Biomechanical properties of flat tissues;

Two-axial stress strain behavior

We define

Homogeneity

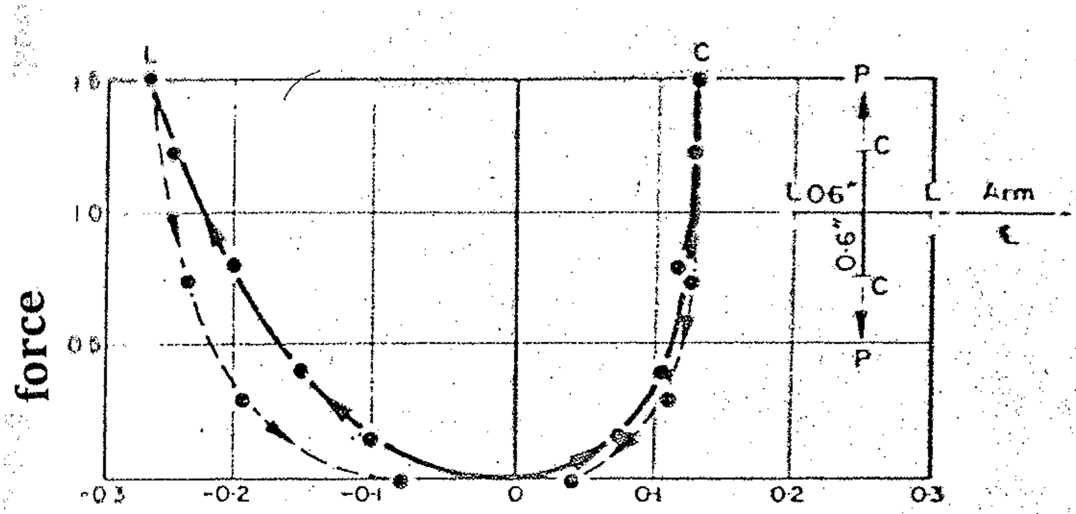
A material is homgeneous if the materials properties are independent from the site; i.e. there is no gradient of the measured quantity over the sample. Otherwise the material is inhomogeneous. In case of coexisting different phases the material is heterogenous.

Isotropy

A material is isotropic if the materials properties do not vary with the direction of measurement or observation, otherwise anisotropic

These definitions hold also for electrical, magnetic, optical, e.g. quantities

Uniaxial test on a skin sample with additional observation of the contraction in the orthogonal direction. Unloading was performed, too.



passive strain

contraction

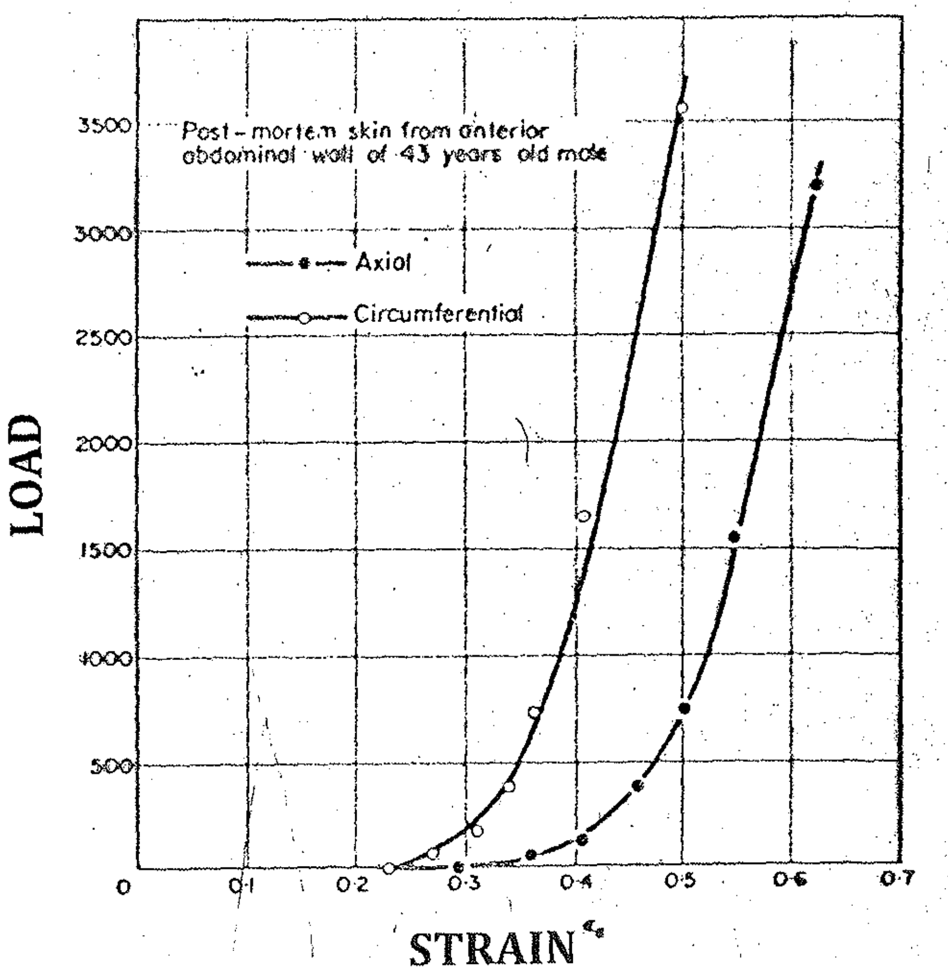
active strain

extension

The right part shows the stress strain plot as usual; the left part shows the contraction measured laterally.

In case of isotropy the skin area tested would be characterized by two parameters, the Young´s modulus and Poisson´s ratio (as a function of strain accounting for nonlinearity).

The stress-strain relationship of a skin sample (abdominal wall) was measured successively in two orthogonal directions (axial and circumferential)



The stress-strain characteristic is different with the two directions indicating an anisotropic biomechanical behavior.

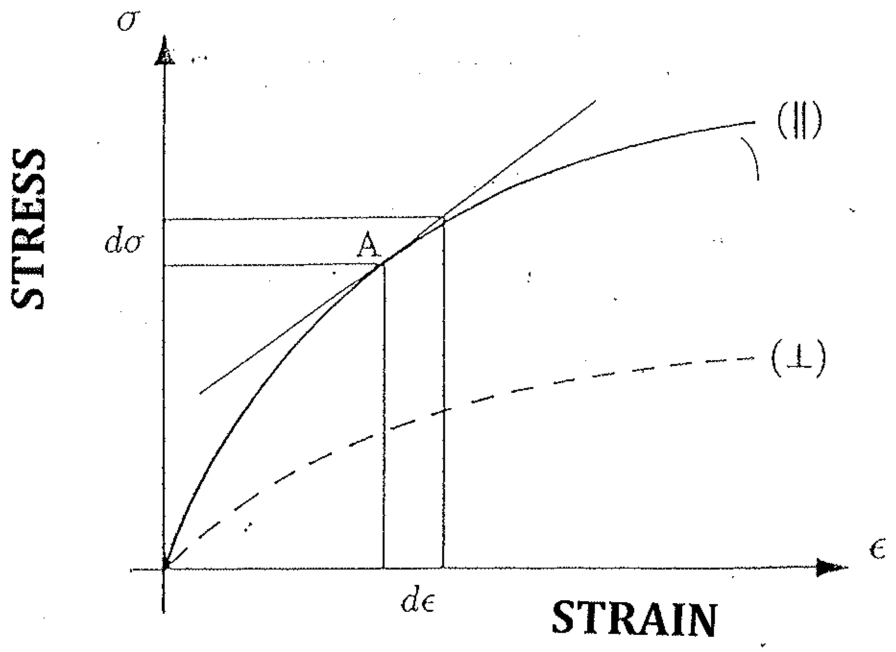
For biomechanical properties of skin samples we expect the following features

i) nonlinear stress strain behavior
   - wavy course of collagen fibrils
   - alignement of the fibers to the axis of applied load

ii) viscoelastic properties
   - hysteresis loop, relaxation phenomenon
   - reorientation of fibers within the proteoglycan matrix when tissue is strained

iii) successively performed uniaxial tests in different orthogonal directions require that original biomechanical properties are restored after the first test
   - we have to perform *preconditioning* of the skin sample
   - or *stress relaxation tests* at several strain levels ond plot the *final elastic value* of stress versus strain

schematic anisotropic stress-strain relationship



One may linearize the stress-strain curves within a small interval of stress and strain and find a reltionship between

Tension stresses $\mathbf{d\sigma_x, d\sigma_y, d\sigma_z}$

And shear stresses $\mathbf{d\tau_{xy}, d\tau_{yz}, d\tau_{zx}}$ on one hand

And the corresponding strains

$\mathbf{d\varepsilon_x, d\varepsilon_y, d\varepsilon_z, d\gamma_{xy}, d\gamma_{yz}, d\gamma_{zx}}$ on the other hand

The elastic coefficients will be writen as matrix

$$\begin{Bmatrix} d\varepsilon_x \\ d\varepsilon_y \\ d\varepsilon_z \\ d\gamma_{yz} \\ d\gamma_{zx} \\ d\gamma_{xy} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \begin{Bmatrix} d\sigma_x \\ d\sigma_y \\ d\sigma_z \\ d\tau_{yz} \\ d\tau_{zx} \\ d\tau_{xy} \end{Bmatrix}$$

In case of an elastic potential it is a symmetric matrix

The biomechanical behavior of tissues is of course 3 dimensional

In case of uniaxial tests or two-dimensional tests one neglegts the other dimensions not measured

A plane state of stress is characterized by $\mathbf{d\sigma_z = d\tau_{yz} = d\tau_{zx} = 0}$.

The state of deformation is three dimensional but the deformation components in the Z-directions do not contribute to the deformation energy

If the components including the Z-directions are not included we will have

$$
\begin{aligned}
d\varepsilon_x &= a_{11}\, d\sigma_x + a_{12}\, d\sigma_y + a_{16}\, d\tau_{xy}, \\
d\varepsilon_y &= a_{21}\, d\sigma_x + a_{22}\, d\sigma_y + a_{26}\, d\tau_{xy}, \\
d\gamma_{xy} &= a_{61}\, d\sigma_x + a_{62}\, d\sigma_y + a_{66}\, d\tau_{xy}.
\end{aligned}
$$

The goal of the two dimensional tests is to determine the remaining coefficients

In case of elasticity the matrix of the remaining coefficients is also symmetric. In case of

- Isotropy, there are two independent parameters, Young´s modulus **E** and Poisson´s ratio $\boldsymbol{\nu}$
- Orthogonal anisotropy $\mathbf{E_x}$, $\mathbf{E_y}$, ν_x, ν_y and shear modulus **G**, with the constraint $\nu_x / E_x = \nu_y / E_y$
- General anisotropy, there are according to symmetry 6 independent parameters

As to the **Orthogonal anisotropy**

If the coordinate system coincides with the principal materials directions we will have a matrix of elastic coefficients of following form

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma \end{bmatrix} = \begin{bmatrix} 1/E_x & -\nu_x/E_x & 0 \\ -\nu_y/E_y & 1/E_y & 0 \\ 0 & 0 & 1/G \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau \end{bmatrix}$$

The matrix is composed of submatrices (block diagonal) such that the system of equations split into a system of two equations and one separate equation for the shear components.

We have different Young´s moduls and Poisson´s ratios for X- and Y-axis

In case of isotropy the Young´s moduls and Poisson´s ratios, respectively, are equal for X- and Y-axis

If the principal materials directions are not known we would not have this simple form of matrix of elastic coefficients. The off-diagonal terms which have been zero (above) would not vanish:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma \end{bmatrix} = \begin{bmatrix} 1/E_x & -\nu_x/E_x & * \\ -\nu_y/E_y & 1/E_y & * \\ * & * & 1/G \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau \end{bmatrix}$$

* is a symbol used for (in general) not vanishing terms. Then there is no distinction from the case of general anisotropy at first sight. If it is possible to transform this matrix to the block-diagonale form by orthogonal transformations of the coordinate system we have found the principal materials directions and found that materials behavior is orthogonal anisotropic.

As a consequence, the shear components γ and τ will be mixed with the axial components ε and σ for an arbitrarily chosen coordinate system

For the experiments it is necessary to decide if tests should be carried out

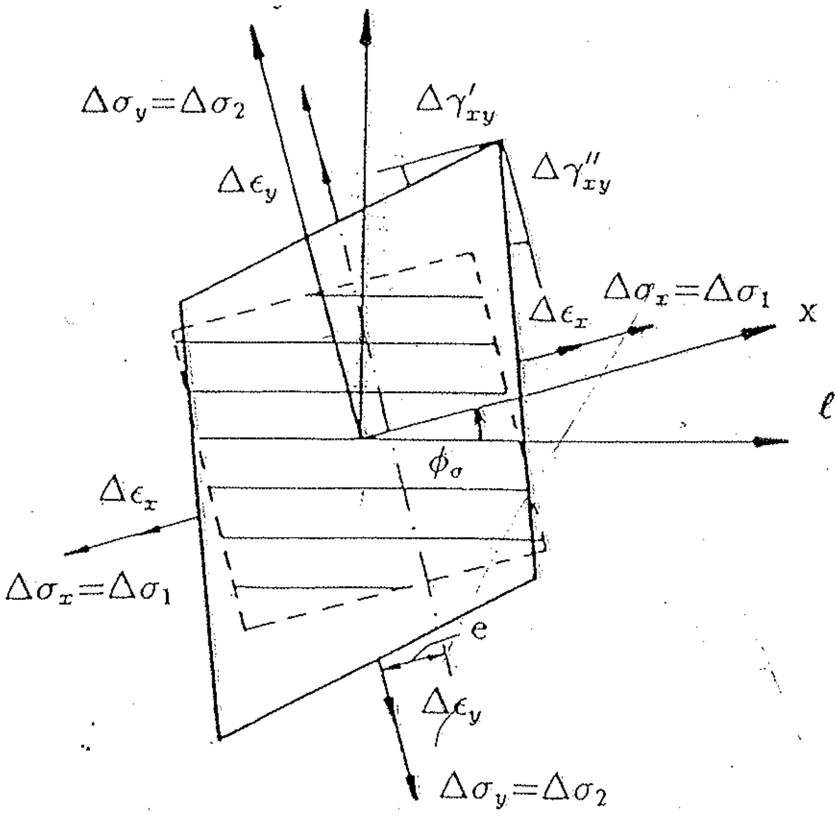
- **load** controlled or
- **strain** controlled

In case of **load controlled** tests the components are prescribed as functions of time, and the strains are measured as materials response.

If the principal materials directions of the specimen are known and the loading is done in these directions an originally rectangular shaped specimen will be also ractangular shaped after loading (at least for linear elasticity)

If the principal materials are not known there will occur shear components of strain, too, resulting in a parallelogram shaped specimen. With the following loading step the applied stresses will not act in line resulting in exerted momenta.

➔ figure



$$\Delta\gamma_{xy} = \Delta\gamma'_{xy} + \Delta\gamma''_{xy}$$

A simple loading mechanism is only possible with known principal materials directions and loading it in these directions. Otherwise, the construction of a two dimensional testing device and the program of the steering of the loading process would be more complicated.

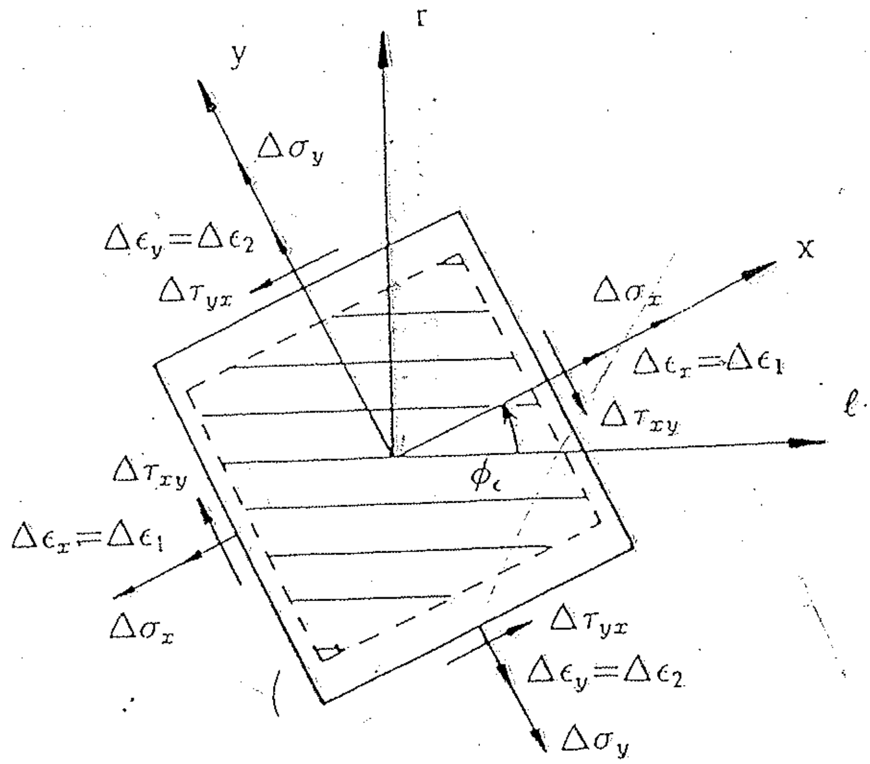
The same would apply in case of specimens with general anisotropy.

In case of **deformation controlled loading** strains ε are prescribed as functions of time and load is recorded as materials response.

If the **principal materials directions** are known and the **line of loading coincides** with these directions only the stress components **σ** are exerted. In case of unknown principal directions or **oblique load application** also the stress component **τ** will be exerted. This will hold in any case for **general anisotropy**. In this case the forces responding to the strain controlled loading are not orthogonal to the circumference of the specimen and it is necessary to measure the **responding load in two independent directions**.

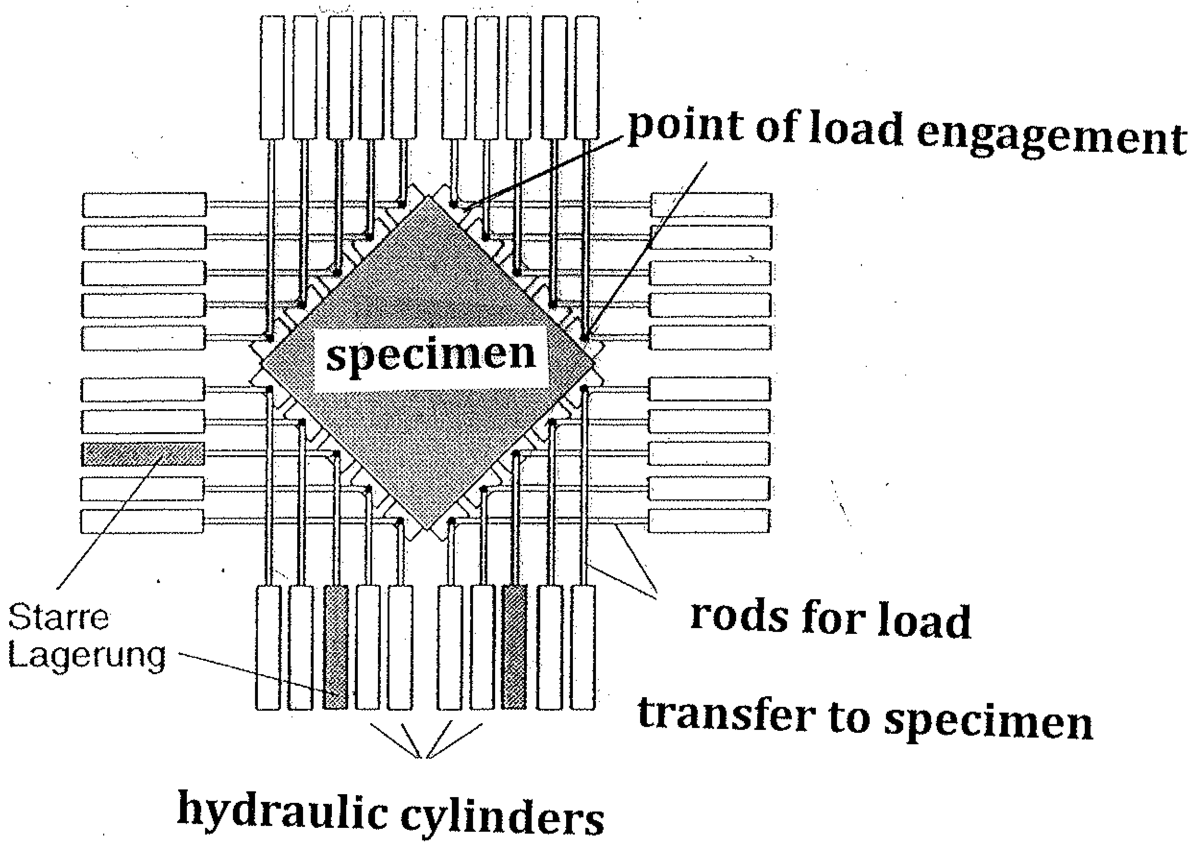
As an advantage may be seen that the rectangular shape of the specimen may be conserved by a proper strain controlled loading procedure.

-> figure



As mentioned the right angles will be right angles after the deformation step. It is necessary to measure the components of load parallel and orthogonal to the circumference of the specimen.

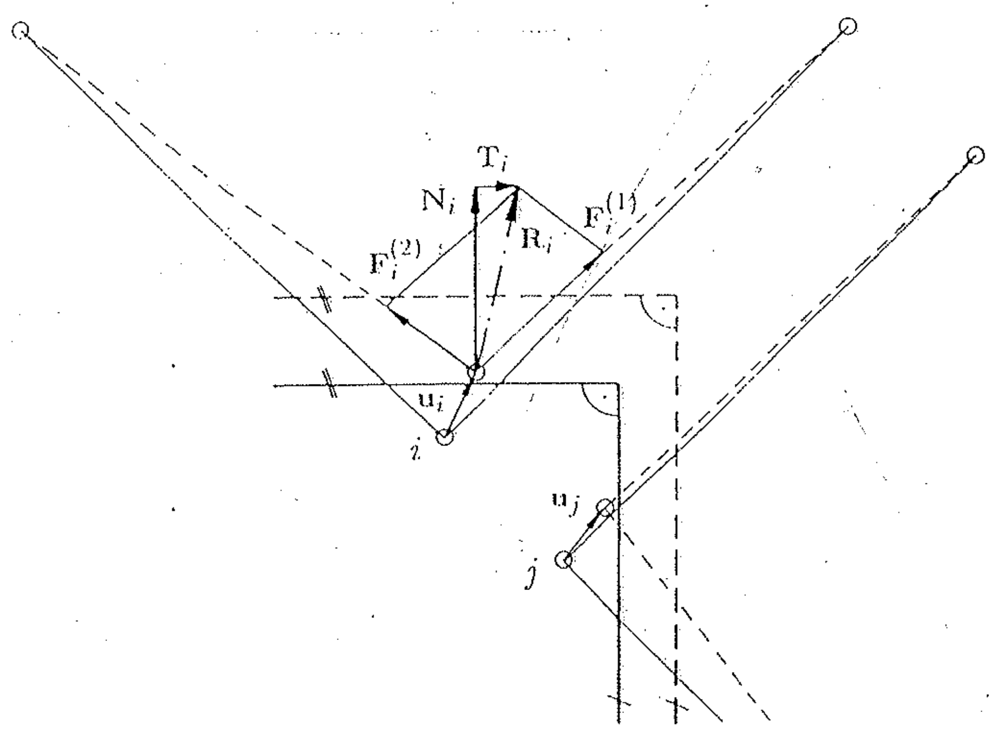
A two dimensional testing device



Loading is performed strain controlled at the indicated points at the circumference of the specimen. Load application in two independent dircetions via two hydraulic cylinders. Strain is prescribed via a PC-program and communicated to the hydraulic pumps.

The resulting forces **orthogonal $F_{\perp}$ and parallel $F_{||}$** to the circumference of the specimen can be derived from the two measured loads

A zoom into one point of load engagement is shown in the following graph



The dashed line show the line of force application after deformation has taken place

The normal and shear components of force are derived from the parallelogram rule to add forces.

As an application in our lab the two dimensional mechanical behavior of samples of wood (orthogonal anisotropy) was investigated

The load axes were equipped with load cells

The load axes were equipped with inductive displacement measuring devices

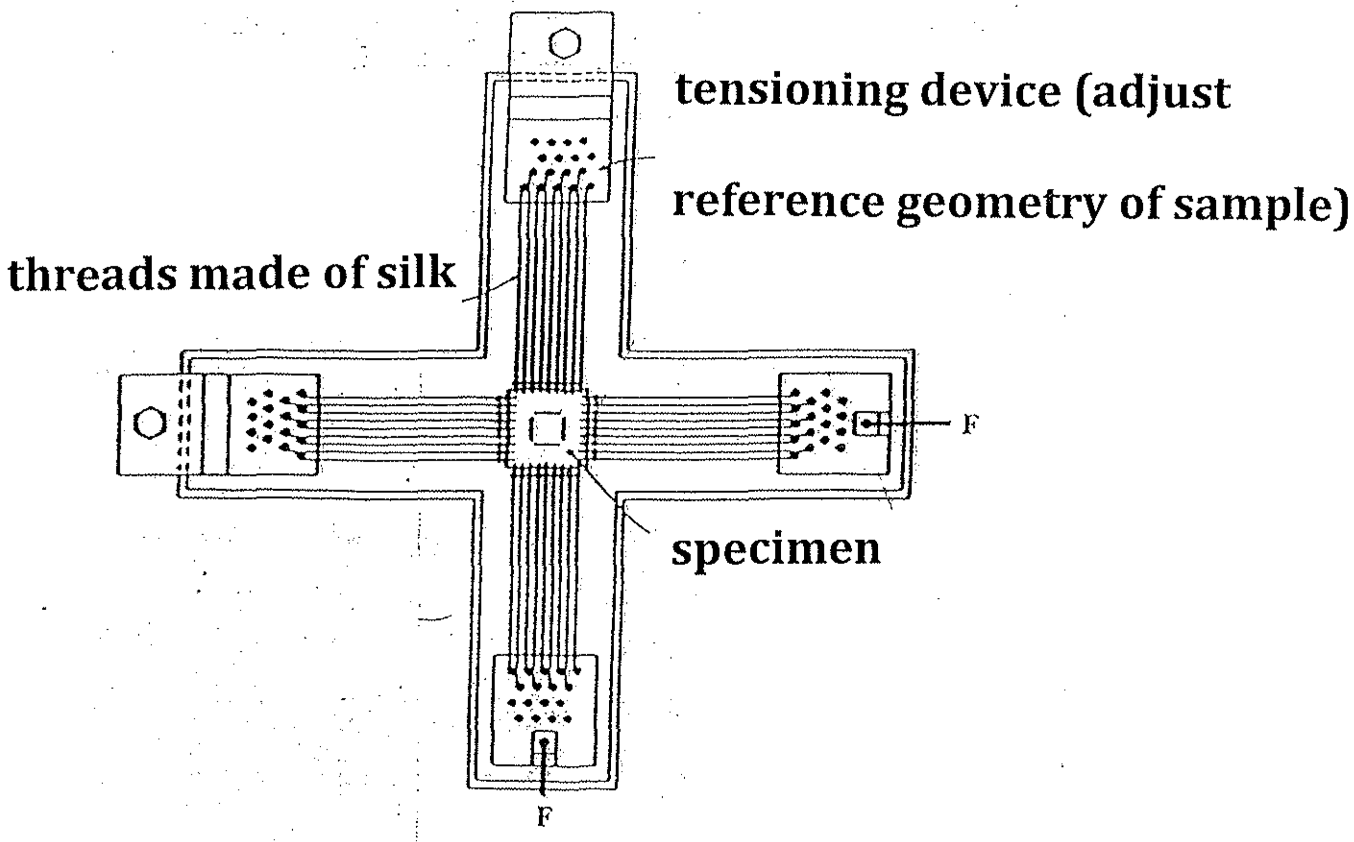
In contrast to samples of skin we have high stiffness and smaller range of strain

Therefore a very stiff frame had to be manifactured

The center of the specimen was nearly fixed (it does not change position when strain controlled loading was applied)

The point mentioned above was a prerequisite to apply an interferetric method. The deformation was measured with the method of specle interferometry (ESPI)

As to **two axial loading of skin samples** (from rabbits) we have the following loading device



- The principal materials directions should be known; this holds in the studies of skin samples from rabbits (from the skin area above the spine, i.e. for reasons of symmetry)
- Tissue clamping such that the materials principal direction coincide with the line of load engagement

Experiments carried out

- hysteresis test (cyclic loading and unloading) with preconditioning. This was performed in body axis and lateral
- the same for the relaxation behavior
- deformation mesurements with a video dimension analyzer

Experiments have be performed uniaxially, i.e.

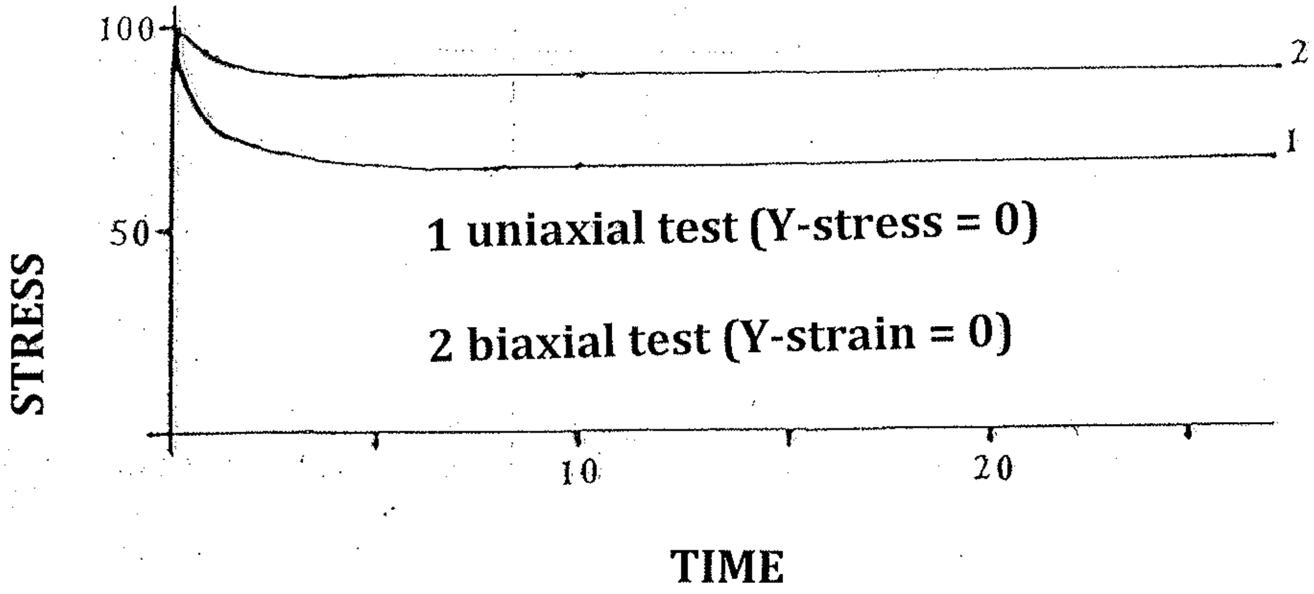
for stress-free circumference of the sample laterally (allow for lateral contraction)

$\sigma_x \neq 0 \quad \sigma_y = 0 \quad \varepsilon_x \neq 0 \quad \varepsilon_y \neq 0$

as well as for locking the lateral contracion (loading sample also laterally to preserve the lateral dimension of the sample)

$\sigma_x \neq 0 \quad \sigma_y \neq 0 \quad \varepsilon_x \neq 0 \quad \varepsilon_y = 0$

Stress reaxation tests have been performed; the result after preconditioning is shown in the graph



1) allow for lateral contraction

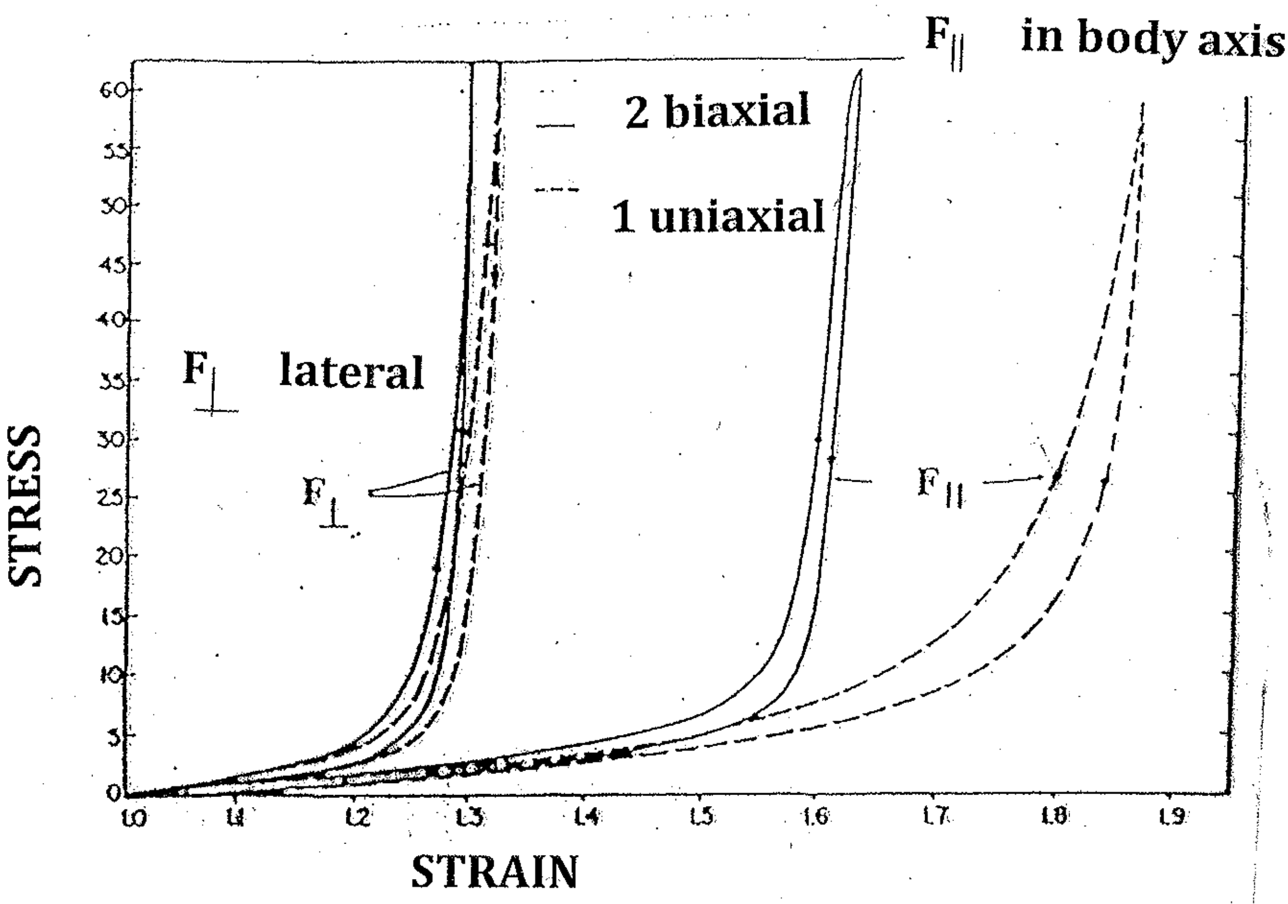
X-strain is kept constant but not that in the Y-direction

2) lock lateral contraction

In addition the Y-strain is kept constant

The extent of stress relaxation (viscous fraction) was larger in case of the uniaxial test

Hysteresis after preconditioning



1) allow for lateral contraction

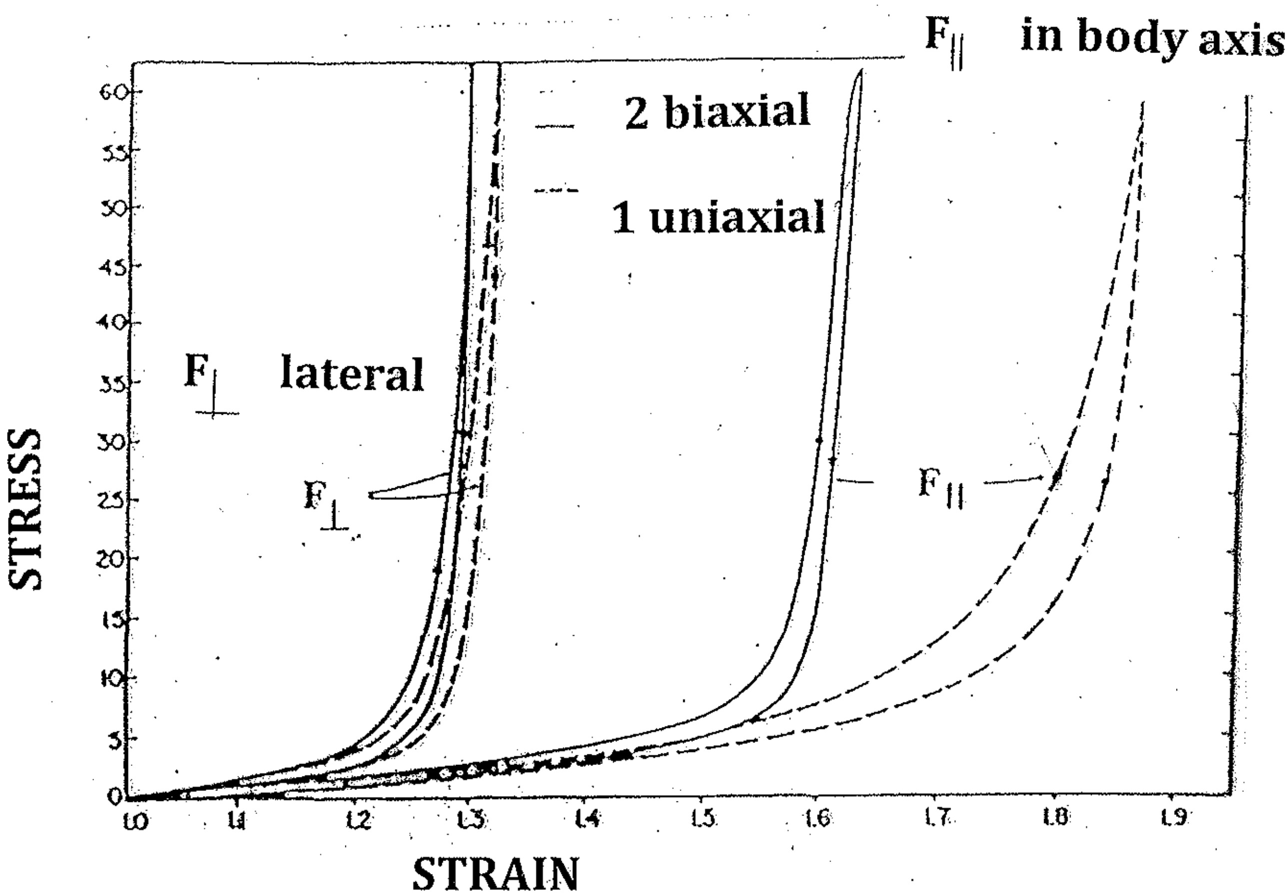
(dashed lines)

2) lock lateral contraction

(full line)

to keep Y-strain = 0 it is necessary to apply a certain Y-stress which generates an additional X-stress

Hysteresis after preconditioning



The stress-strain relationship shows a higher stiffness for the loading in lateral direction

For the biaxial tests the stiffnesses are larger than in the uniaxial case for both, the $F_{parallel}$ and $F_{lateral}$, with this increase more pronounced in the body axis

Some conclusions

- the viscous fraction (according to stress relaxation) does not vanish after preconditioning
- hysteresis does not vanish after preconditioning
- this observation is found for both test modes, uniaxial and biaxial
- constitutive equations have been given for the loading and unloading branch of stress strain behavior. They have to be computed separately
- therefore the material does not behave elastically (by definition as independency from previous loadings)
- The stress-strain points of the curves are not equilibrium states in the sense of thermodynamics; it would be necessary to slow down the strain rate far beneath the typical relaxation time constants of the material->reversible conduction of experimental process.

Biaxial testing of specimens of human skin

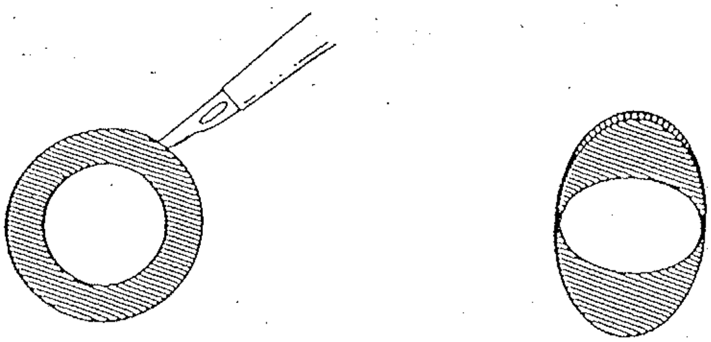
Questions raised

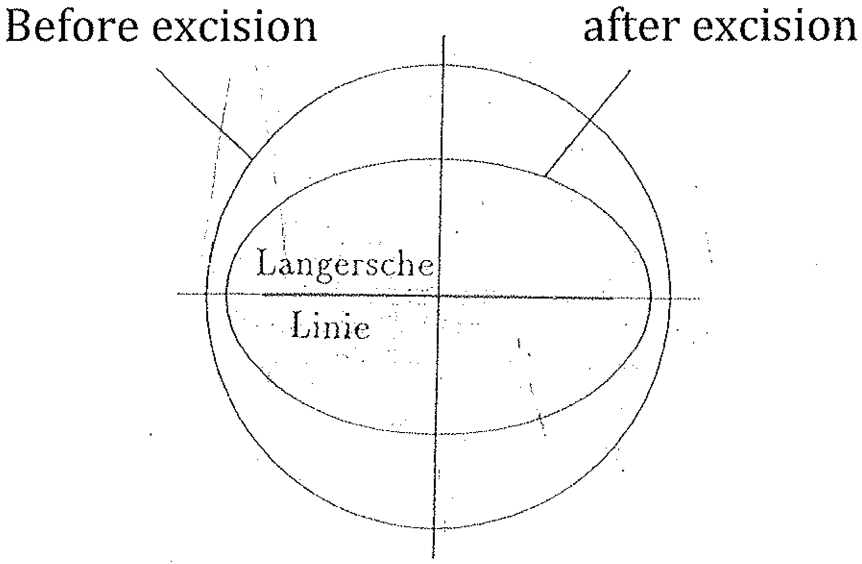
- in vivo stresses of human skin as dependent from body site and posture
- which loads, e.g. in skin of the shoulder region are exerted when elevating an arm
- how do the in vivo stresses and stresses according to movements of limbs change with other parameters of individua, as for example age, body weight, state of health, ..
- the role of the Langer´s cleavage lines

As I was told Duyptren (1834) was the first who studied deformation of skin after „excision of a circular shaped specimen“ (in this case injuries by fire-arms)

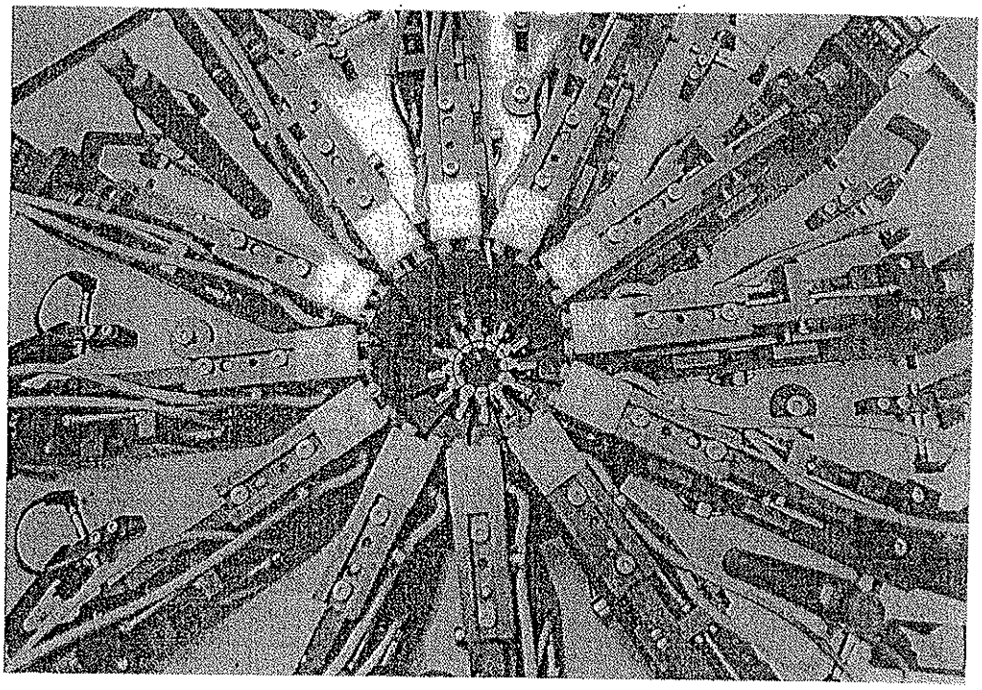
Langer (1850) studied schematically the deformation of skin after circular shaped holes have been punched by an awl. The circles had then the form of ellipses. When drawing lines through the long axes of these ellipses we have the Langer´s cleavage lines. It was stated that following these lines the surgical incisions wouls be optimal for a healing without forming scars.

But it turned that this is not true for all body sites. There was a number of researchers doing experiments on that theme. They found also the conclusions that the Langer lines correspond more to wrinkle lines or they are lines of minimum extensibility or minimum in vivo stress.





Testing equipment for skin samples



i) 12 axes for circular shaped skin specimens

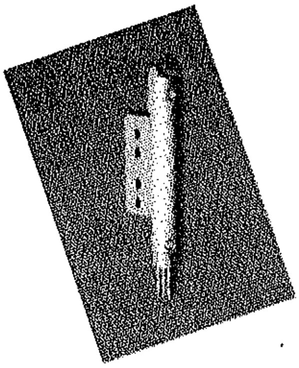
ii) 12 carriages with spindle drives (by stepping motors) for radial displacements

iii) these carriages can rotate about a svivel axis to allow also movement deviating from the radial direction (circumferential)

iv) 12 load cells for load engagement in an excentric manner

v) 12 pincushions to fix the specimen to the axes

vi) a bath with buffered saline



Testing routines

- specimens (different anatomical sites) were taken from fresh cadavers (institute for forensic medicine)

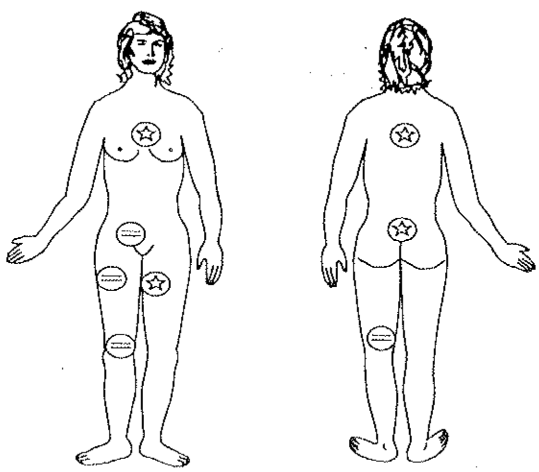
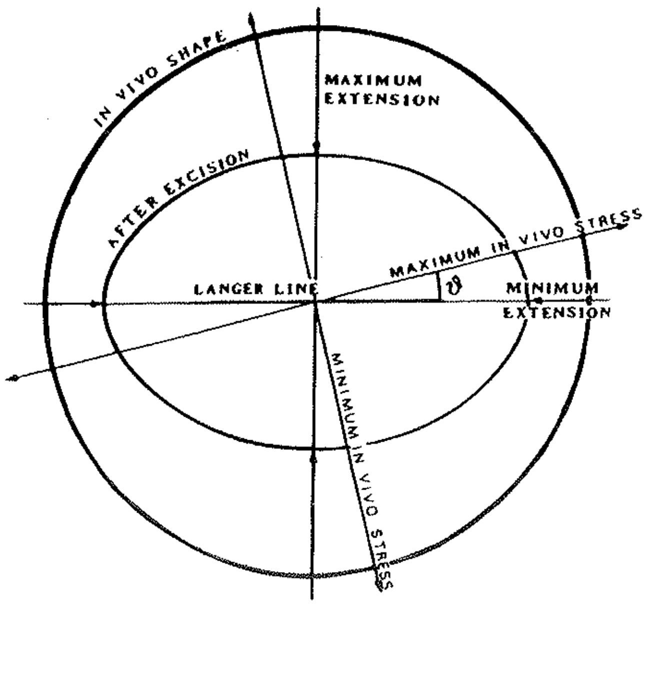
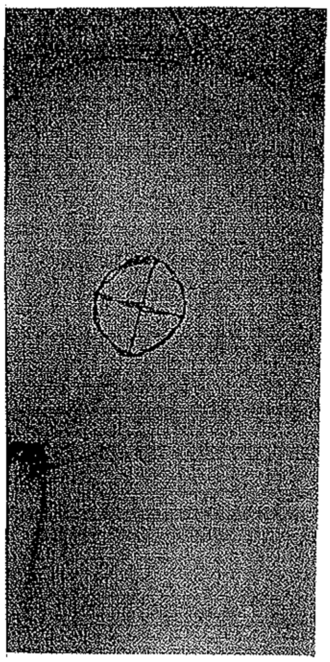


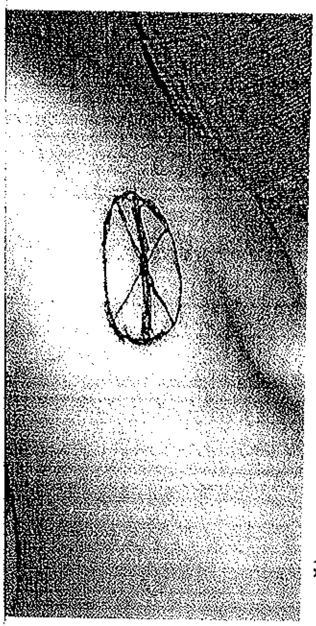
FIGURE 1 . Anatomical Sites of the Skin Samples Tested (=

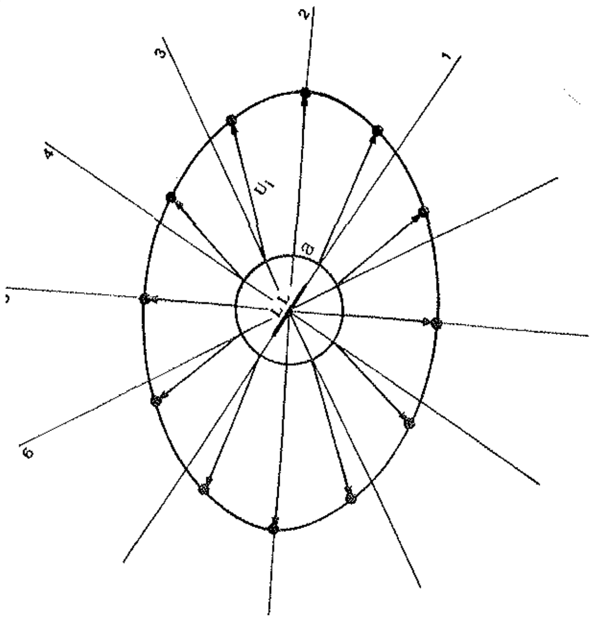
- To give an estimate for the stresses at the „in vivo“ configuration we extended the specimens to the configuration before excision
- The forces at the 12 load cells were converted into stresses (maximum and minimum principal stress)



- Then specimens were extended to deformation values which have been determined at the cadaver, e.g. by elevating an arm. Thus, an original circular shaped line deformed to give an ellipse. By measuring the forces we determined at least an estimate of skin stress according to that movement of the arm.







- In order to compare results to in situ measurements a large number of „in vivo“ measurment methods are found in literature. One of them is the so called suction cup method. A vacuum (at least reduced air pressure) is applied to a circular area of skin and the height of the formed dome is measured

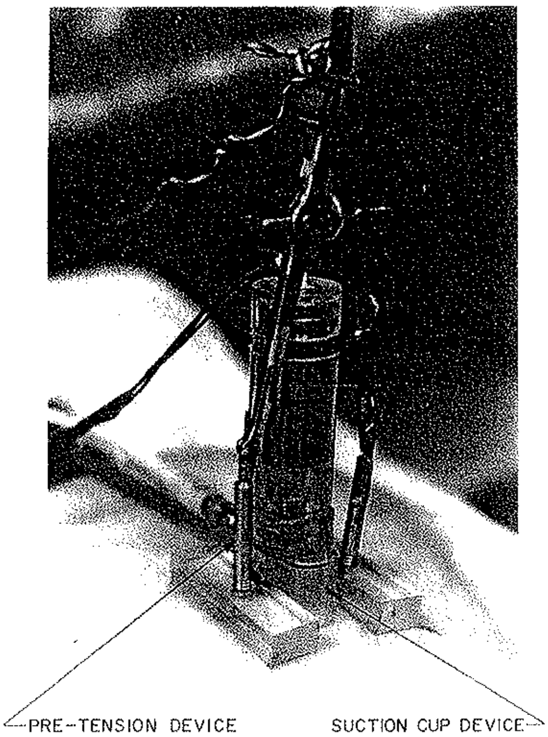
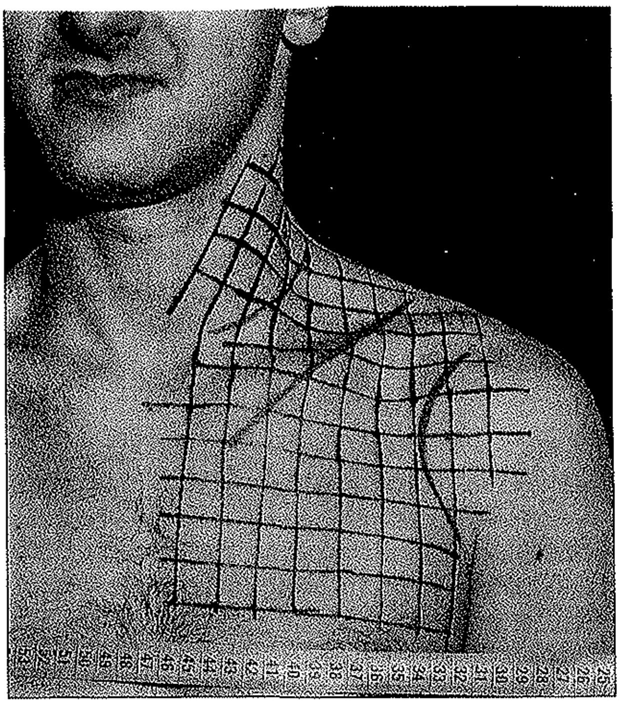
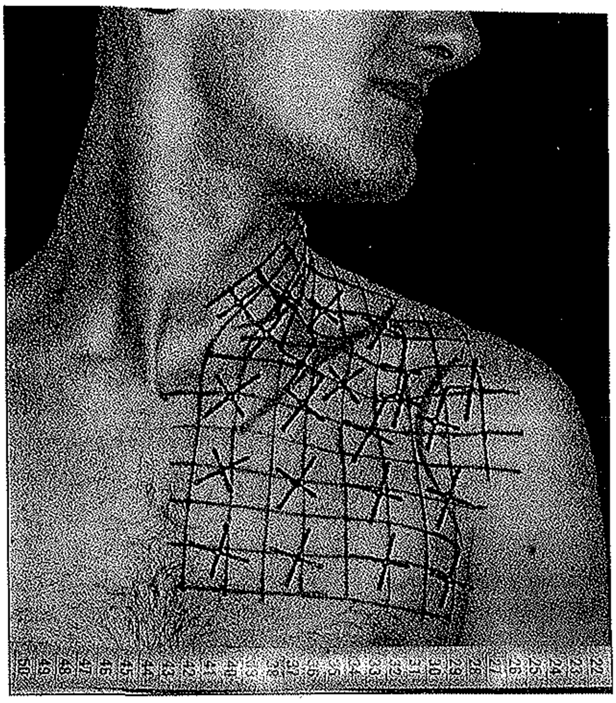


FIG. 2. A typical test situation with the pre-tension and suction cup devices applied to the upper back.

- Ultrasonic measurements using shear wave propagation was also employed
- Another method is to mark a grid on a certain area of skin of a volunteer, and monitor the changes due to, e.g. elevate an arm, turn head as to say yes or no, etc...

The crosses mark the principal strain directions. The 3 lines which are covered by the grid indicate possible lines of incision in case of surgery of „plexus brachialis“-> med. The surgeon was interested in how the concerning area of skin is deformed by daily activities.