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Original Contributions

Mechanical Properties and Young's Modulus of Human Skin in Vivo

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Summary. The mechanical properties of the in vivo dermis were measured by means of a torque applied to the skin. The resulting deformation of 2–6°, including the immediate and delayed visco-elastic components, as well as the relaxation were measured, and the raw values corrected for a constant skin thickness. The experiment performed on 138 individuals from 3 to 89 years old revealed a diminished elasticity and stretchability after the age of 30, associated with an increase in the visco-elastic component. The Young's modulus doubles with age. The results are discussed in terms of the various models proposed to explain dermal structure.

Key words: Skin biomechanics – Ageing – Collagen – Dermis – Young's modulus

Zusammenfassung. Die mechanischen Eigenschaften der Haut in vivo wurden anhand eines Drehmoments gemssen. Die so erhaltene Deformierung (2 und 6°), ihre sofortige und ihre viskoelastische verzögerte Komponente, sowie ihre Erschlaffung wurden gemessen und für eine konstante Hautdicke korrigiert. Der Versuch betraf 138 Personen im Alter von 3 bis 89 Jahren und zeigt eine Verminderung der Elastizität und der Dehnbarkeit mit Erhöhung der viskoelastischen Komponente nach 30 Jahren. Das Youngsche Modul verdoppelt sich mit zunehmendem Alter. Die Ergebnisse werden in bezug auf die verschiedenen Hautstruktur Modelle diskutiert.

Schlüsselwörter: Biomechanik der Haut – Altern – Kollagen – Haut – Youngsches Modul.

The biomechanical properties of the dermis were studied in vivo by means of a torque. The torque, maintained at a constant strenght, was applied through the

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intermediary of a disc fixed on the skin's surface. The torque rotated the disc to an angle θ measuring the distension of the skin. The simultaneous measurement of the skin fold thickness allowed the calculation of this angle in terms of a constant thickness. Thus, it was possible to establish for a given force, a point on the stress-strain curve.

In an earlier work [10], we calculated a point on this curve situated on the lower portion of the linear zone. The present work proposes to define another point on this linear zone for a larger stress, and to deduce the slope of the graph. The chosen stress was $28.6 \cdot 10^{-3}\,\mathrm{N} \cdot \mathrm{m}$, inducing a twist θ of $2-6°$, varying among the individuals. This strain falls within the limits of the demands made on the skin by usual stress. The 2 min manipulation is completely painless.

As we shall see, this work also allows a definition of additional biomechanical parameters, and an hypothesis for the genesis of tissue modification.

Material and Methods

The apparatus and protocol used were described in our previous publication [10]. The only difference lies in the greater intensity of the applied force ($28.6 \cdot 10^{-3}\,\mathrm{N} \cdot \mathrm{m}$).

The 138 individuals examined had no dermatological anomaly at the test site. Table 1 of the previous publication [10] shows the age and sex distribution.

The displacement curve, plotted as a function of time, maintains the same form as that for lesser strains (Fig. 2 in [10]). The parameters used were immediate distension (Ue), final distension after 2 min (Uf), delayed distension (Uv) calculated as Uf-Ue and immediate retraction (Ur). Late retraction, total retraction, and residual strain were not taken into consideration because they correspond to weak skin strains that might be overly influenced by the rubbing forces of the testing apparatus.

Immediately after the application of the twist the skin fold thickness was measured at the same site. The statistical results of the measurement are shown in Fig. 4 of our previous paper [10]. Each individual measurement of the skin fold was used to calculate the biomechanical parameter values for a given individual for a thickness of 1 mm. These normalised parameters are marked with an asterisk (Ue*, Uv*, etc...).

The mathematical calculation of the skin's strain due to the twist is shown in the appendix, as well as that of the Young modulus. The Student-Fischer *t*-test was used for statistical analysis to compare the means, with a corrected formula for a sample of less than 30.

Results

Absolute Parameters

The modification of the raw and normalised parameters for a constant skin thickness are presented in Figs. 1–4. All the curves are characterised by a sudden decrease at about the age of 30. Seven out of eight parameters show a statistically significant difference (Table 1) both in men and in women, yet no significant difference was noted between the sexes.

Relative Parameters

Calculations were made for each age group concerning two relative parameters: Uv/Ue and Ur/Ue (Figs. 5a and 6). These two parameters are of value: firstly, they are independent of skin thickness and, secondly, Ur represents the skin's aptitude to return to its initial state after having withstood a 2 min strain.

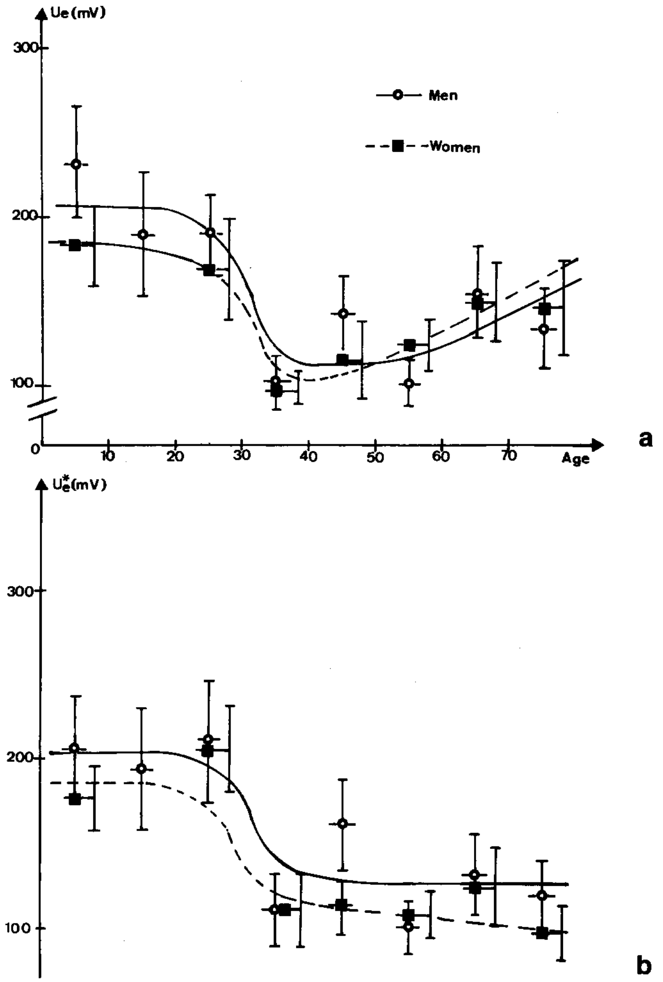

Fig. 1. a *Ue* and **b** *Ue** as a function of *age*. Ordinates in mV. Mean and standard error of the mean

The visco-elastic proportion of the total distension (Uv/Ue) rose progressively with age (Fig. 5a). No significant difference was noted between the sexes, only a greater variation of the values according to age was found in the men.

The ratio of immediate retraction over immediate distension (Ur/Ue) decreased only after the age of 50 in women (Fig. 6). In men, this ratio decreased twice: once at the age of 20, and again at 40. Before the age of 20, the male values were greater than the female values.

Stretchability

Cutaneous rigidity (the Young's modulus) may be evaluated by the slope of the linear portion of the stress strain curve (Fig. 3 in [10]). From our experiment a point on this curve is located by its abscissa being the parameter Ue* and its ordinate

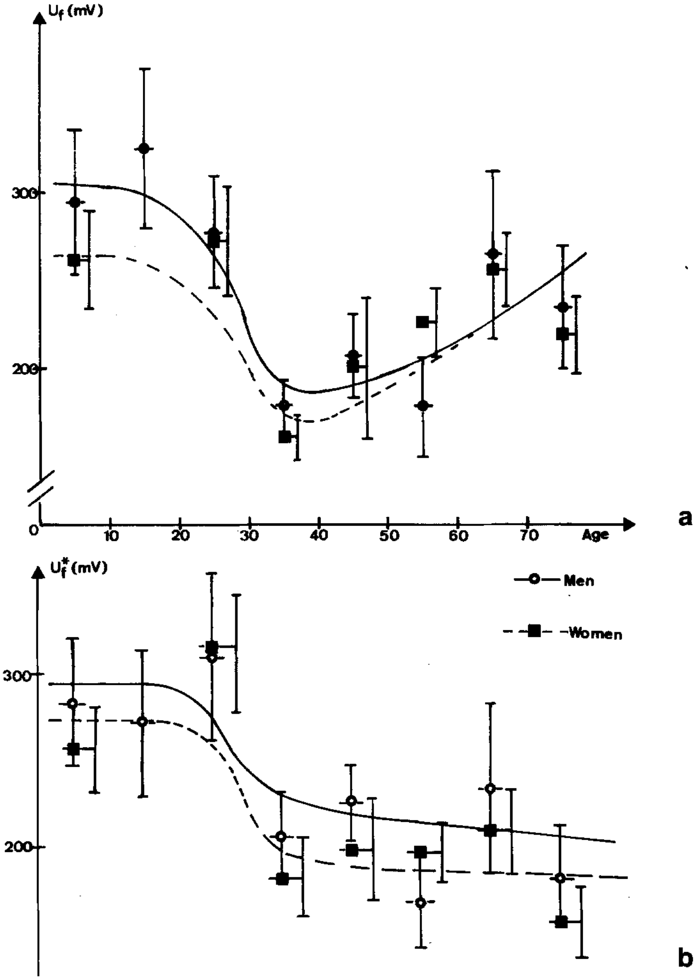

Fig. 2. a *Uf* and **b** *Uf** as a function of *age*. Ordinates in mV. Mean and standard error of the mean

being the applied twist. When calculating for each age group the difference between Ue* for a strong torque and Ue* for a weak torque (Fig. 5 bottom in [10]), and then dividing by the difference of the torques, one obtains a value that varies inversely to the Young's modulus. The difference between the torques remaining constant, it suffices to observe the difference among the Ue*s to obtain the variation of this inverse as a function of age (Fig. 5b).

We noted that two populations appeared. One less than 30 years old with a low Young modulus (strechable skin), the other over 30 with an elevated Young modulus (skin less stretchable). The difference was highly significant ($P < 0.001$). A torque of $28.6 \cdot 10^{-3}$ N · m displaced the skin 5.6° in young individuals, and 2.0° in older people. The calculation of the theoretical relationship between twist and strain (calculations in the Appendix) gave a Young's modulus of $4.2 \cdot 10^5$ N · m^{-2} for the young and $8.5 \cdot 10^5$ N · m^{-2} for the older.

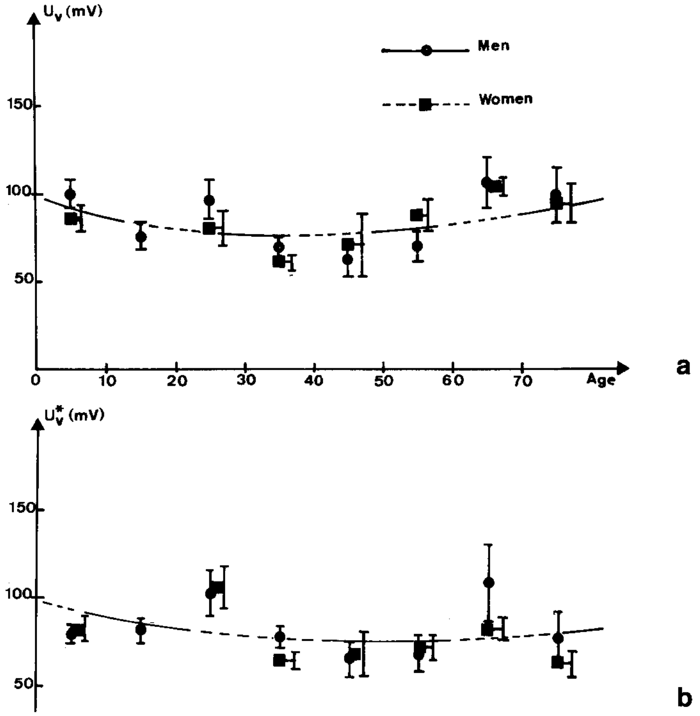

Fig. 3. **a** *Uv* and **b** *Uv** as a function of *age*. Ordinates in mV. Mean and standard error of the mean

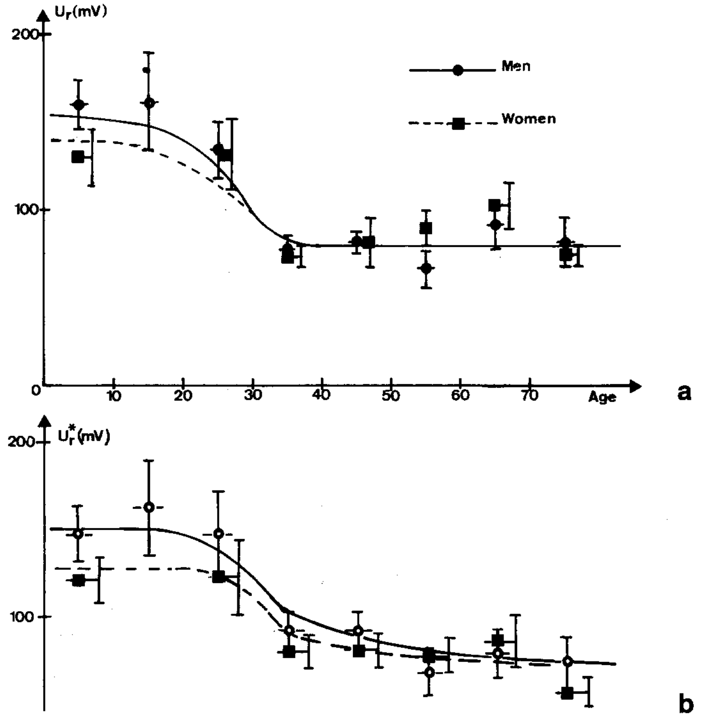

Fig. 4. **a** *Ur* and **b** *Ur** against *age*. Ordinates in mV. Mean and standard error of the mean

Table 1. Result of statistical comparison between people aged under and over 30, for each parameter. The first figure is the probability (P) of chance in the difference. The second figure, in brackets, is the total number of subjects

Parameter	Ue	Ue*	Uv	Uv*
Men	0.001 (63)	0.001 (63)	NS (61)	NS (61)
Women	0.02 (70)	0.001 (67)	NS (65)	0.005 (65)
Parameter	Uf	Uf*	Ur	Ur*
Men	0.02 (59)	0.005 (61)	0.001 (63)	0.001 (62)
Women	0.01 (68)	0.001 (64)	0.001 (67)	0.001 (65)

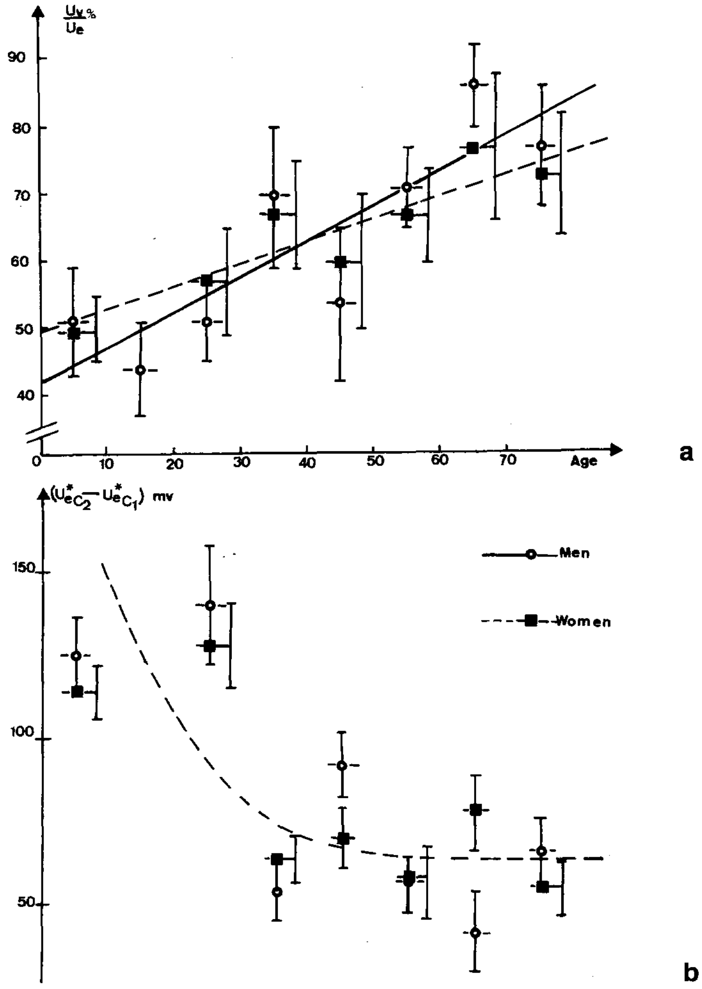

Fig. 5. a *Uv*/*Ue* against *age*. Mean and standard error of the mean. **b** Difference between strain at high stress ($Ue^*_{C_2}$) and low stress ($Ue^*_{C_1}$) plotted against *age*. Ordinates in mV. Mean and standard error of the mean

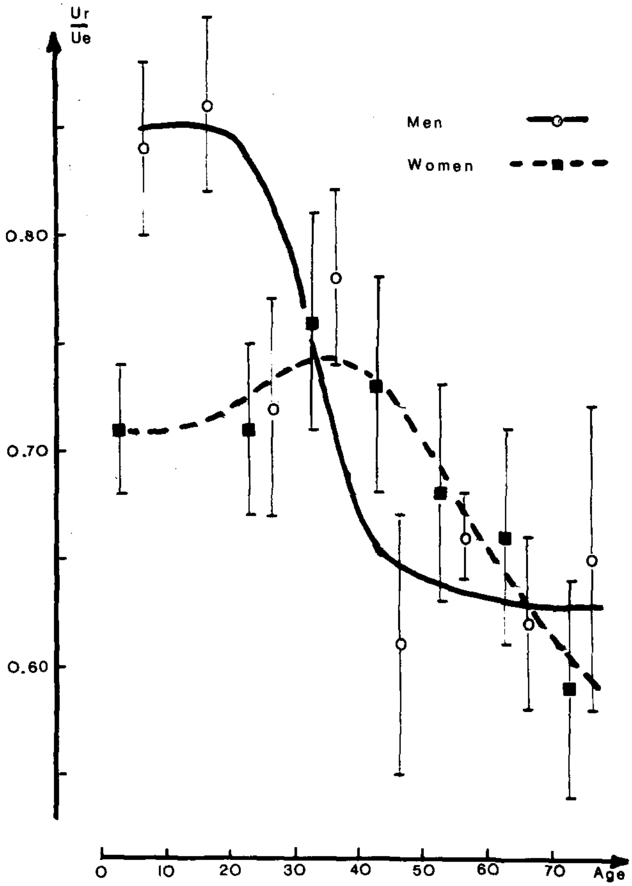

Fig. 6. *Ur/Ue* against *age*; mean and standar error of the mean

Discussion

The application of a $28.6 \cdot 10^{-3}$ N · m torque twists the skin an angle of 2–6° and lies within the limits of the strains to which the skin is commonly exposed. Under the conditions where it was applied, the effect of the twist was limited to an area between the central rotating disc and the peripheral immobile ring. The resistance of the hypodermal-dermal connections is pratically negligible on the dorsal aspect of the forearm, the area where all the tests were performed, since the skin is readily moveable over the underlying muscle. Furthermore, the human stratum corneum of the back, under uniaxial stress at 22° C and 82 % relative humidity has a Young's modulus near to $2.10 \cdot 10^6$ N · m^{-2} [2]. This is about 2–4 times higher than what we have found for the total skin on the dorsal aspect of the forearm in vivo.

The biomechanical parameters vary significantly with age. Immediate distension (Ue*) and immediate retraction (Ur*) remain stable until about the age of 30, but then drop suddenly by 50%. The Young's modulus follows this evolution inversely with a sudden increase of 50 % towards the age of 30. This rise in dermal rigidity with age was also found by Grahame and Holt [6], using a suction apparatus. They found an increase in the Young's modulus mostly from the age of 45, with values generally greater in women. We also found a larger Young's modulus in women in the age groups 0–10, 20–30, 40–50, and above 70. However, this difference was not statistically significant.

Alexander and Cook [1], using an apparatus similar to ours, found the same phenomenon, but noted a diminished Young's modulus from the age of 6–20, and two populations after the age of 60 – one with an elevated Young's modulus, the other with an extremely low modulus. However, Pierard and Lapière [11] using a similar method, found no variation in the skin's deformability with age.

Finlay [3, 4], using an apparatus similar to ours, applied a torque of $25 \cdot 10^{-3}$ $N \cdot m$ to the forearm, with the resulting angle of deformation falling between 2 and 4°. He noted a diminished extensibility with increasing age within the interval of the ages 8–65, paralleled by a slowed cutaneous retraction after the release of the stress. Our observations confirm those of Finlay.

However, Sanders [12], using an $80 \cdot 10^{-3}$ $N \cdot m$ torque on the forearm, found a regularly progressive rise in skin distension with increasing age, between 9 and 60 years, which contradicts our findings. An explanation for this disagreement probably resides in the absence of a skin attachment by the peripheral ring in the Sander's apparatus. Furthermore, the author established only a single point of the stress-strain curve and made the linear portion of the curve start at the origin. So he did not consider the TOE region, which further diminishes the slope of the curve.

Jansen and Rottier [9] measured the unidirectional linear extension of an excised strip of human skin. They noted that the most significant modifications occurred in men between the ages of 35 and 55, being a diminished rupture force and maximum elongation, involving an accentuated rigidity of the tegument.

Starting with the elongations that we found for the weak twists (situated in the beginning of the linear phase) and for the strong twists (situated at the end of the linear phase) we found the Young's modulus close to $4.2 \cdot 10^5$ $N \cdot m^{-2}$ in young individuals, and $8.5 \cdot 10^5$ $N \cdot m^{-2}$ in older individuals. These results are about 100 times smaller than those of Grahame and Holt [6]. The discordance is probably due to the difference in the anatomical structures brought into play with the employed techniques.

In our experiments, the skin distortion always disappeared when the stress was removed, though several hours were necessary. The following day, the same test could be applied to the same place with equivalent results. Thus, we really were within the linear phase of the stress-strain curve. However, a viscosity factor was added: we clearly found it after 2 min of applied stress, characterised by parameter Uv. Herein might lie the explanation for the constantly inferior values of immediate retraction (Ur) as compared to immediate distension (Ue).

This viscosity factor was studied most particularly by parameters Uv*, Uv/Ue, and Ur/Ue. Stretchability Uv* showed two spikes: one between the ages of 20 and 30, and the other between 60 and 70, most apparent in men. The first spike corresponds to a sudden drop in Ur/Ue confirming that Ur decreases when viscosity increases. However, the rise in Uv/Ue which one expects in the same age group, is seen in the following decade. The second spike corresponds to a momentary elevation of the ratio Uv/Ue without any notable change in Ur/Ue. We have no explanation for these discordances, other than a possible masking effect by simultaneous variations of elastic parameter Ue.

What is the relationship between the parameters that were studied and the structure of skin tissue? The dermis has an architecture consisting of a system of linking collagen fibres. This system is stretched in the direction of the maximum tension of the skin, along the Langer lines. One may make the comparison to a fabric comprised of oblong links (Viidik [15]). Between the collagen fibres one finds elastic fibres. All the fibres are immersed in the fundamental substance composed of water, proteins, and macromolecules, among which are glycosaminoglycans (GAG). The latter play a role as a lubricant during the deformation of the collagen system, and might be responsible as well for the viscous aspect of the deformation.

According to Wilkes et al. [18] and the Strathclyde School, the linear phase of the stress-strain curve corresponds to the stretching of collagen fibres previously realigned within the direction of the traction. For Wijn et al [16, 17] the elastic tissue plays the principal role in twists inferior to 10°. If one believes in the fabric model of Bull's oblong chain links proposed by Viidik, it is a deformation of the system rather than an elongation of the collagen fibres, that occurs during the linear phase of the stress-strain curve. This model alone would account for the hysteresis of the stress-strain curve. It would explain the possibility of a return of the system to its initial position by the intrinsic elasticity of the intersecting points whose resting position coresponds to a given angle between the fibres. The elastic system would only contribute by accelerating the return to the initial position.

In the conditions of our experiments and according to the Viidik model, the deformation of the collagen system alone might account for parameters Ue*, Uf*, and Ur*. Our results would explain a greater rigidity of the system with age, a diminished aptitude to allow deformation, confirming the reported findings [7]. The alteration could be related to an increase in inter-chain links [8] and to an increased diameter of the molecules [14], all of which are phenomena found during the ageing process.

The visco-elastic parameter Uv* remained stable for a constant skin thickness, outside of the non-significant spikes of the second and sixth decades. On the other hand, the drop of Ur/Ue with increased age could reveal either an alteration in the return to normal force which is constituted by the elastic tissue, or a diminished level of GAG with increased shear forces [13]. We know that the ratio of chondroitine-sulfate/keratan-sulfate diminishes in the dermis with age [7].

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Appendix

Determination of the Strain and Young's Modulus of Skin

As far as the skin of the forearm has a large mobility towards the underlying tissues the following assumption has been accepted: it is the skin comprised between the central disc and the guard ring which resists the disc rotation through a strain homogeneous across the whole thickness (Fig. 7).

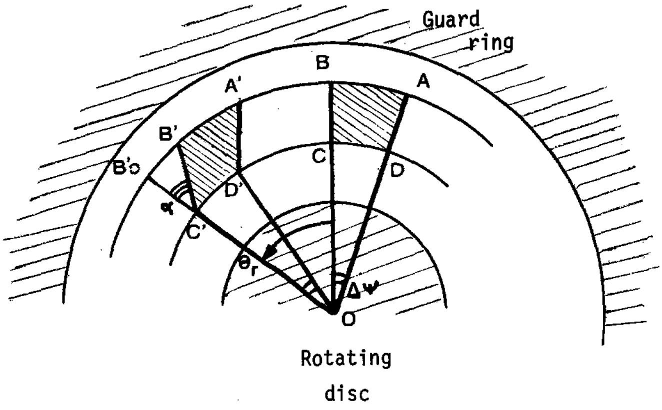

Fig. 7. Skin surface deformation during torque application α: shear angle of an infinitesimal element (*i.e., area ABCD which becomes A′B′C′D′*). $\theta(r)$: rotation angle of skin at radius r

Let us write: r: distance from the current point to the centre 0

$(R_1 < r < R_2)$
R_1: disc radius
R_2: guard ring radius
e: skin thickness
$\theta\,(r)$: rotation angle of skin at radius r $[0 < \theta(r) < \theta_0]$
α: shear angle of an infinitesimal volume element.

Let us consider a volume element defined by the area ABCD (Fig. 7) and the skin thickness e. ABCD is defined as the area comprised between the radii r and $r + dr$ and the angle $\Delta\Psi$ in 0.

During the torsion test, this volume element is strained. The area ABCD transforms into A′B′C′D′ such that:

$$AA' = BB- = (r + dr)\cdot\theta\,(r + dr) \tag{1}$$

$$DD' = CC' = r\cdot\theta\,(r). \tag{2}$$

The above volume element will be sheared with the shear angle $tg\,\alpha$ and one has:

$$tg\alpha \simeq = \frac{B'_0B - BB'}{dr} \tag{3}$$

with $BB'_0 = (r + dr)\cdot\theta(r)$ one gets $\alpha \simeq r\frac{d\theta}{dr}$. (4)

It is then possible to write the relationship between the force momentum $d\,M = F\,dr$ and the twist angle θ.

Indeed, the shearing of a parellelepipedic body as shown in Fig. 8a is given by the well known relation:

$F = \mu S\alpha$ (5), μ being the Lamé's coefficient which is usually close to 0.4 E

with (4): $dM = \mu Sn\,\frac{d\theta}{dr}\,dr$

and as in our case:

$S = r\Delta\Psi e = 2\pi$ re,

one gets: $\mathrm{DM} = 4\pi\mu e\,\frac{r^2\,d\theta}{2}$.

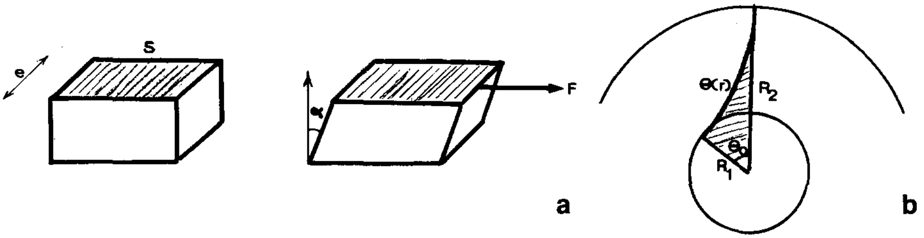

Fig. 8. a Volume deformation. *e*: skin thickness; *S*: surface submitted to shear; *F*: shear force; α shear angle. **b** Variations of rotation angle of skin [$\theta(r)$] along the interval in between rotating disc and guard ring. R_1: radius of disc; R_2: radius of guard ring

The integer of $^1/_2\, r^2 d\theta$ represents the hatched surface on Fig. 8b. Therefore, the calculation of M is no longer possible if the relationship $\theta(r)$ is not given. If we assume a linear law, the value of this area becomes:

$$\frac{R_1\,(R_2-R_1)\,\theta}{2}+\frac{R_1^2\,\theta}{2}$$

which leads to the expression of the Young's modulus

$$E=\frac{M}{2\pi\cdot 0.4e\cdot R_1\cdot R_2\,\theta}\,.$$

Remark

With this linear approximation it is not possible to go to the limit by making R_2 tend toward infinity to obtain Sanders' equation (this author did not use a guard ring). It is not possible to do so because the surface defined by $\theta(r)$, R_1 and R_2 (hatched in Fig. 8b) does not tend toward infinity while R_2 does, as obviously no more skin deformation occurs at a small distance from the central disc.

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