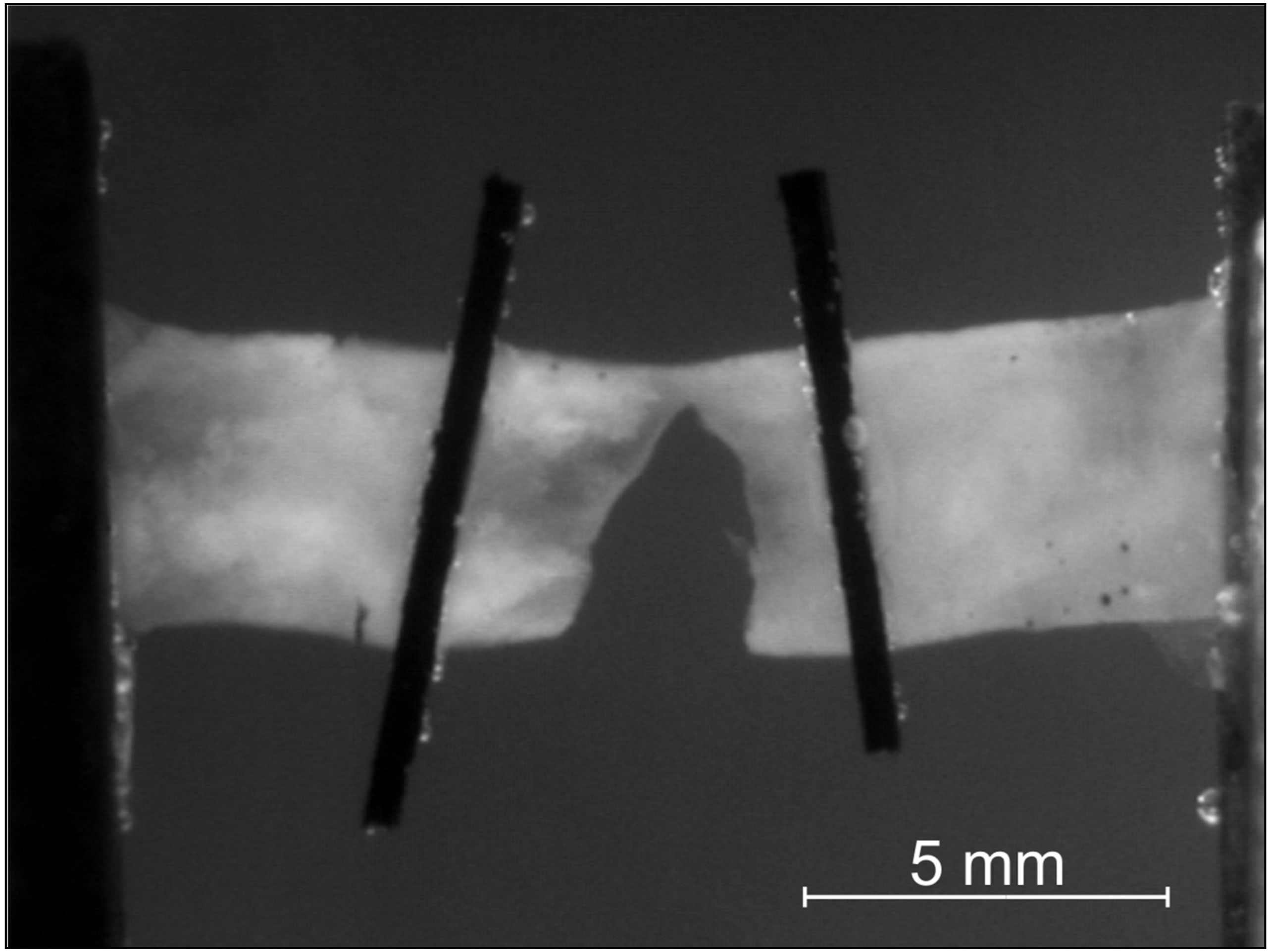
(Holzapfel et al. 2005)



Uniaxial Tensile Test

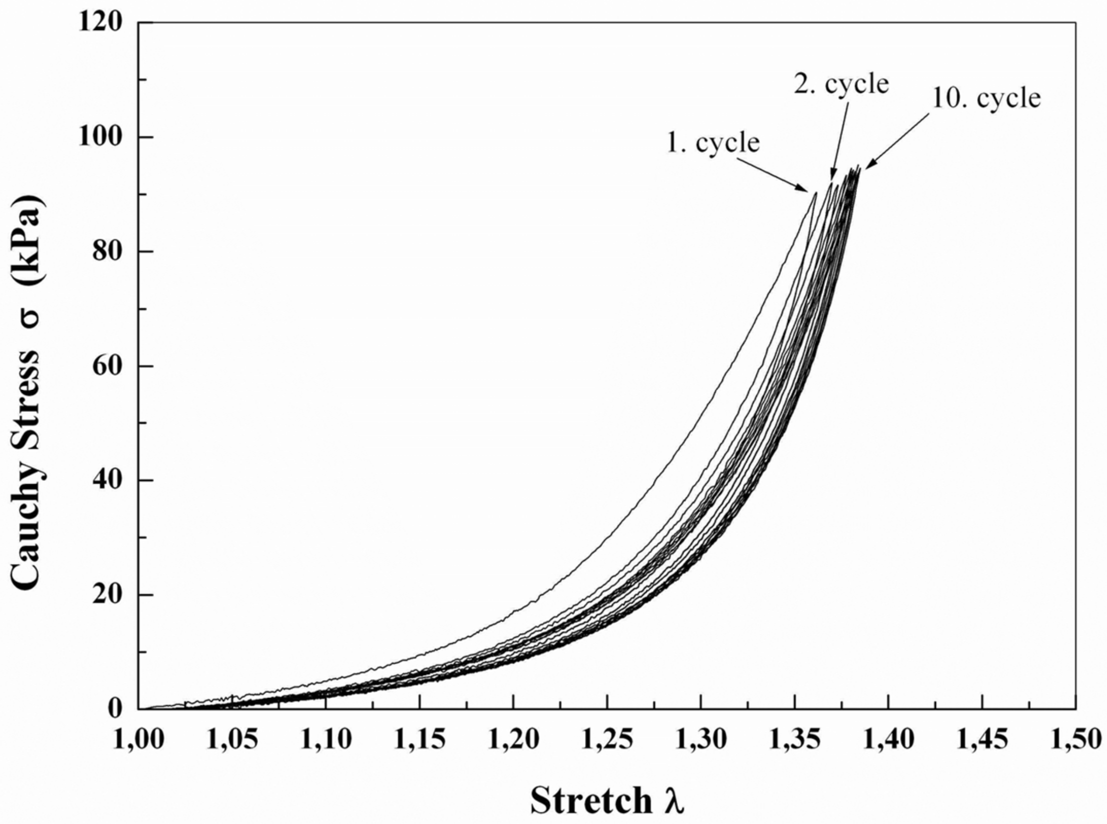


Videoextensometer



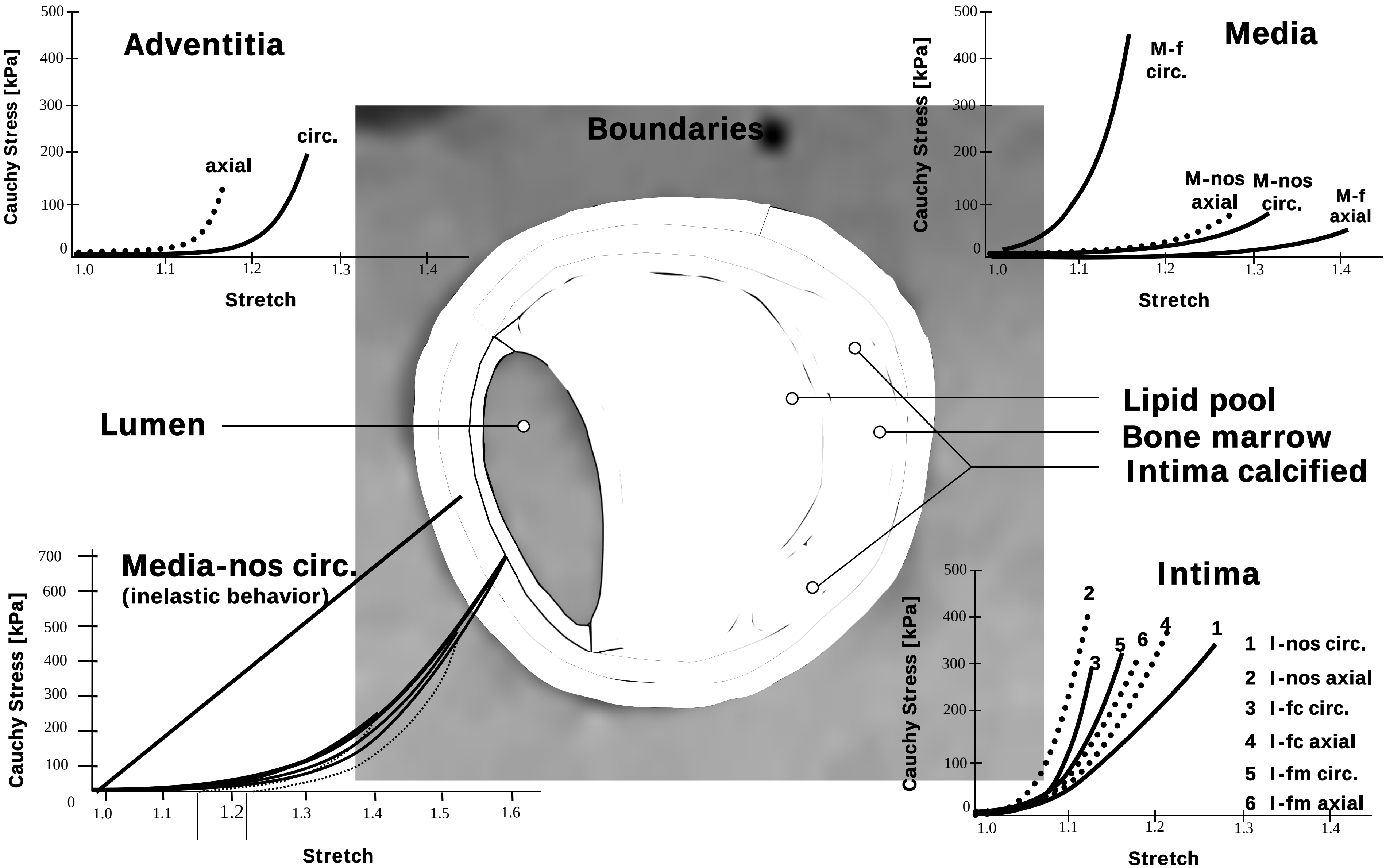
Preconditioning Behavior: Human LAD

- Weakening of material in the first few load cycles
- Converges to a preconditioned state



Holzapfel et al., 2005, AJP

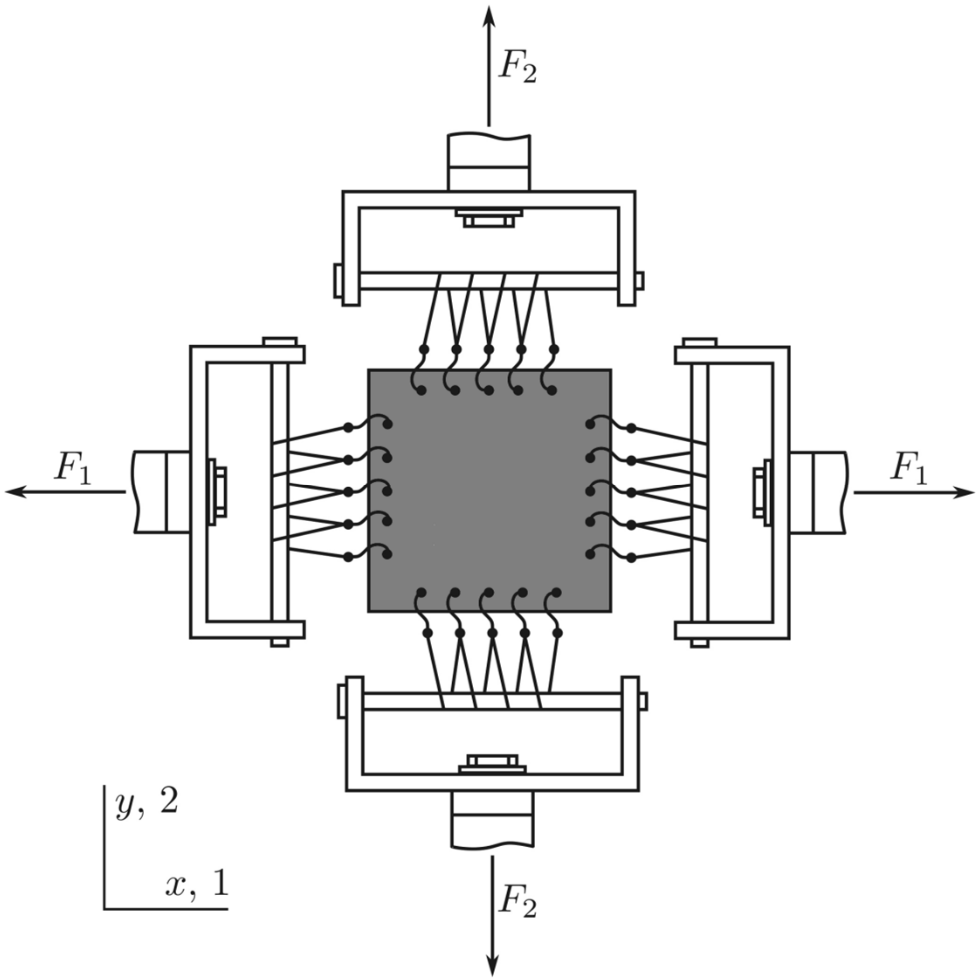
Uniaxial Tensile Test



Planar Biaxial Tensile Test

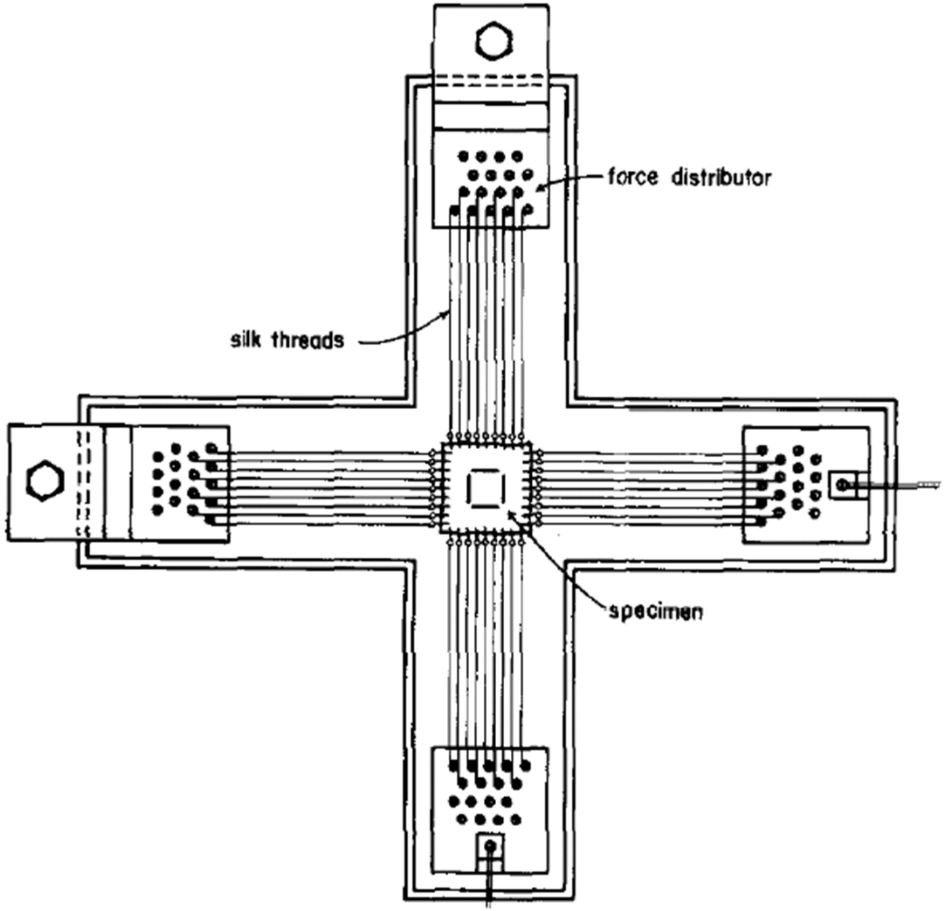
Sample preparation of flat specimens

(Haspinger 2013)



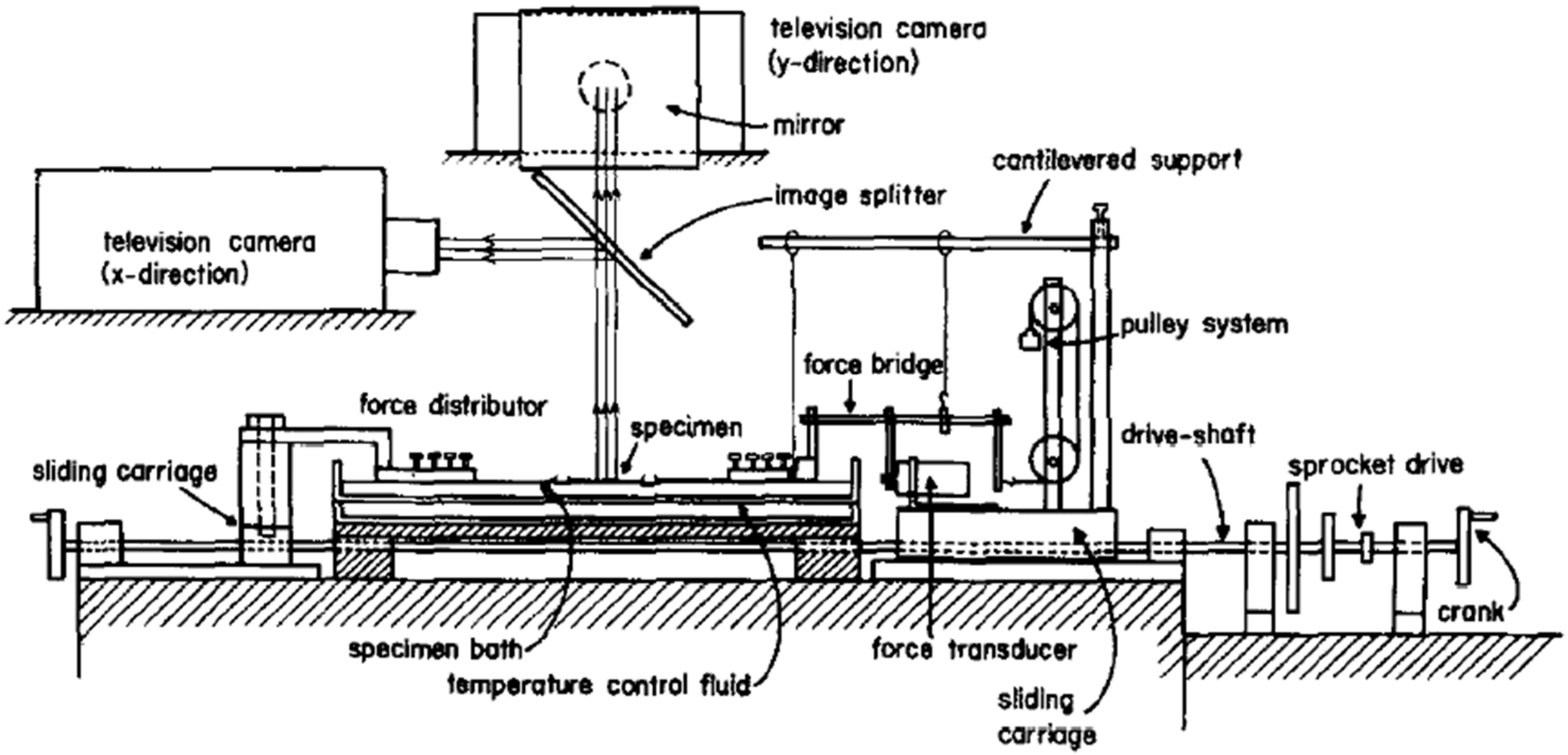
Setup of specimen hooking and force distribution

(Lanir and Fung JBIO 1974)



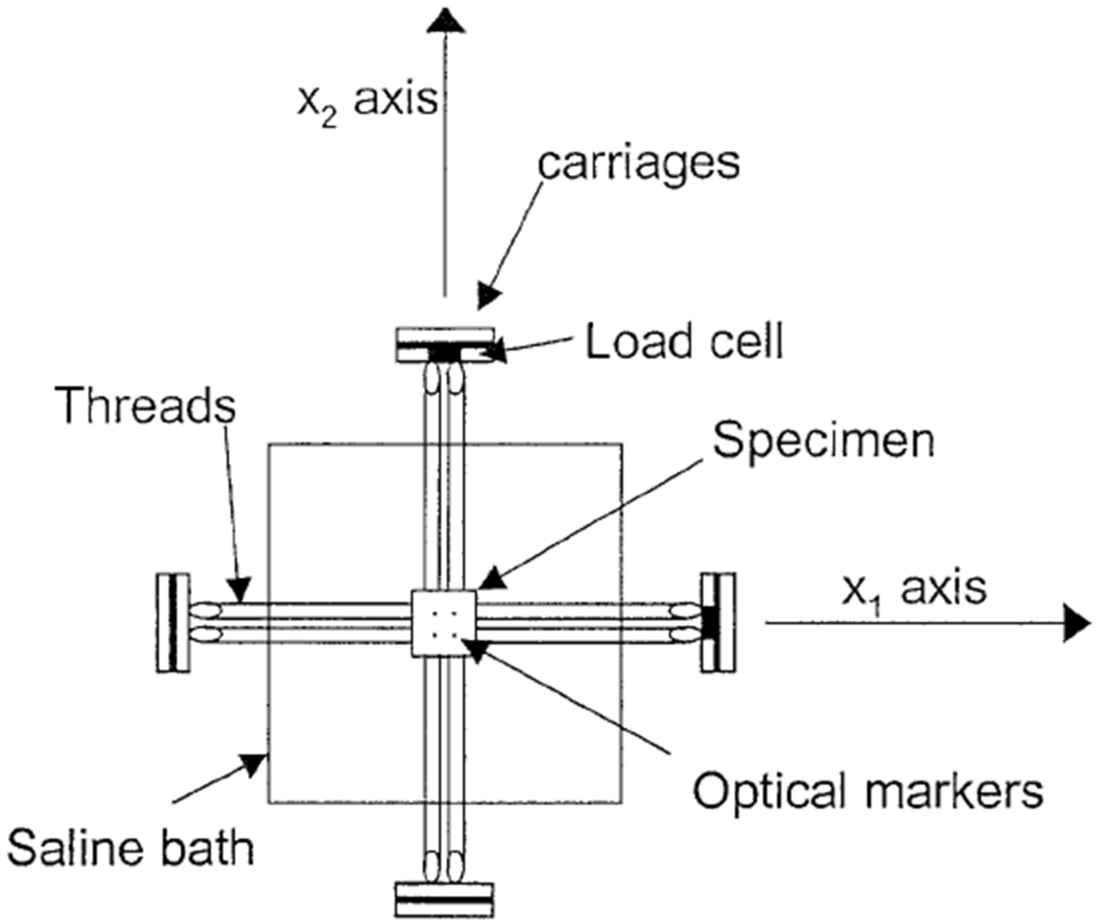
Schematic of mechanism and optical system

(Lanir and Fung JBIO 1974)



Schematic of biaxial testing device

(Sacks JE 2000)



(a)

Schematic of biaxial testing device

(Sacks JE 2000)

Consider homogeneous biaxial deformation

$$x_1 = \lambda_1 X_1 + \kappa_1 X_2, \qquad x_1 = \lambda_2 X_2 + \kappa_2 X_1, \qquad x_3 = \lambda_3 X_3,$$

- **X** and **x** are locations of material particles in reference and deformed state, respectively
- λ_i and κ_i are components of **F** (λ_i are stretch ratios, κ_i are measures of in-plane shear
- λ_3 is calculated from incompressibility constrain

Schematic of biaxial testing device

Consider homogeneous biaxial deformation

The output of the biaxial machine yields following quantities:

- Two stretch ratios
- Applied forces

The thickness of the tissue has to be measured optically prior testing (reference configuration)
Specimen geometry (width and length) is known in reference configuration

Schematic of biaxial testing device

Consider homogeneous biaxial deformation

The Cauchy stress (actual, current force divided by current area) can be defined as follows:

$$\sigma_{11} = \frac{f_1}{t x_2} \qquad \sigma_{22} = \frac{f_2}{t x_1}$$

assuming incompressibility simplifies analysis, as thickness *t* is purely dependent on changes in width and hight:

$$t = \frac{T X_1 X_2}{x_1 x_2}$$

Using the definition of the stretches $\lambda_1 = \frac{x_1}{X_1} \qquad \lambda_2 = \frac{x_2}{X_2}$

The Cauchy stress can be then calculated as follows

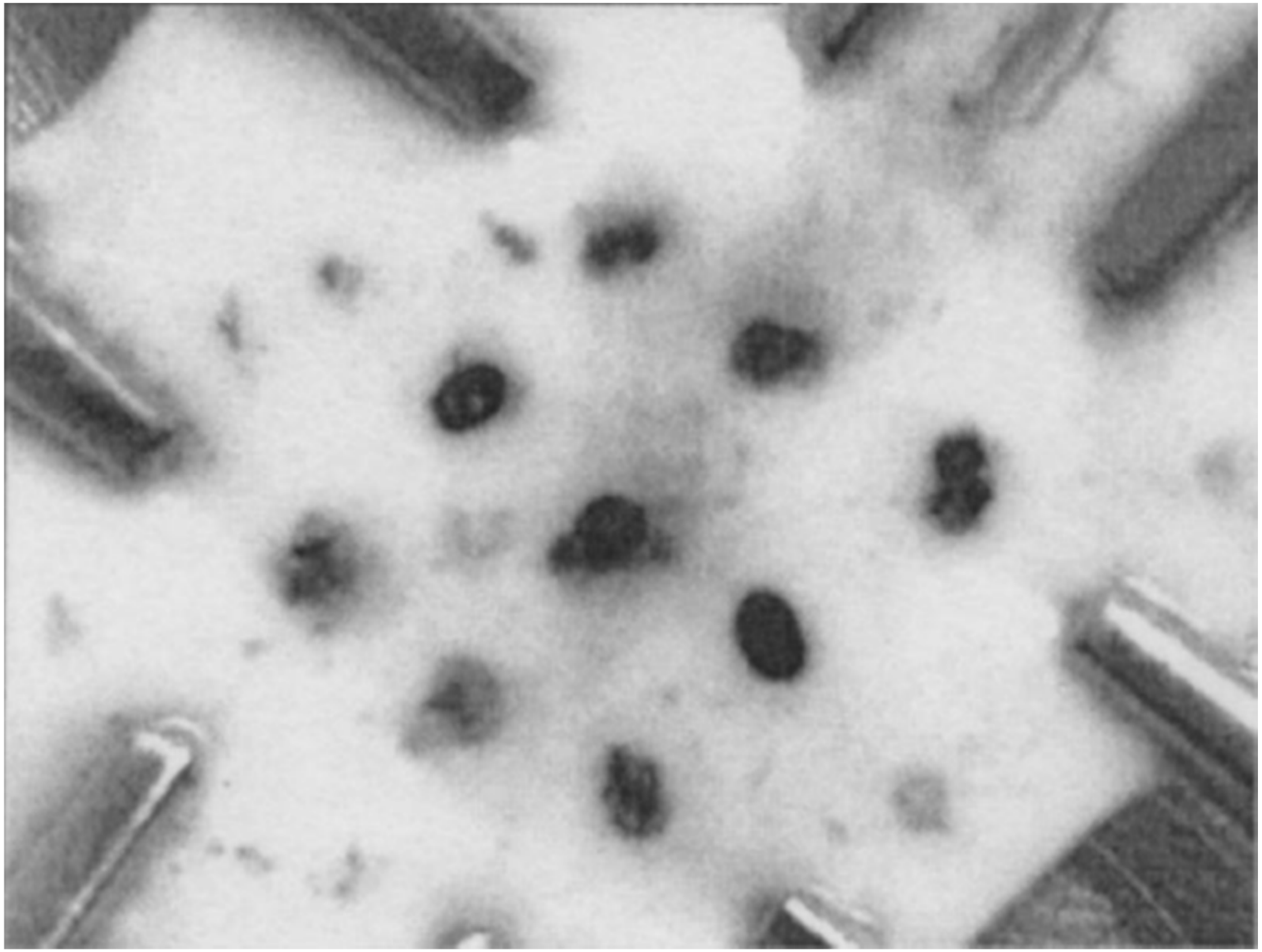
$$\sigma_{11} = \frac{f_1 \lambda_1}{T X_2} \qquad \sigma_{22} = \frac{f_2 \lambda_2}{T X_1}$$

Biaxial Tensile Test

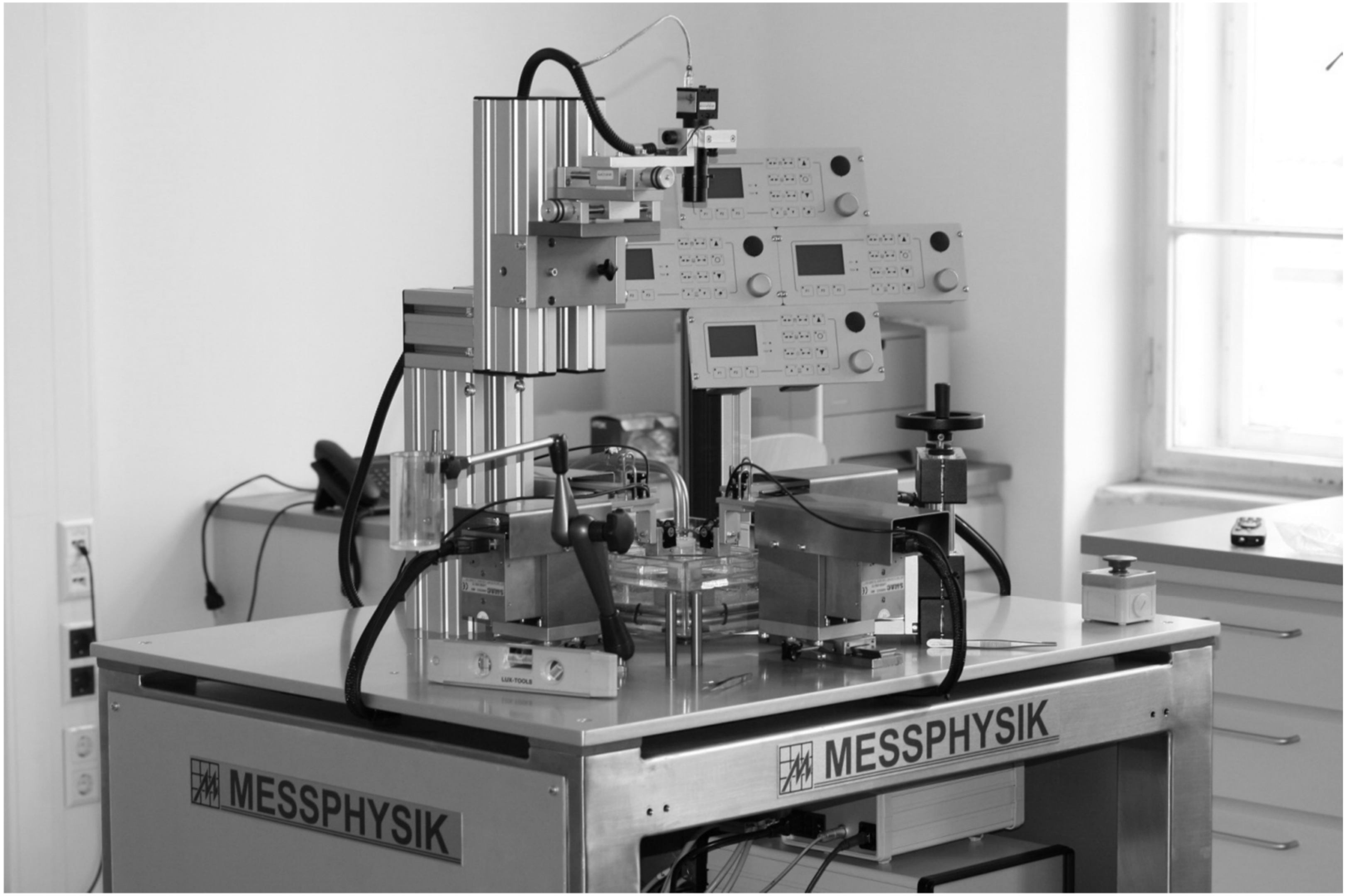
Markers serve for stretch calculations

Crocodile clips are used to clamp the tissue

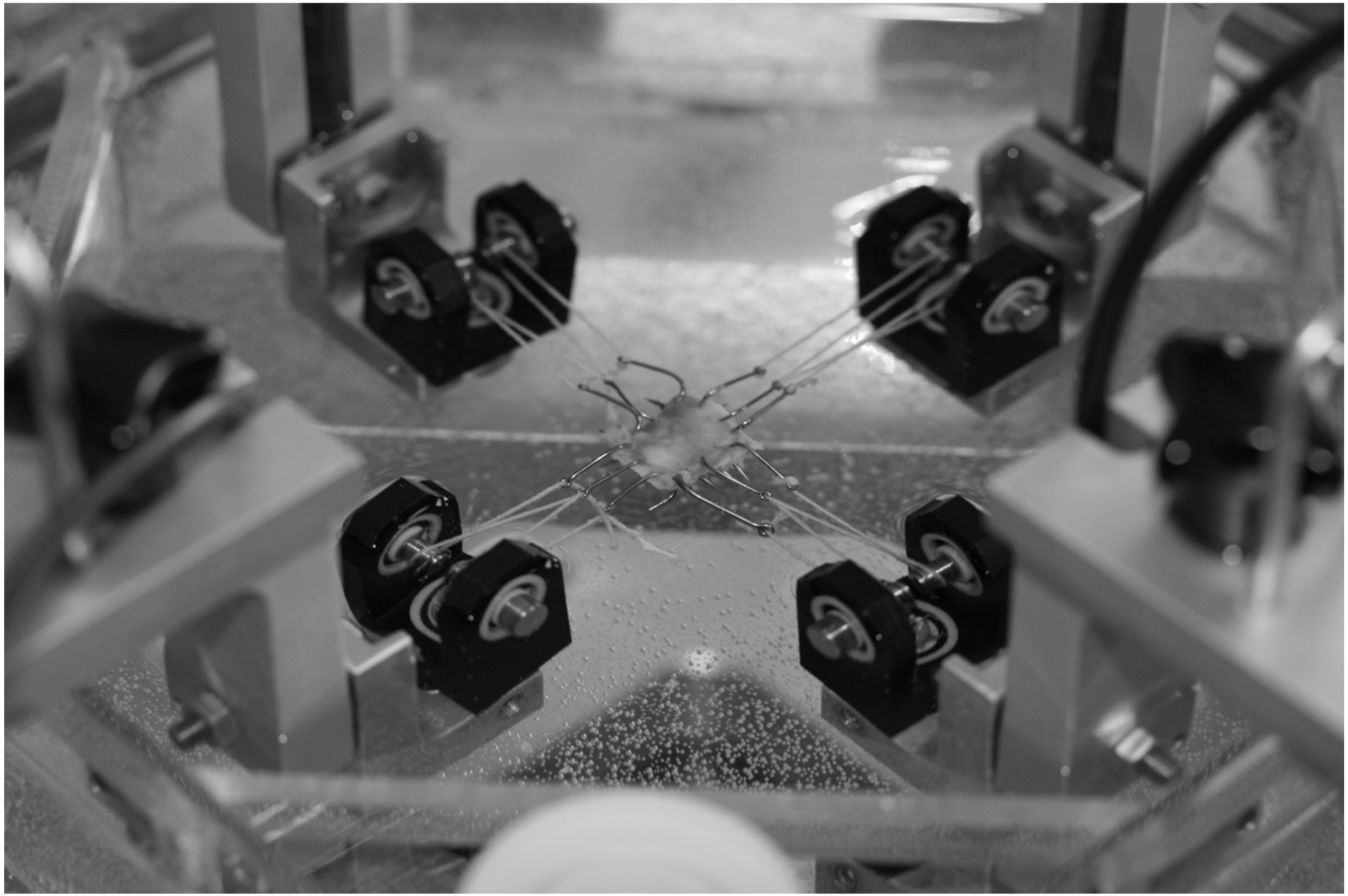
(Prendergast et al. ASME 2003)



Biaxial device of the Institute of Biomechanics



Experimental setup in biaxial device



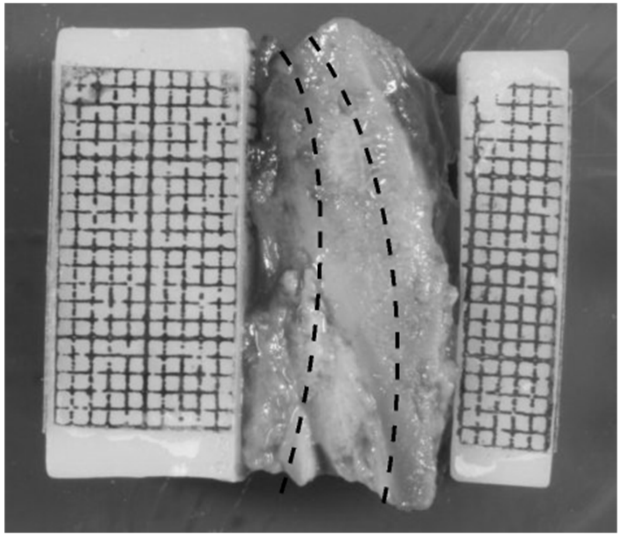
Analysis of Results

Example: intraluminal thrombus (ILT) from abdominal aortic aneurysm (AAA)

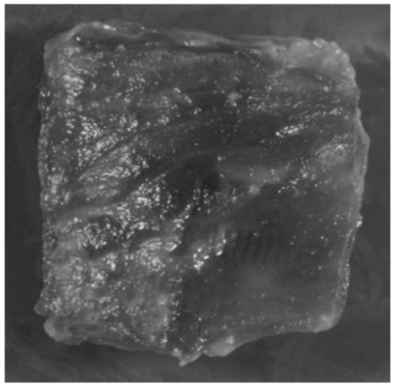
Work of J. Tong

Biaxial Tensile Test

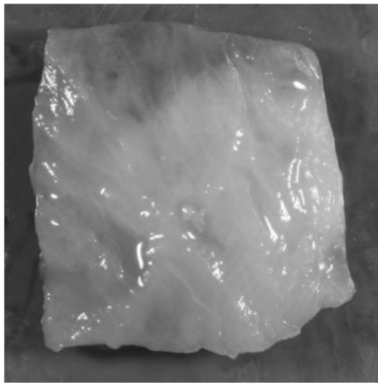
Layer separation of ILT



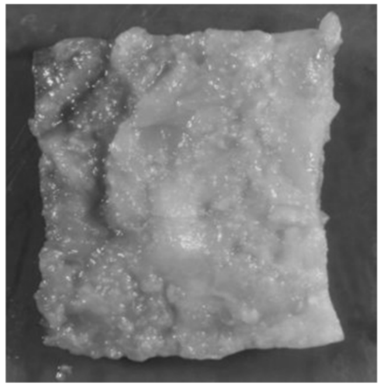
thrombus



luminal



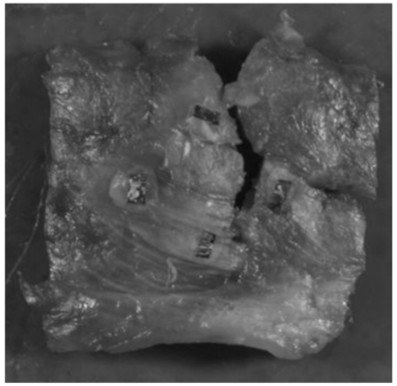
medial layer



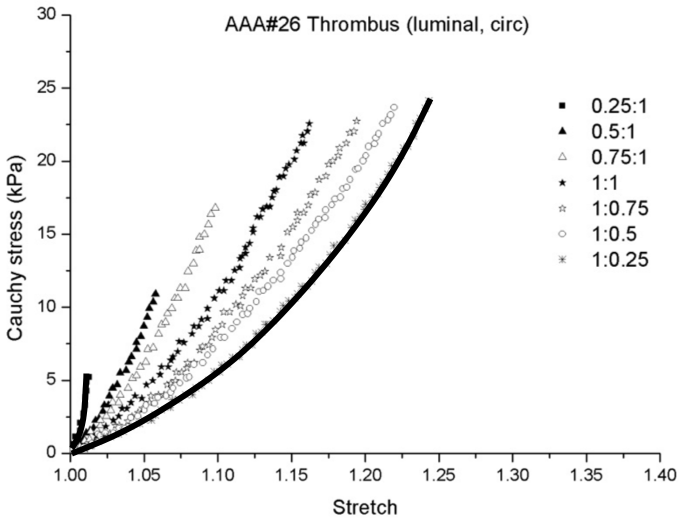
abluminal

Biaxial Tensile Test

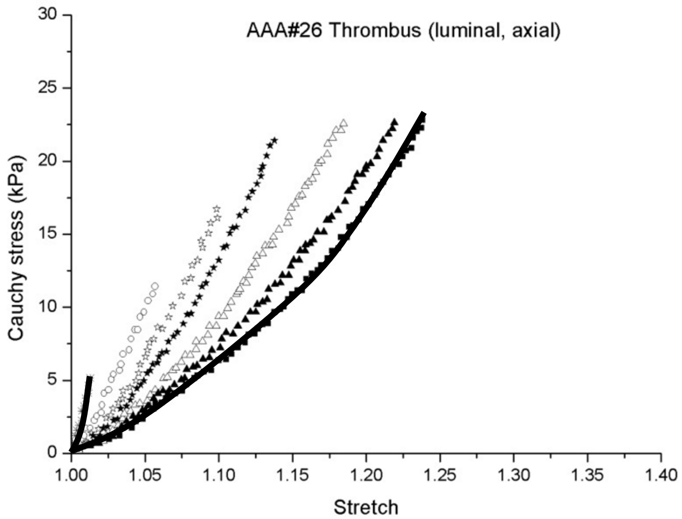
Luminal layer of ILT



luminal (ruptured)



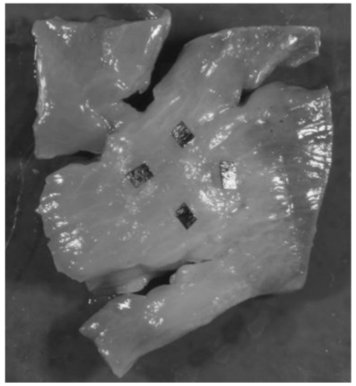
circumferential



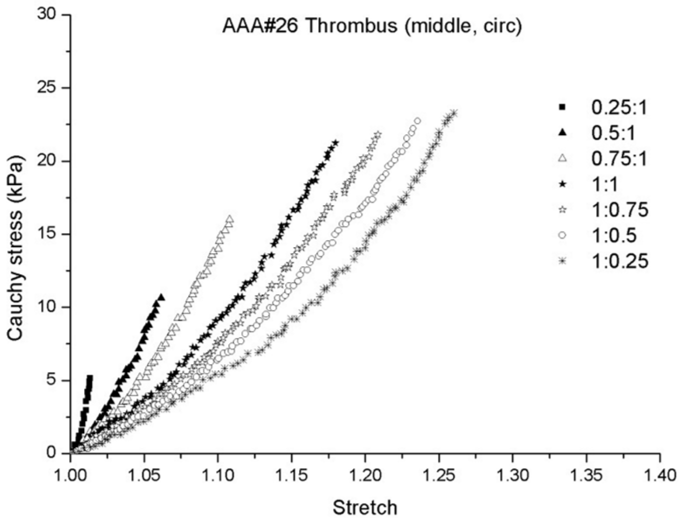
axial

Biaxial Tensile Test

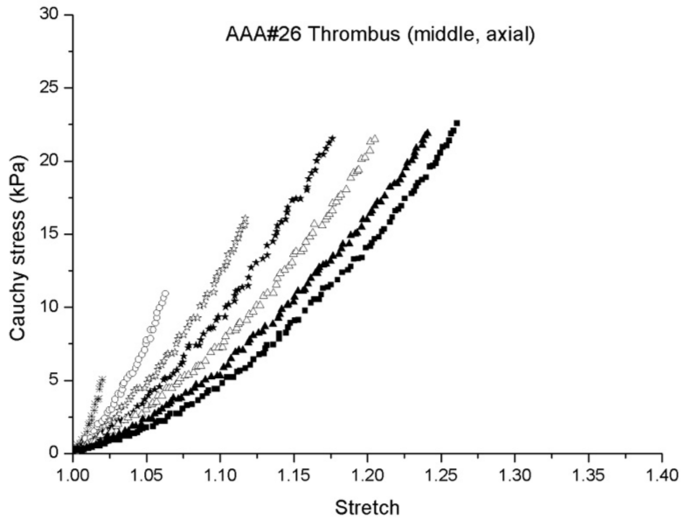
Medial layer of ILT



medial layer (ruptured)



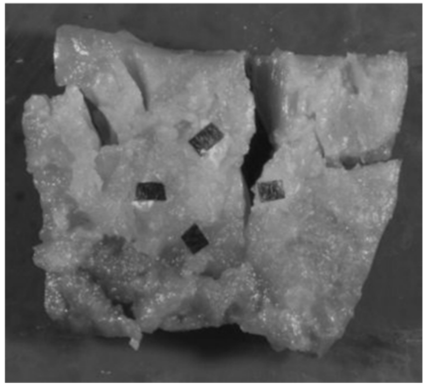
circumferential



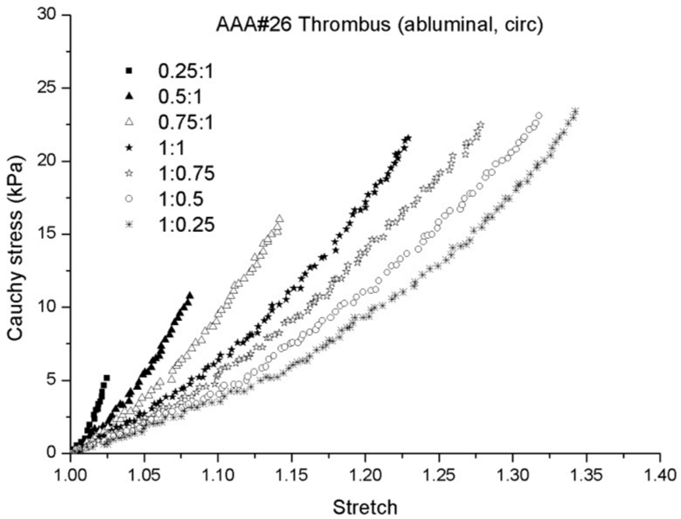
axial

Biaxial Tensile Test

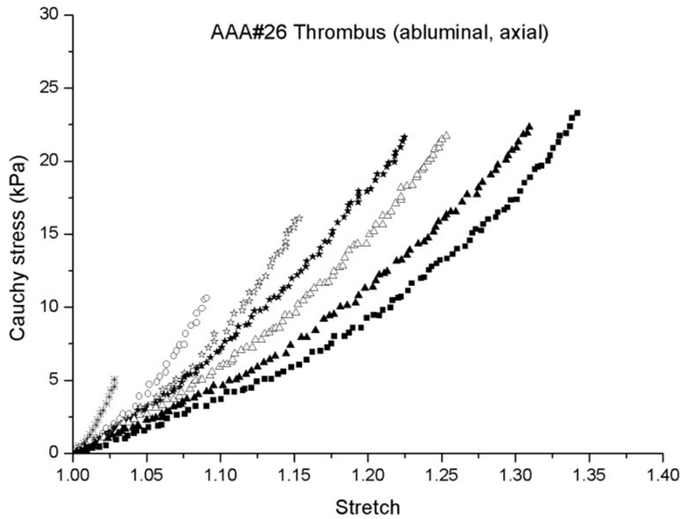
Abluminal layer of ILT



abluminal (ruptured)



circumferential

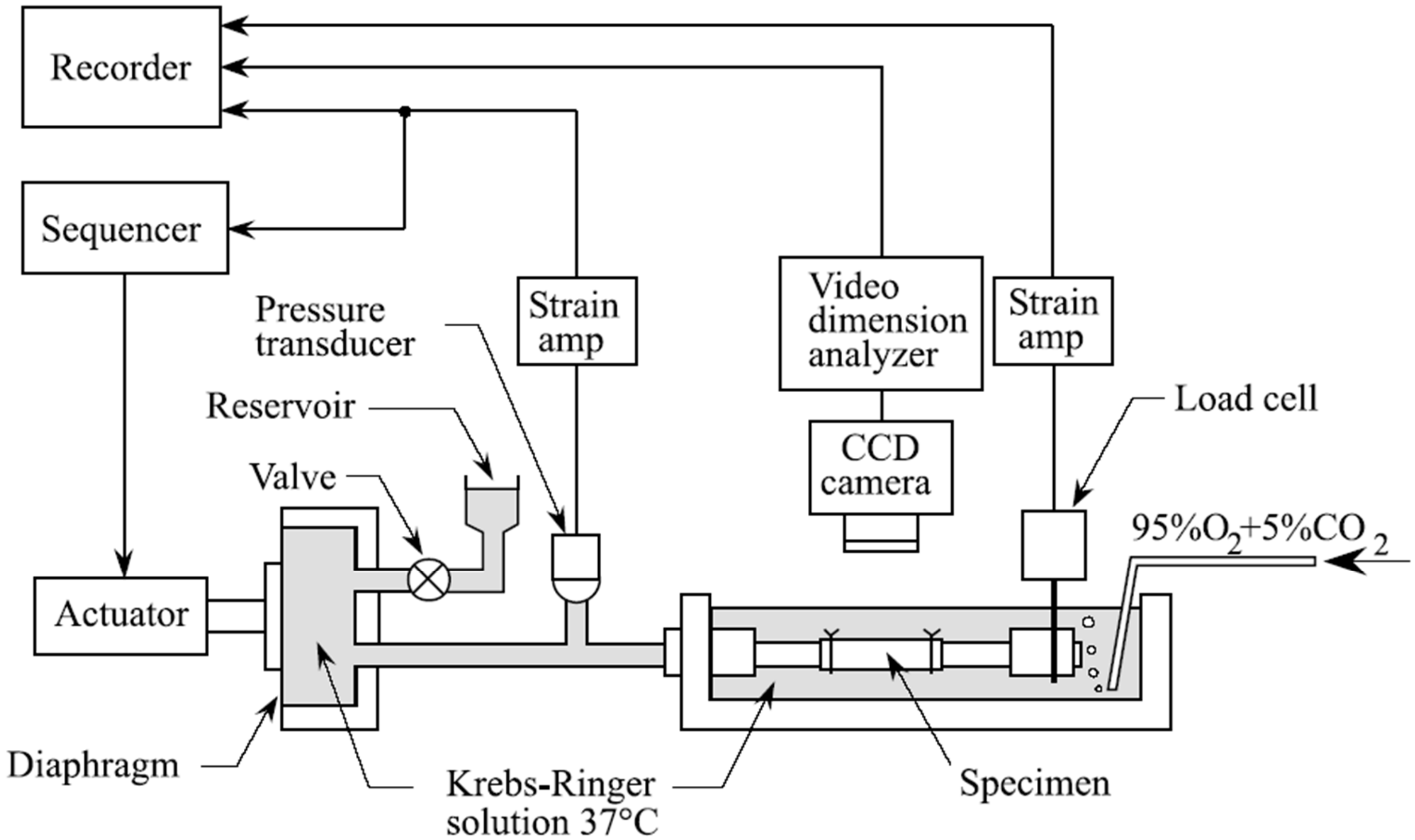


axial

Tube Testing (Bi- and Triaxial)

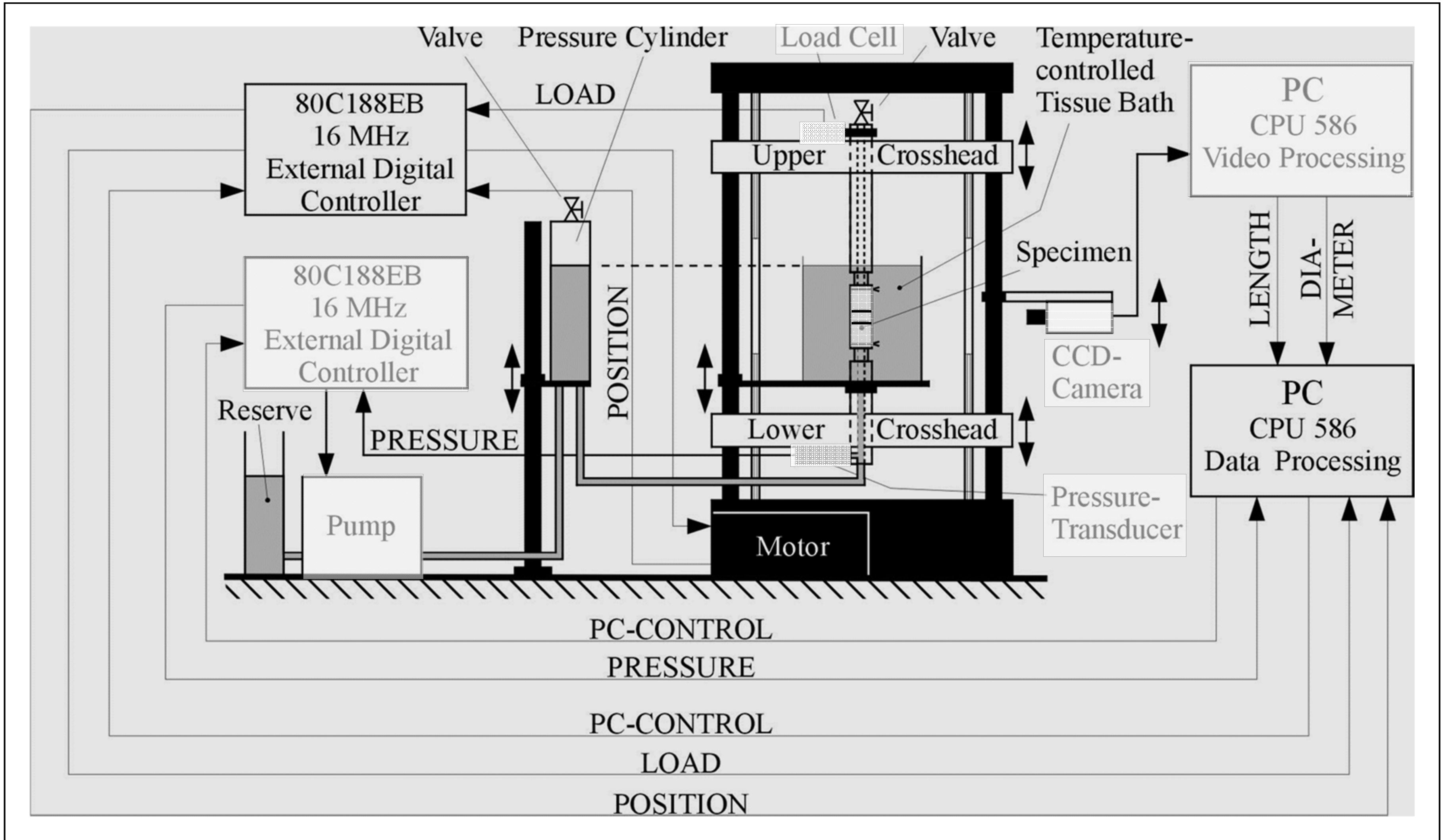
Schematic of experimental setup

(Hayashi 2000)



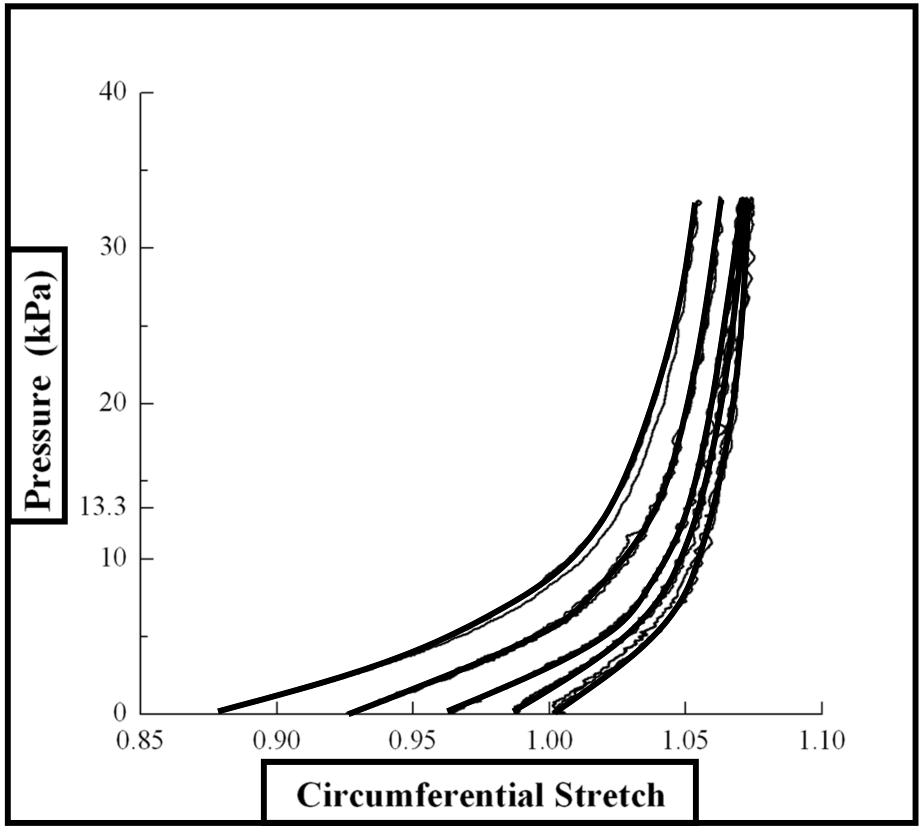
Arterial tube testing in Graz

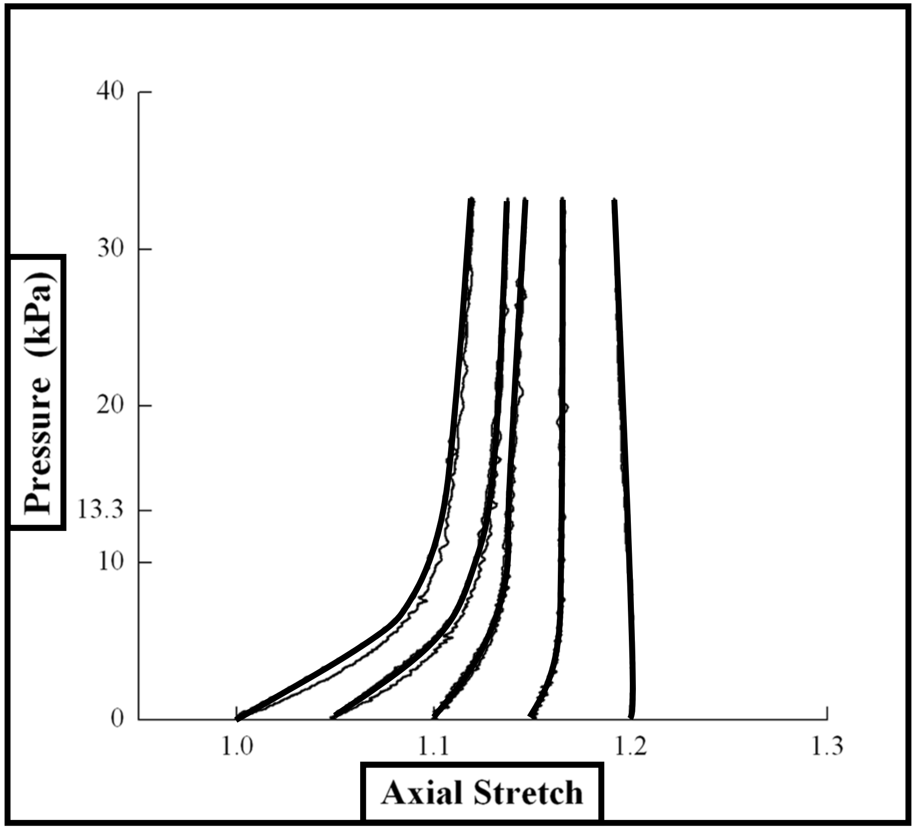
(Schulze-Bauer et al. AJP 2003)



Common Carotid Artery: Evaluation

- The in vivo axial stretch is around 1.2
- No length change during cardiac cycle for CCA



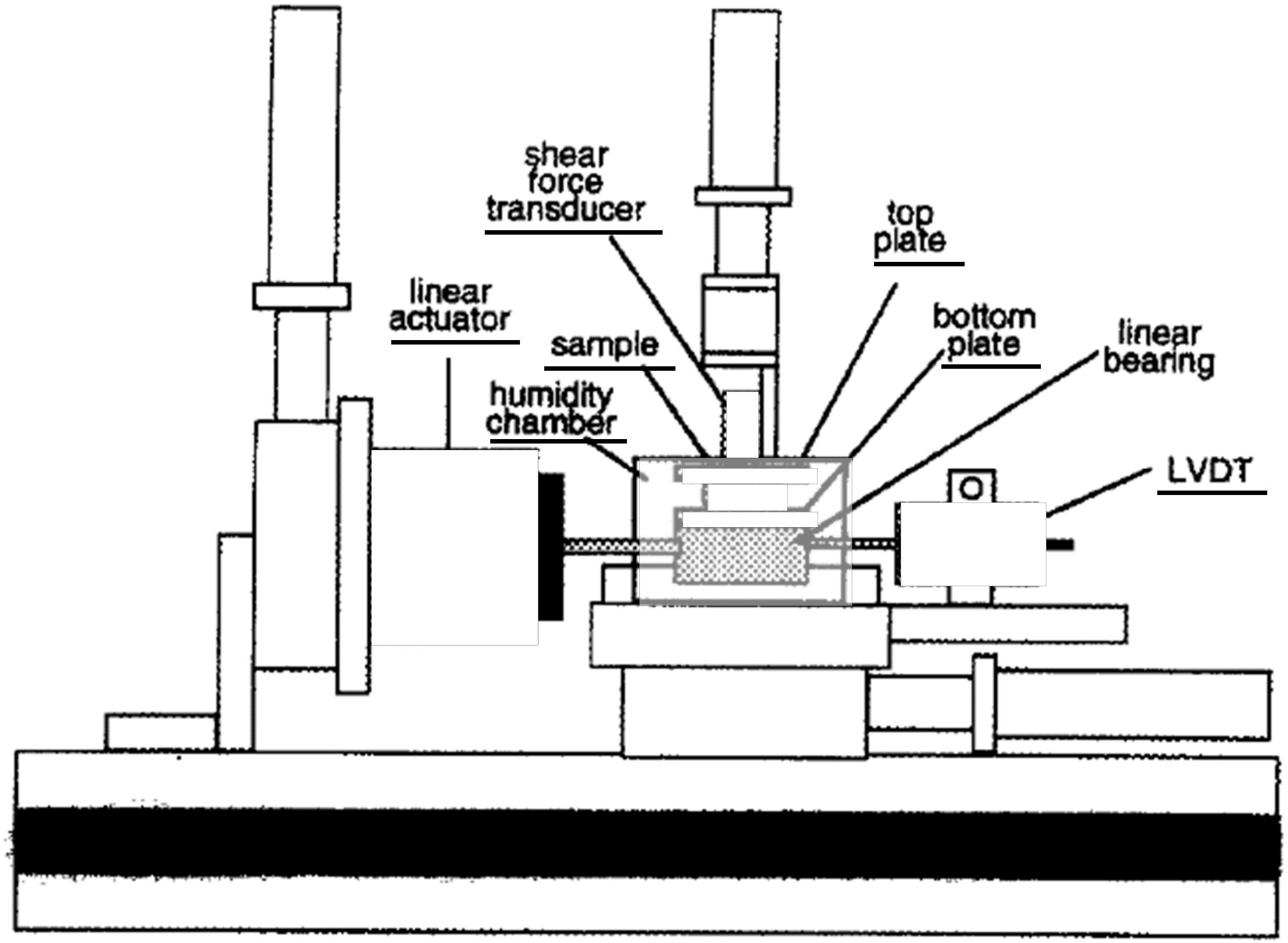


Shear Testing

Shear Test

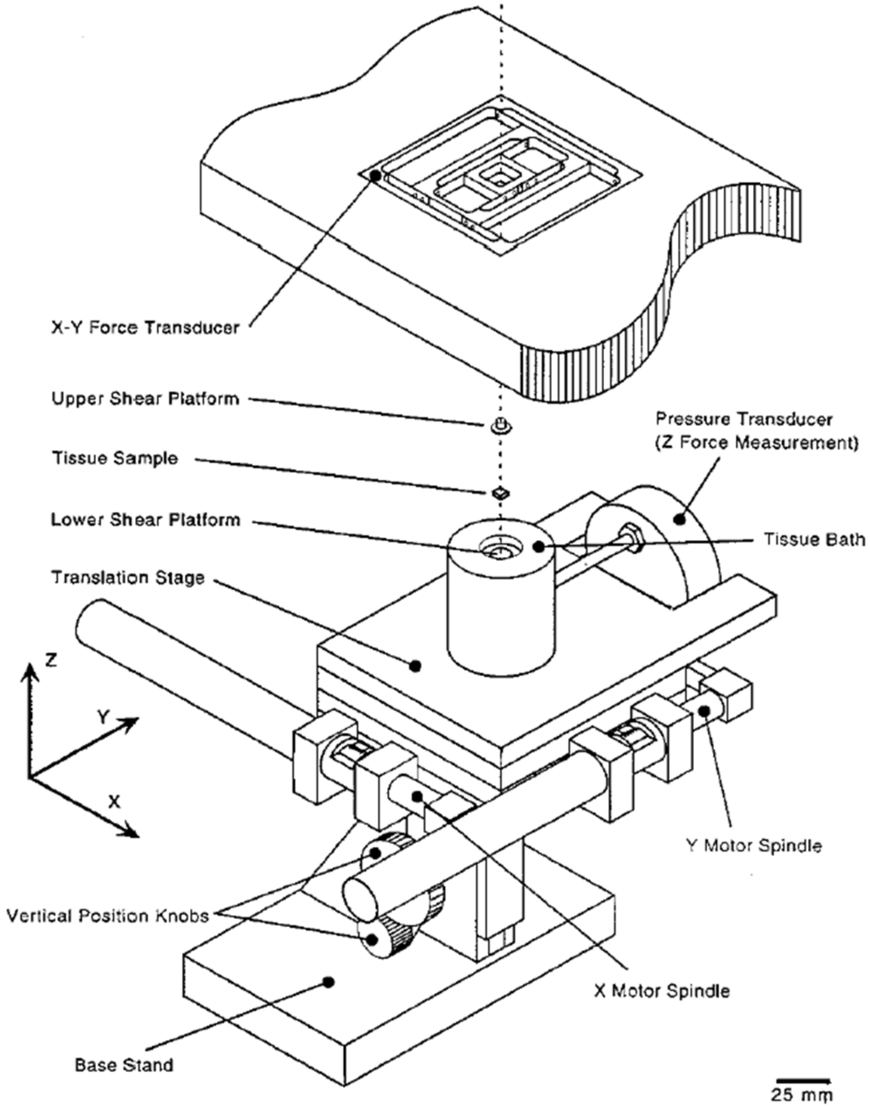
Schematic of shear testing apparatus – 2 axes

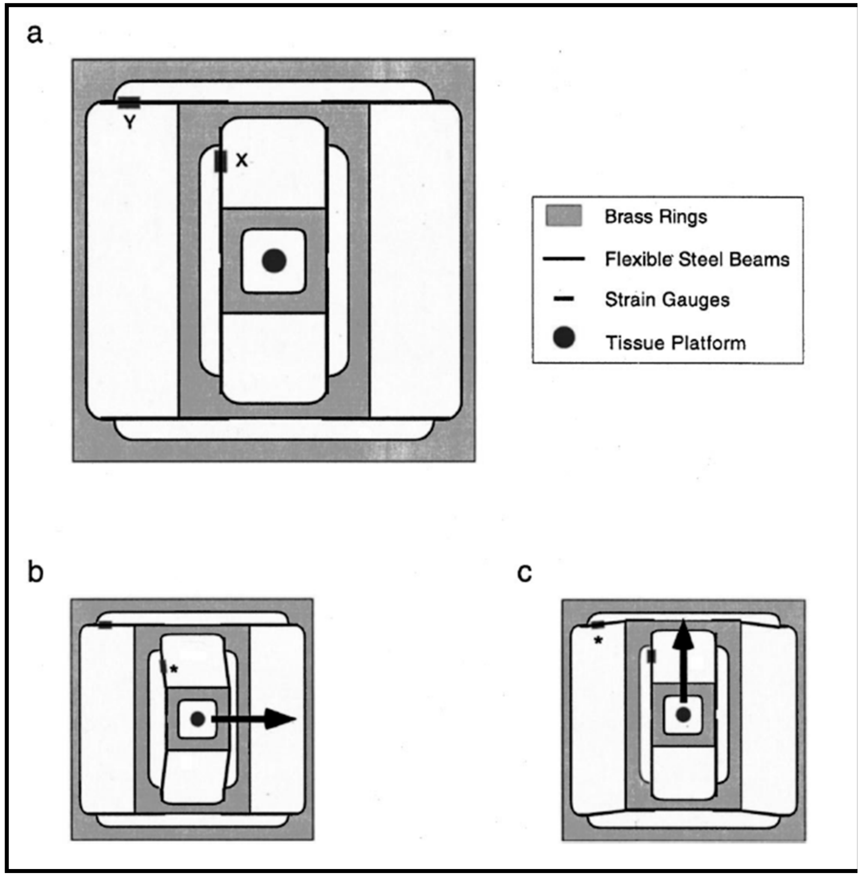
(Arbogast et al JBIO 1997)



Schematic of shear testing apparatus – 3 axes

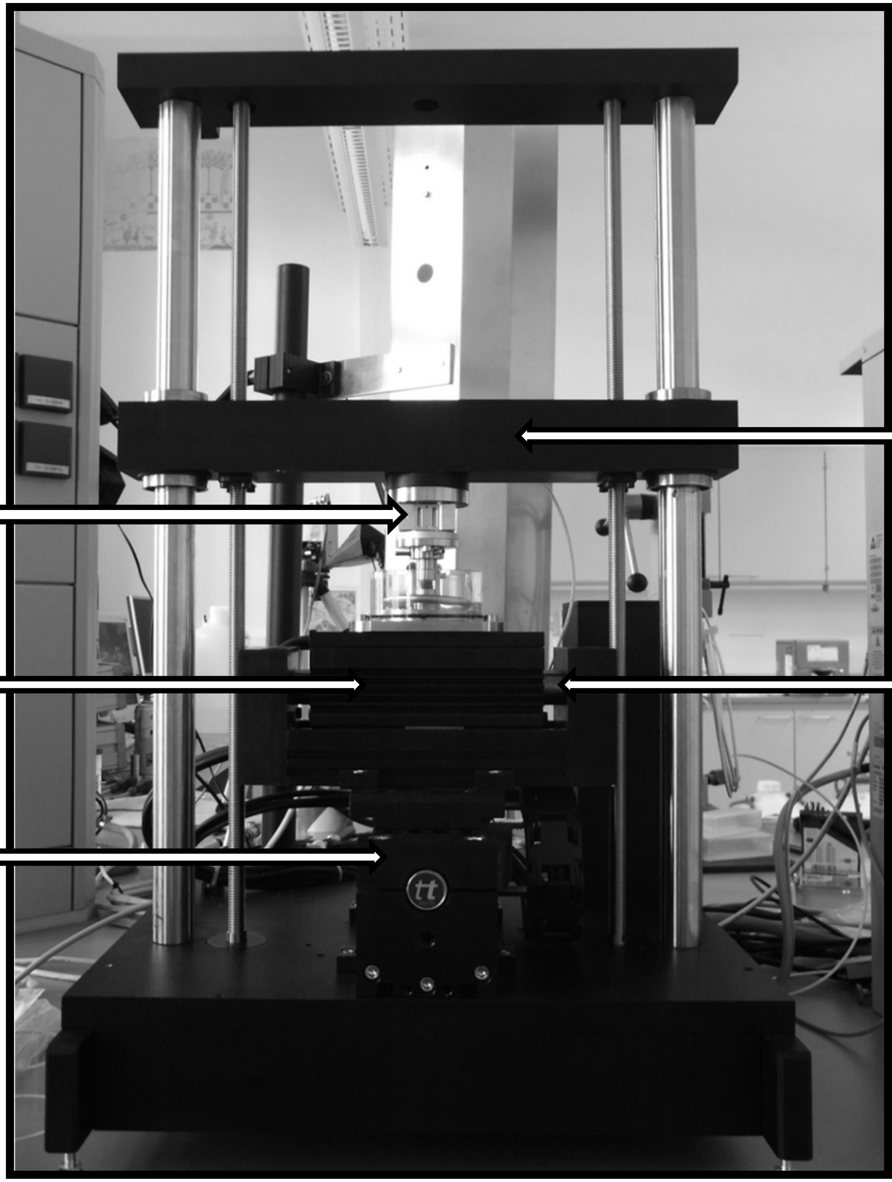
(Dokos et al. ASME 2000)





Shear Test

Shear testing apparatus in Graz – 3 axes



z-cross head

load cell

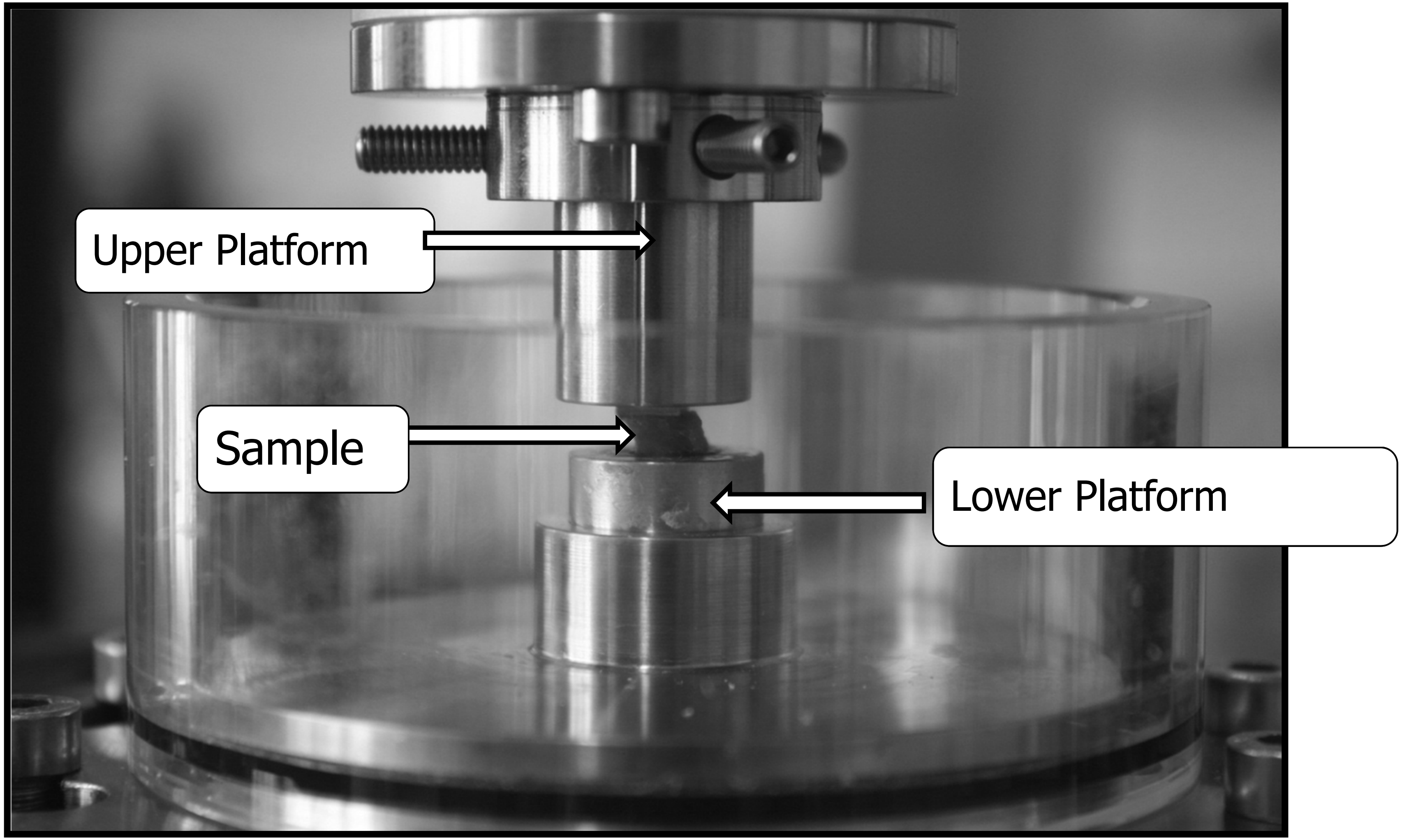
x-cross head

guide bolt

y-cross head

Shear testing apparatus in Graz – 3 axes

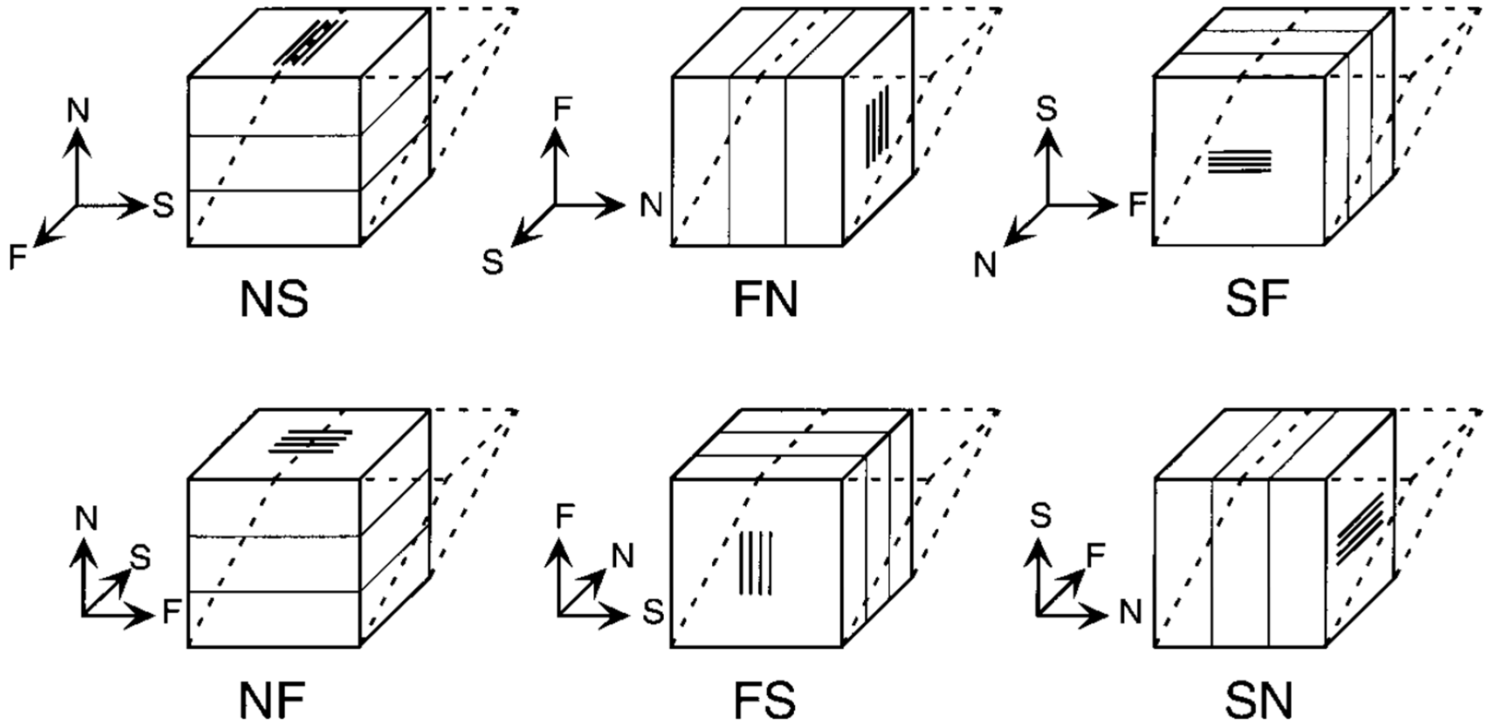
Close up of the sample chamber



Possibilities of shear directions depending on fibers and sheets

Recall the anatomy of the myocardium!

(Dokos et al. 2002)



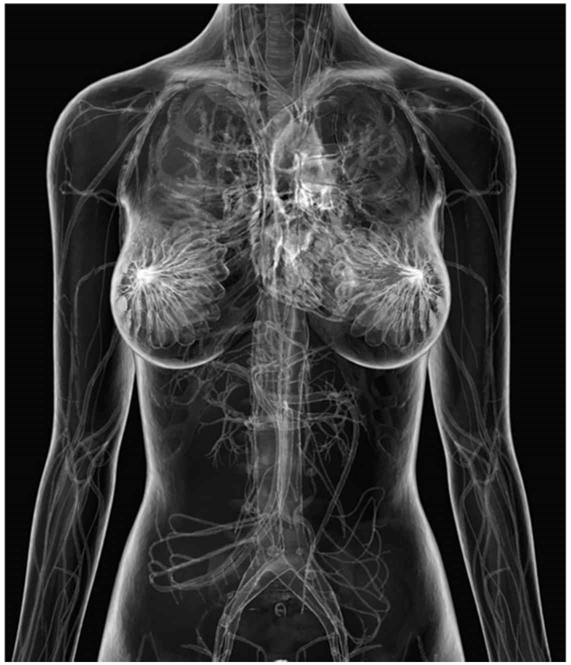
Shear Test

Example: shear testing of adipose tissue

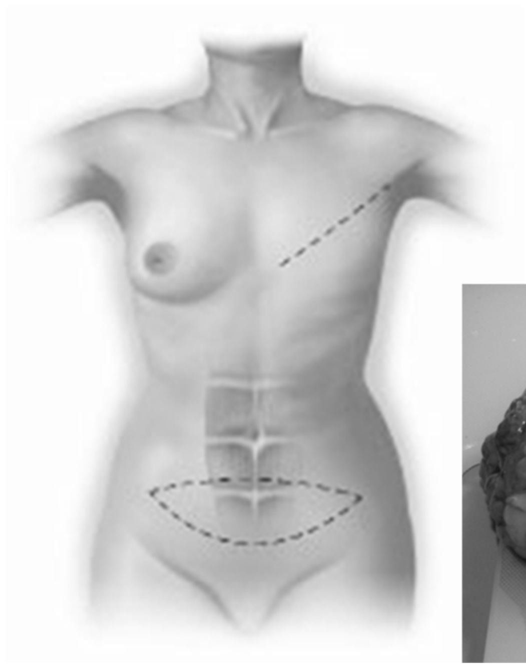
Work of G. Sommer

Background: Breast cancer

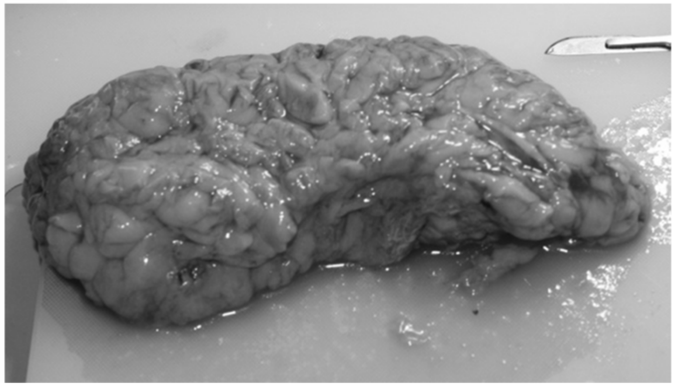
Radical total mastectomy and reconstruction with abdominal fat



(Manas Informatics Pvt. Ltd).



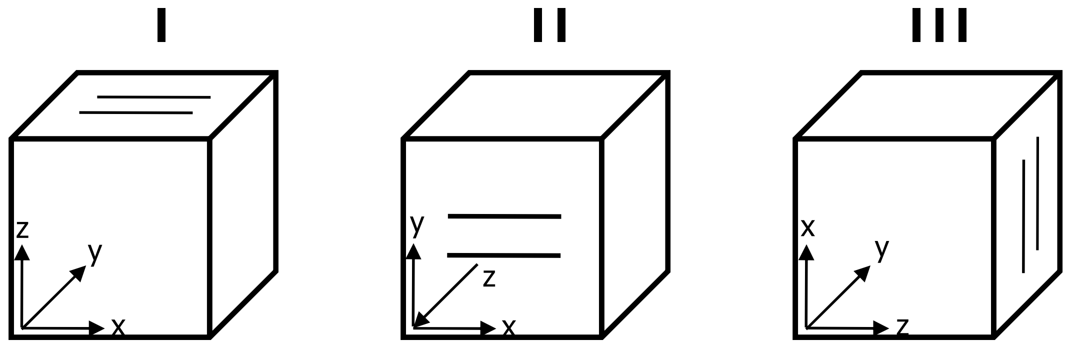
(Mentor Corporation)

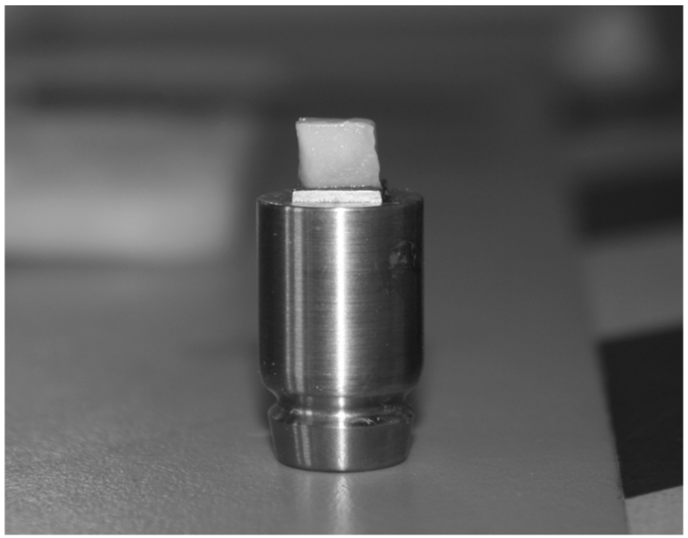


Development of force-feedback applications (haptic modelling)

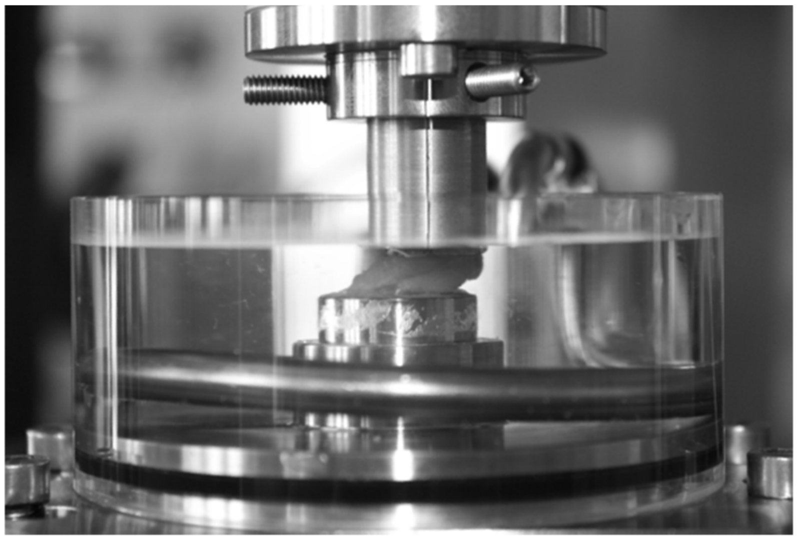
Example: shear testing of adipose tissue

Preparation of cube-shaped specimens with different orientations





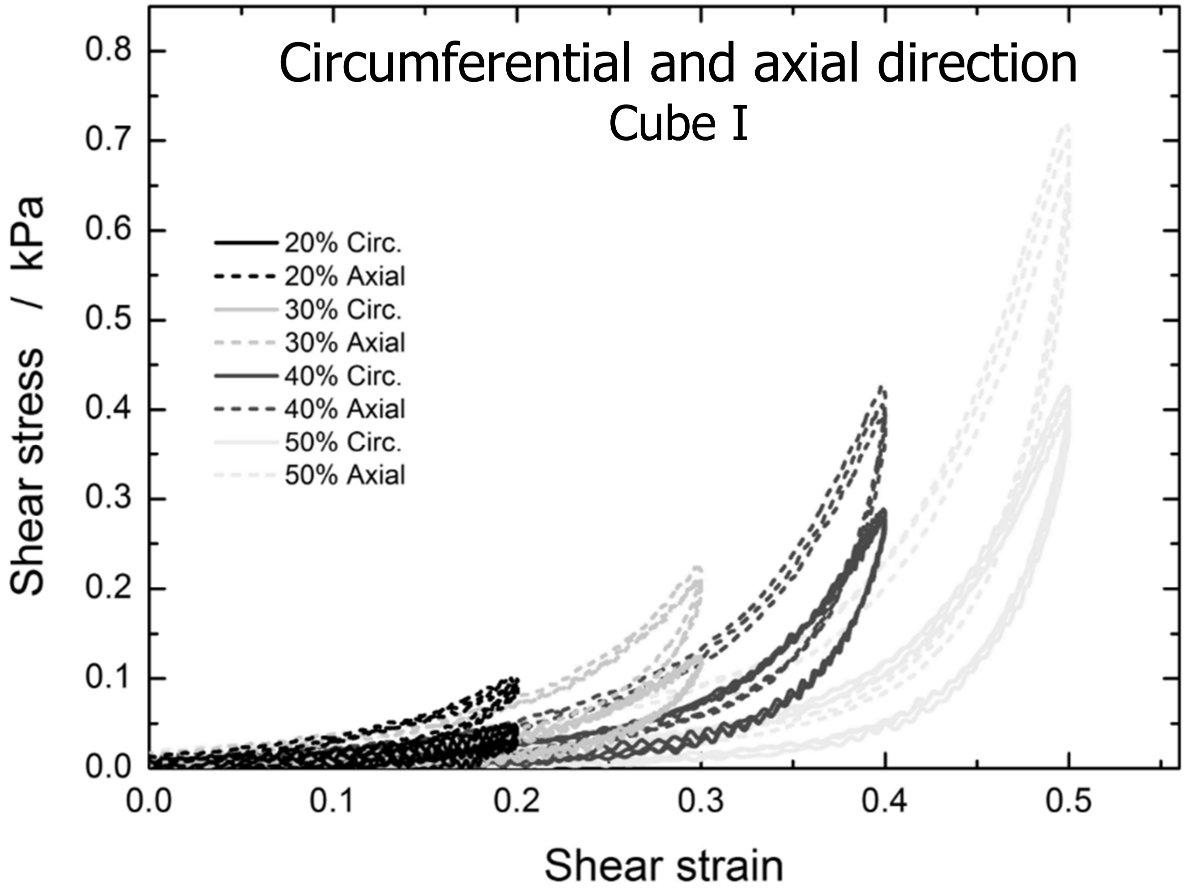
Specimen glued to specimen-holder

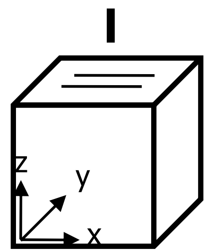


Specimen during shearing

Example: shear testing of adipose tissue

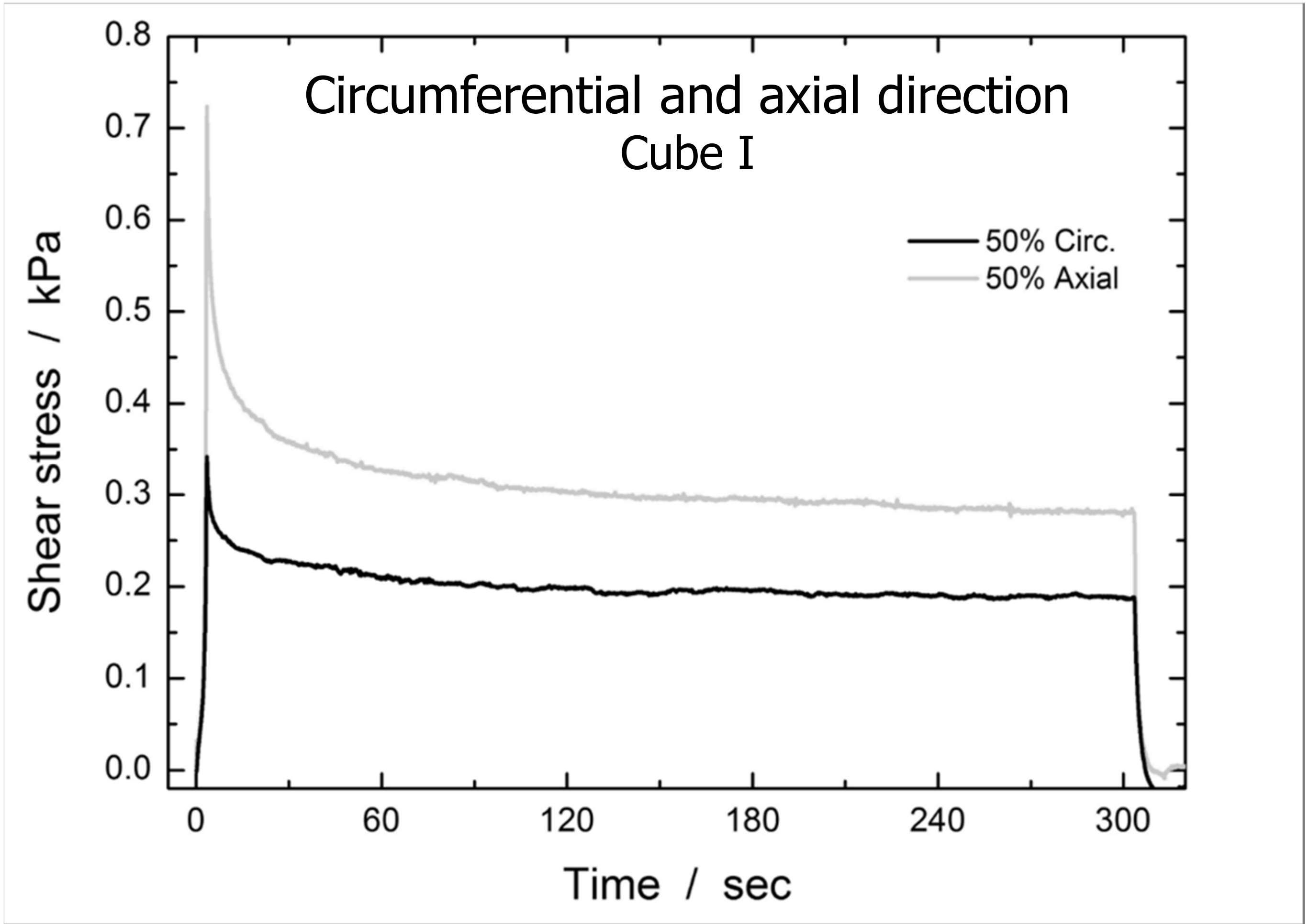
Representative shear behavior

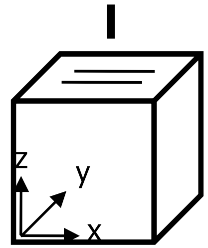




Example: shear testing of adipose tissue

Representative relaxation behavior



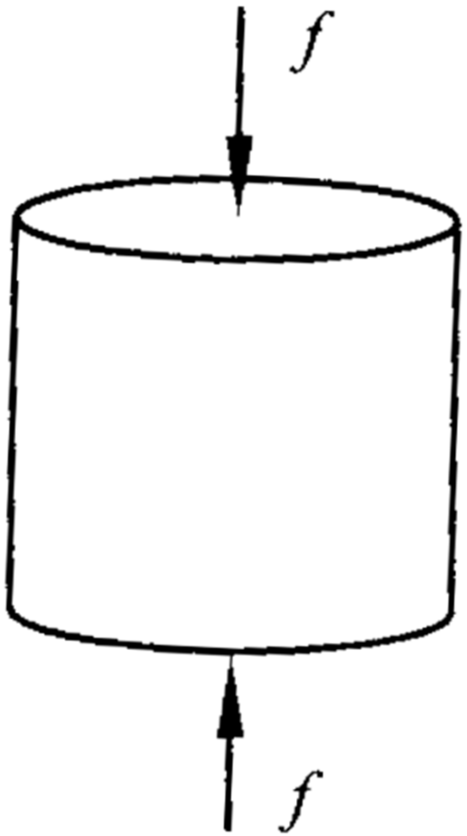


Other Testing Methods

Other Methods

Uniaxial compression test

Schematic



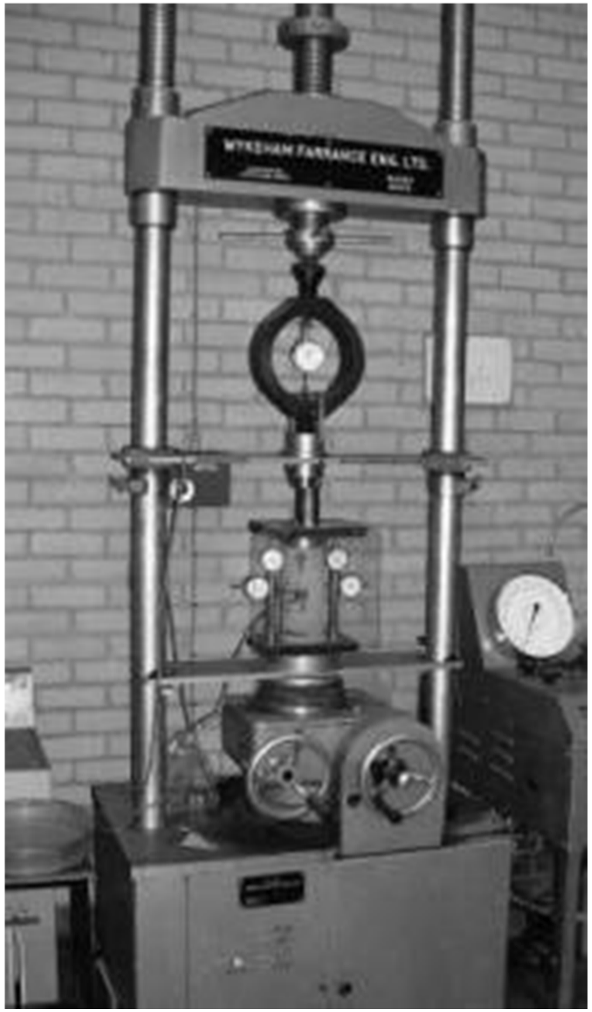
www.claisse.info/Soils%20tests.htm

Experimental apparatus

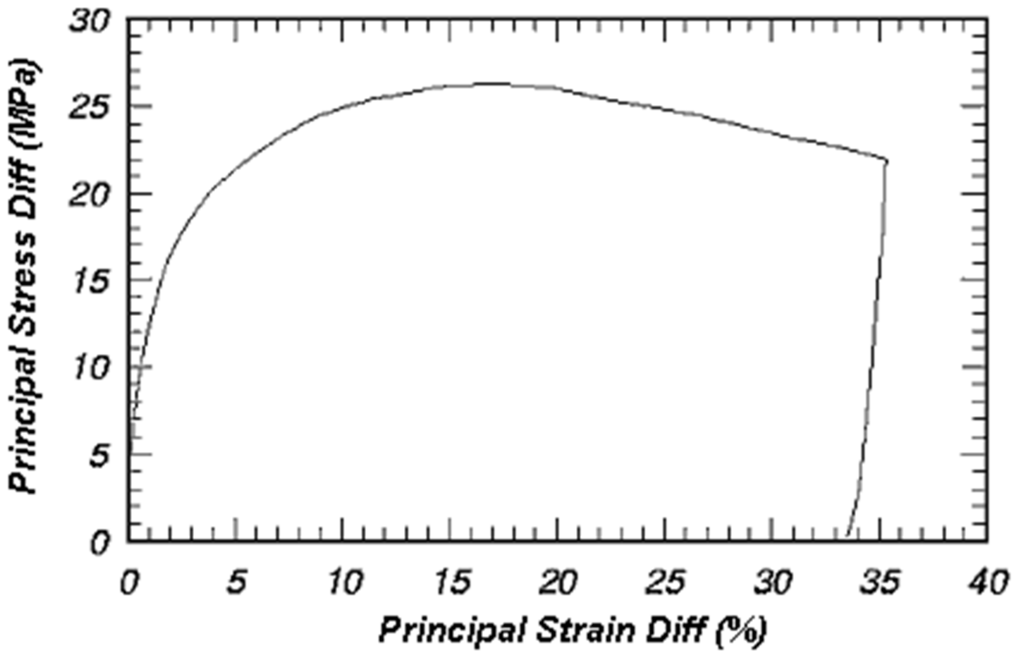
Other Methods

Uniaxial compression test

Experimental Apparatus



Plot

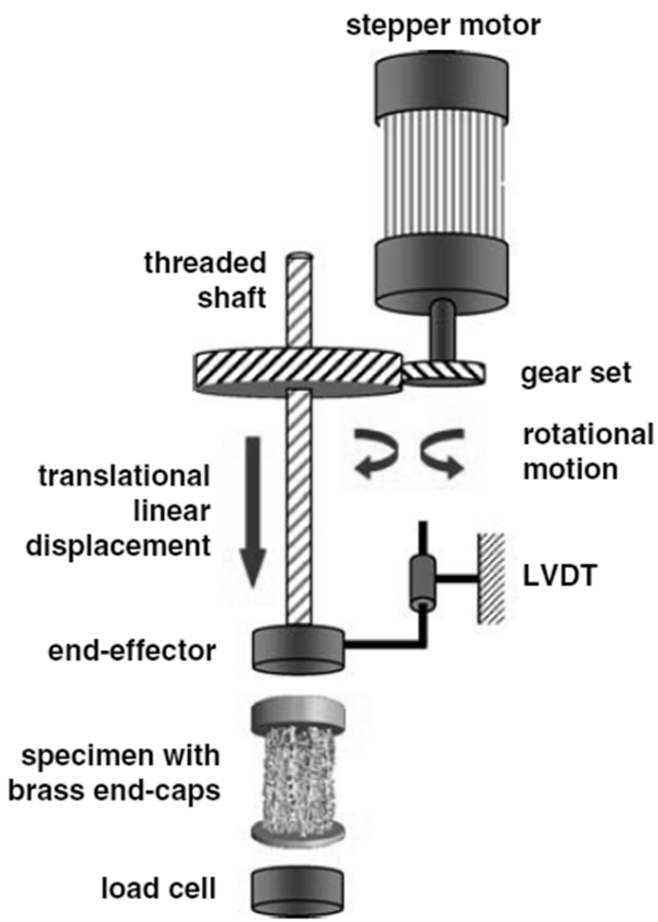


www.claisse.info/Soils%20tests.htm

Other Methods

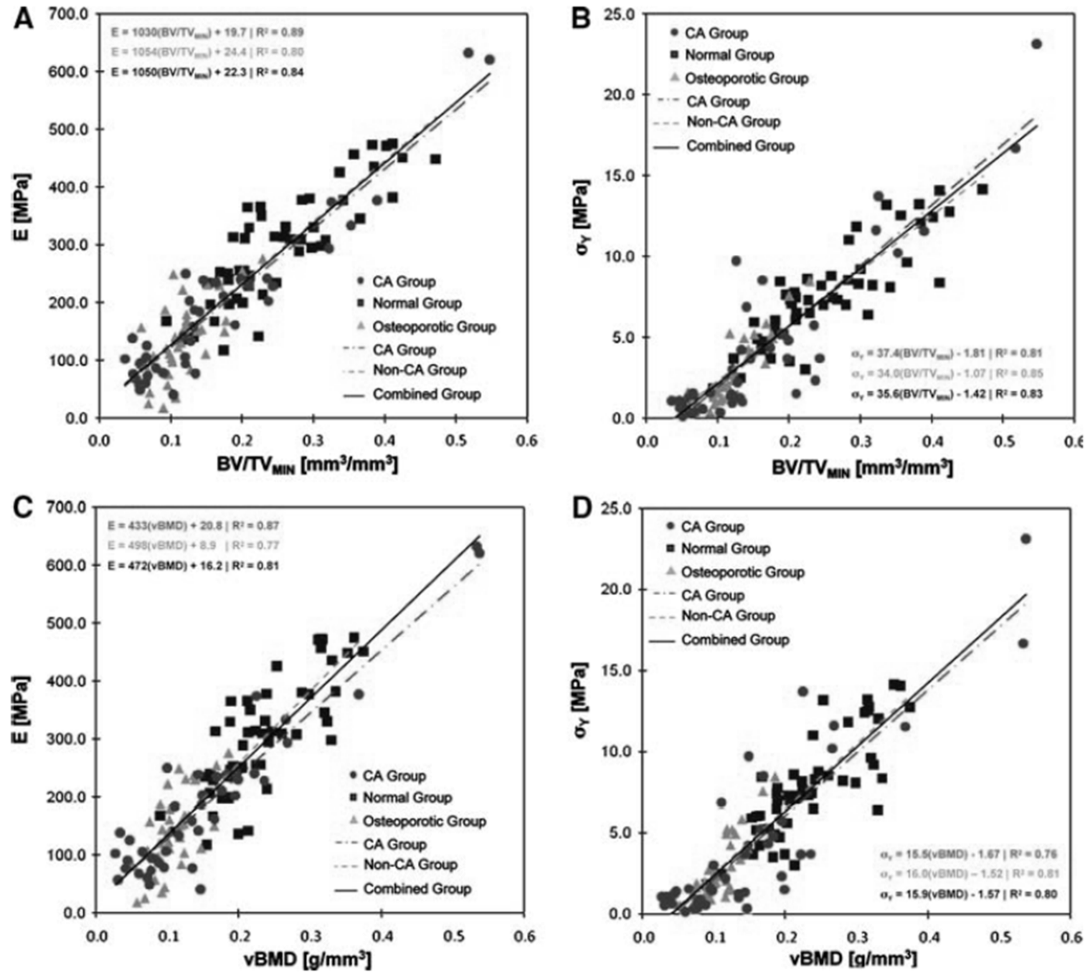
Uniaxial compression test

Experimental Apparatus



Linear variablen Differential-Transformators (LVDT)

Plot



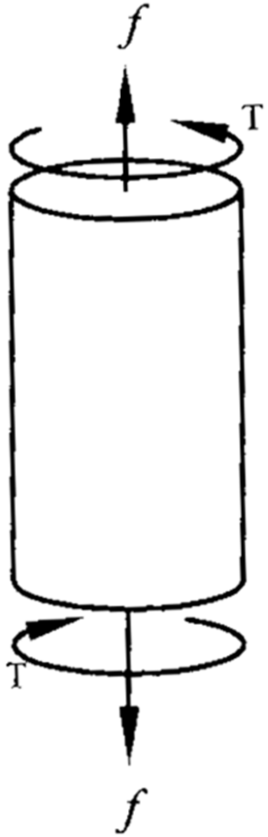
Average bone volume fraction (BV/TV_{AVG}), μCT %

Bone mineral density $vBMD = \rho_{TISSUE} \cdot BV/TV_{AVG}$

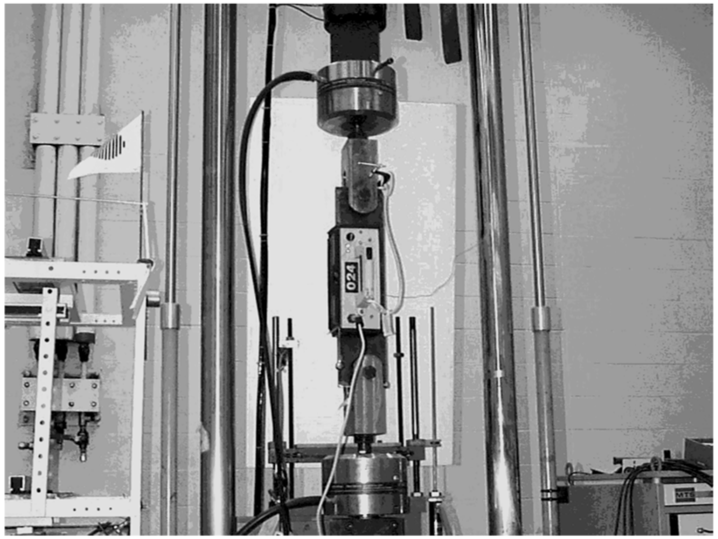
Nazarian et al., Calcified Tissue Int., 2008

Tension-torsion test

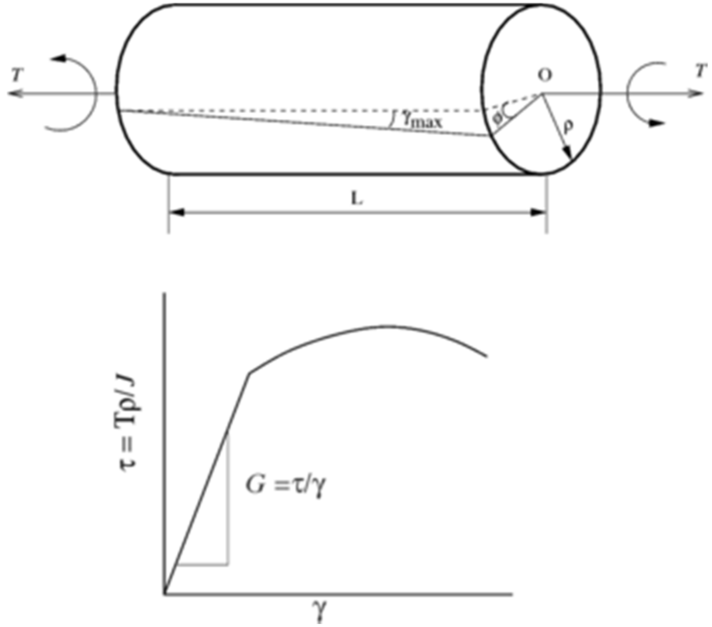
Schematic



Experimental apparatus



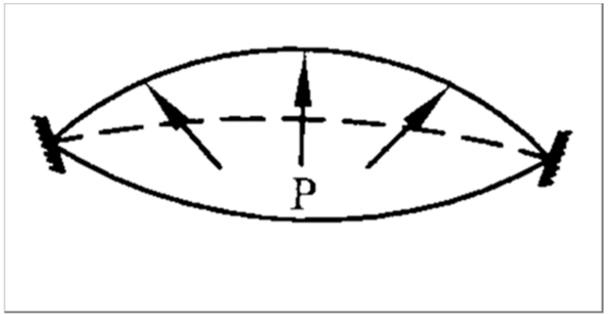
Plot



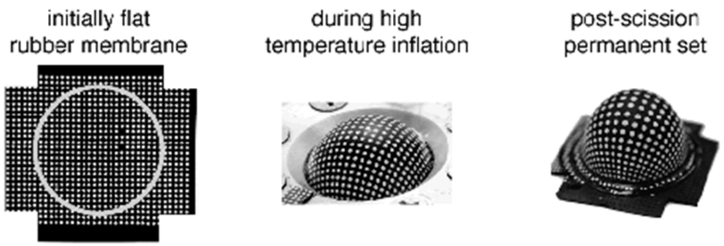
nees.buffalo.edu/seesl/a22.html

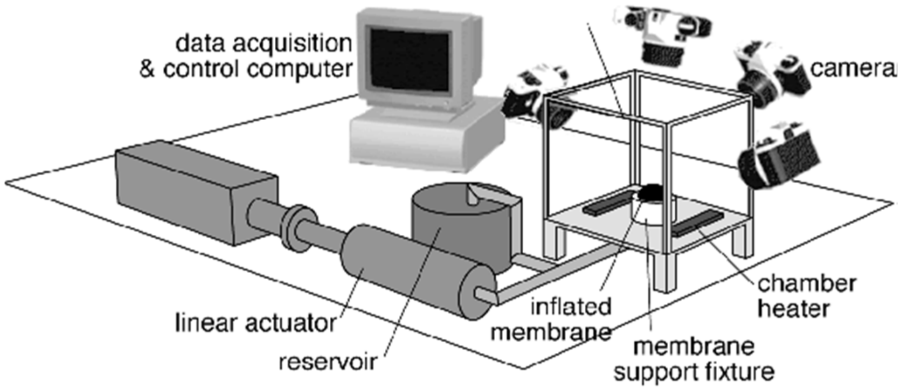
Membrane inflation test

Schematic

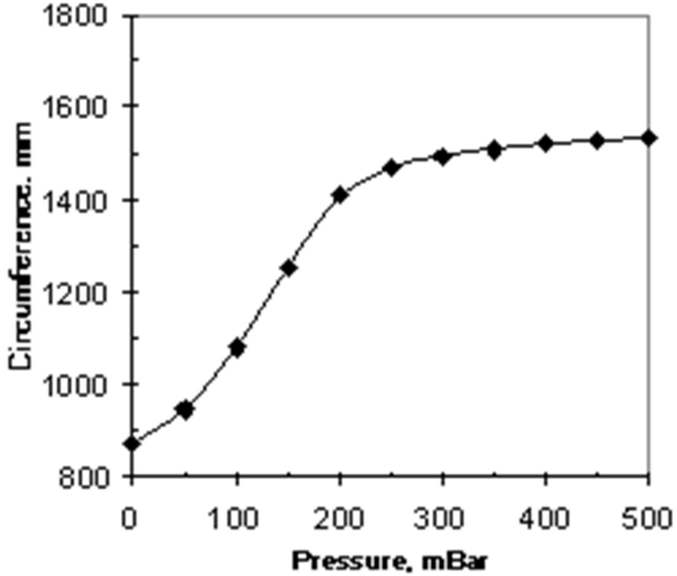


Experimental apparatus





Plot (rubber membrane)

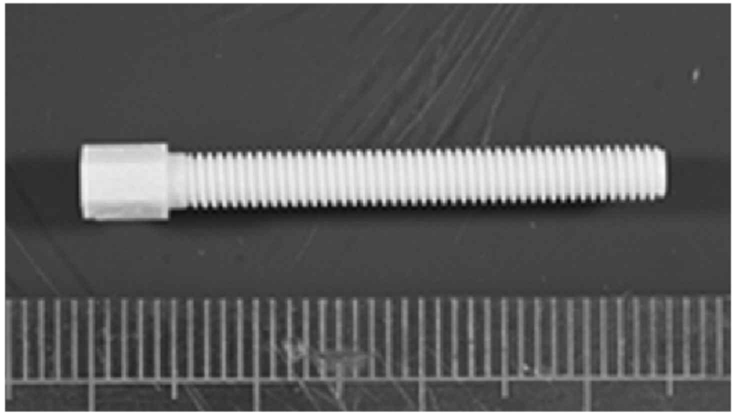


www.mech.ed.ac.uk/.../wavepower/valve/index.htm

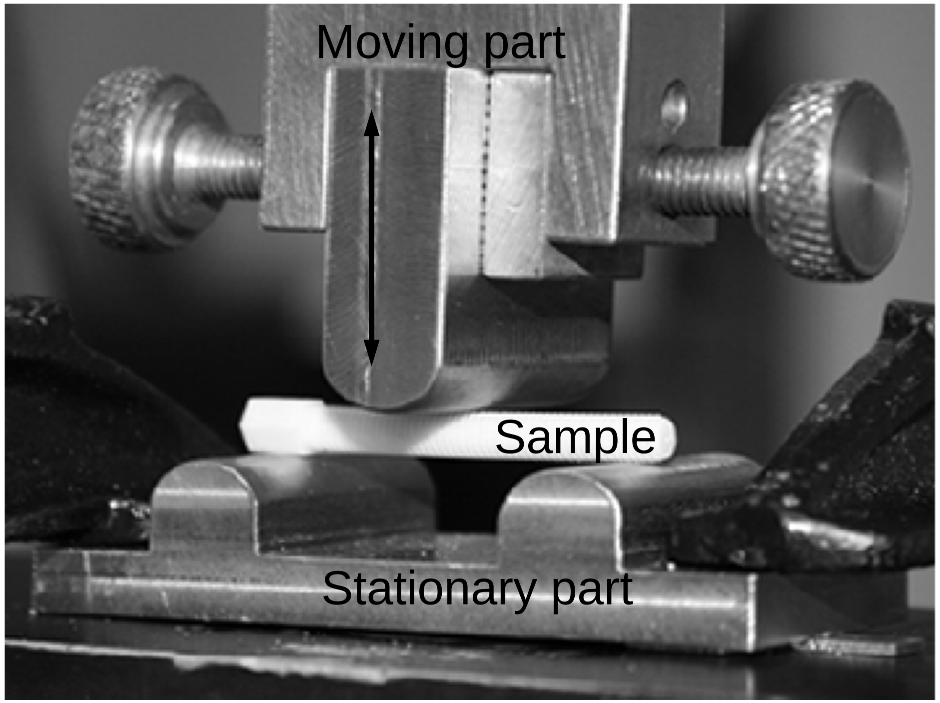
Other Methods

Three-point bending test: bone screws

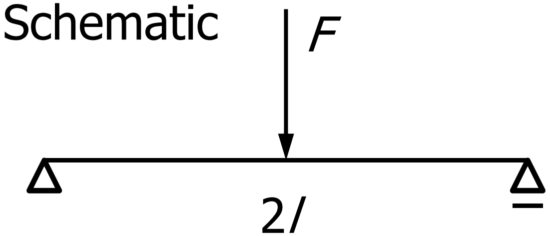
- Human cortical bone
- Löwenherz thread
- 3-point bending DIN 53457



Bone screw in the testing apparatus



Schematic



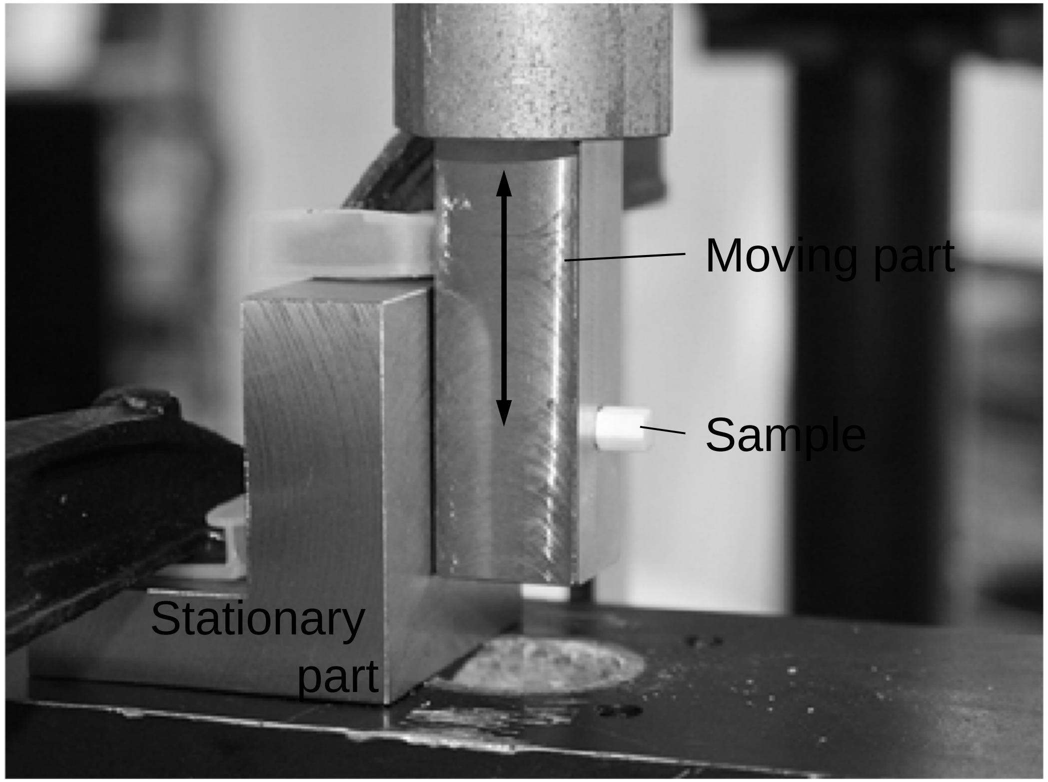
$$\sigma = \frac{2Fl}{\pi r^3}$$

Bachelor's thesis of Lukas Peicha

Shear testing on bone screws

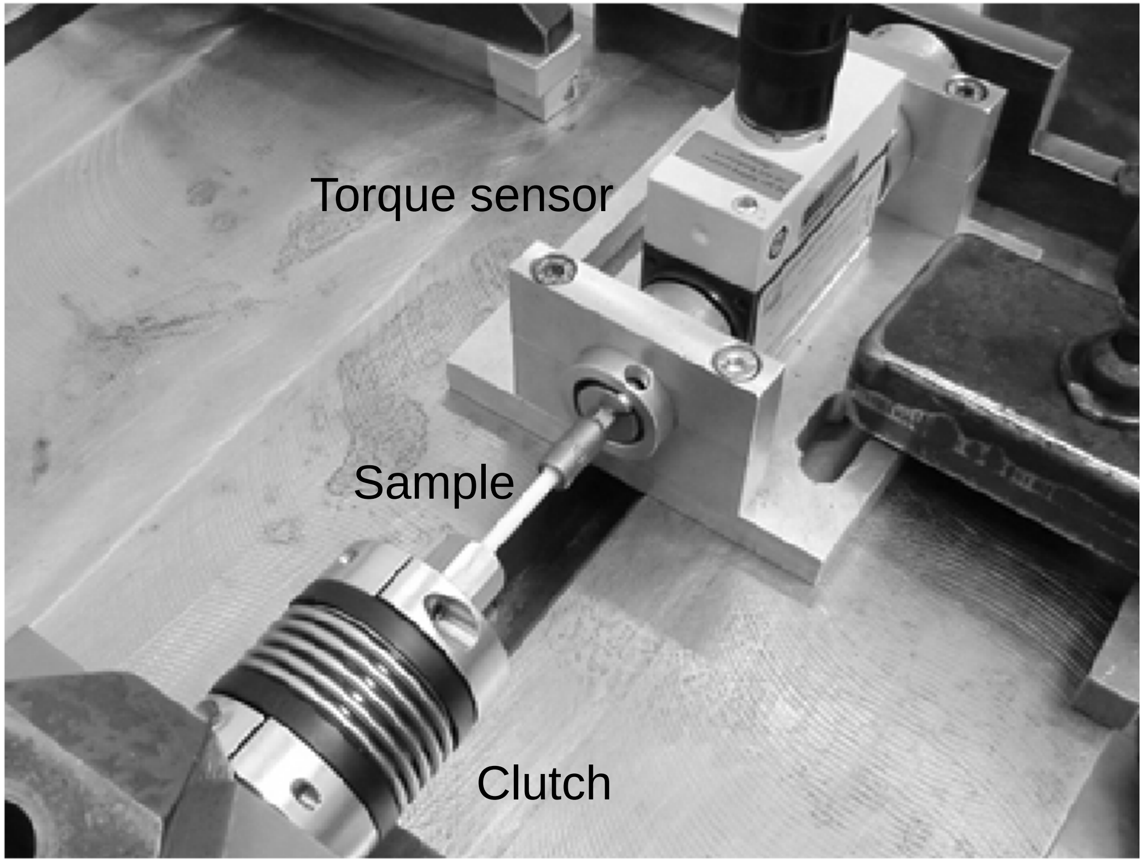
- Shear test DIN 50141

$$\tau = \frac{4F}{d^2\pi}$$



Bone screw in the testing apparatus

Torsion testing on bone screws



Bone screw in the testing apparatus