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DYNAMIC MECHANICAL TESTING OF HUMAN SKIN *'IN VIVO'**

BRYAN FINLAY
BioEngineering Unit, University of Strathclyde, Glasgow, Scotland

Abstract—The problems involved in measurement of the dynamic mechanical properties of human skin *in vivo* are examined. On the basis of these observations, the design of a rotary position servo for *in vivo* testing is outlined. Using this device, certain hitherto unidentified characteristics of the mechanical behaviour of human skin are illustrated.

INTRODUCTION

A DESIRE to define the mechanical properties of the human body and its tissues has existed for the last two to three centuries. During that time, numerous attempts have been made to analyse human skin *'in vitro'* whilst the number of *in vivo* studies has been significantly less.

The complex arrangement of collagen fibres in the dermis, Fig. 1, together with other fibrous and cellular components in an embedding ground substance does not make theoretical studies at the present state of knowledge an easy approach to the problem. Under these circumstances, empirical results yield the most information about the tissue, leading eventually to a realistic theoretical model.

Dupuytren (1834) recorded the observation that a blade of circular cross section when pressed vertically into the skin produced on removal an elliptical hole rather than the possibly expected circular hole. Langer (1861) conducted a series of carefully controlled experiments on cadavers to investigate Dupuytren's observations fully. Routine puncture investigations indicated certain differences between adults and children as well as between individuals, but general trends in the form of continuous lines joining the major axes of adjacent ellipses were observable. Figure 2 shows a reproduction of a portion of Langer's original results giving diagrammatic summaries of his observations. These observations constitute a fraction of the work reported in Langer's paper, which also compared puncture lines with wrinkle lines, together with microscopical investigations of these areas.

Time-controlled mechanical tests *in vitro* that take into account the non-linear visco-elastic properties of the skin have been reported in detail by Evans (1965), Ridge (1964), Kenedi, Gibson and Daly (1965) and Daly (1966).

From a general survey of the literature available, it becomes apparent that if, for example, a surgeon wishes to have information on the mechanical properties of skin in a given area, then he must conduct specific tests in that area. Statistical surveys show that the correlation of test results between sites and between individuals is not good enough to justify surgical procedures based on general findings whether *in vitro* or *in vivo*.

Evans designed a device (Evans and Siesennop, 1967) that would apply uniaxial tensile strain to skin *in vivo*. Figure 3 shows the device in a typical test situation. A constant speed electric motor, *A*, drives a lead screw, B, through a gear chain, *C*, so that the arms, *D*, move apart at a constant rate of 0·67 mm/sec. Two tabs, *E*, are attached to the skin by double-sided adhesive tape whilst being attached to each other by a cord which passes over each of the arms, *D*. The two arms are strain-gauged to give a measure of the force in the cord connecting the two tabs.

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Fig. 2. Langer's lines. A reproduction of the work of Langer (1861).

Gibson, Stark and Evans (1969), have reported the use of this device in anisotropy studies of human skin over the chest. A typical test result is shown in Fig. 4, with the portion, *AB*, being attributed to the stretching of the randomly coiled collagen fibres. As the coils are straightened out and the fibres start to align themselves, then the curve continues between *BC*. Further straining causes more fibre alignments and the curve proceeds from *C* to *D*. Over the ranges tested, the terminal portion, *CD*, is reported as a straight line. Producing this line, *CD*, backwards to intercept the strain axis yields a measurement, *X*. Testing on four axes at 45° to each other at a given site will yield four separate values of *X*.

If these values are plotted on their respective axes (equally about the centre point) then the resulting points are generally found to lie upon an ellipse with the major axis representing the direction of maximum extensibility. Ellipses obtained by Gibson *et al.* (1969) for the chest region are shown in Fig. 5, where a typical set of Langer's Lines are shown sketched in the background. Although such a uni-axial tensile test gives excellent information concerning the directional properties at a given site, it has certain limitations that prohibit the sensible comparison of values between test sites and between individuals. The initial distance between the tabs can be accurately defined but the surrounding area

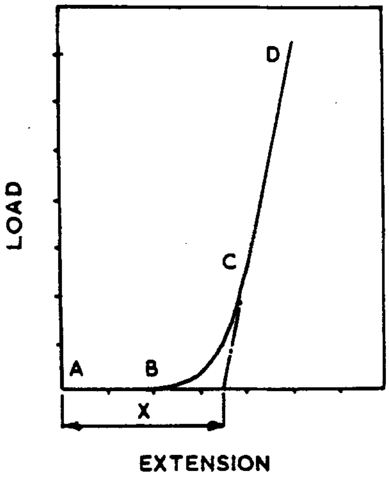

Fig. 4. Load-extension curve from a uni-axial quasi-static test on skin.

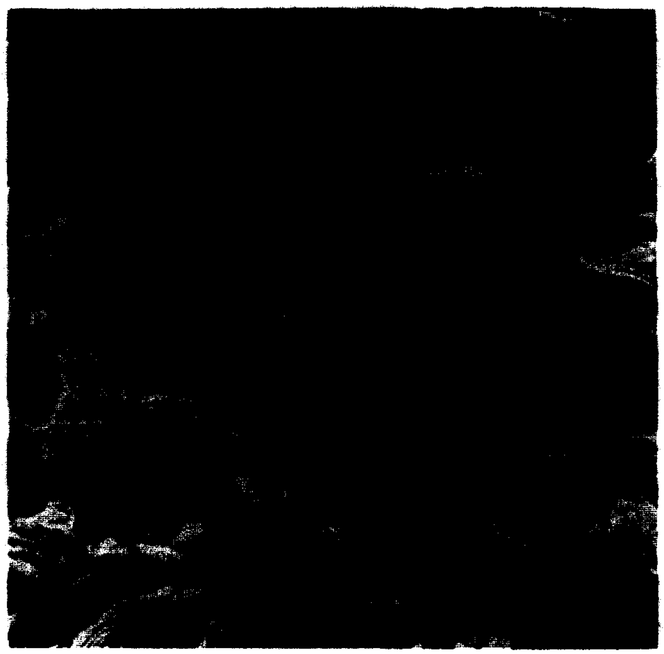

Fig. 1. A scanning electron micrograph of the mid dermis of a two year old female showing the complex arrangement of collagen fibres.

Fig. 3. Uni-axial quasi-static testing *in vivo*—after Gibson, Stark and Evans (1969).

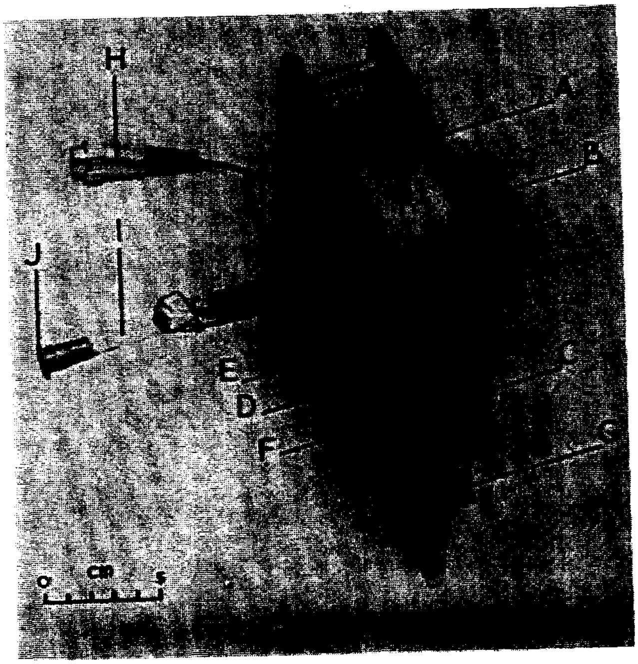

Fig. 8. The assembled rotary position servo.

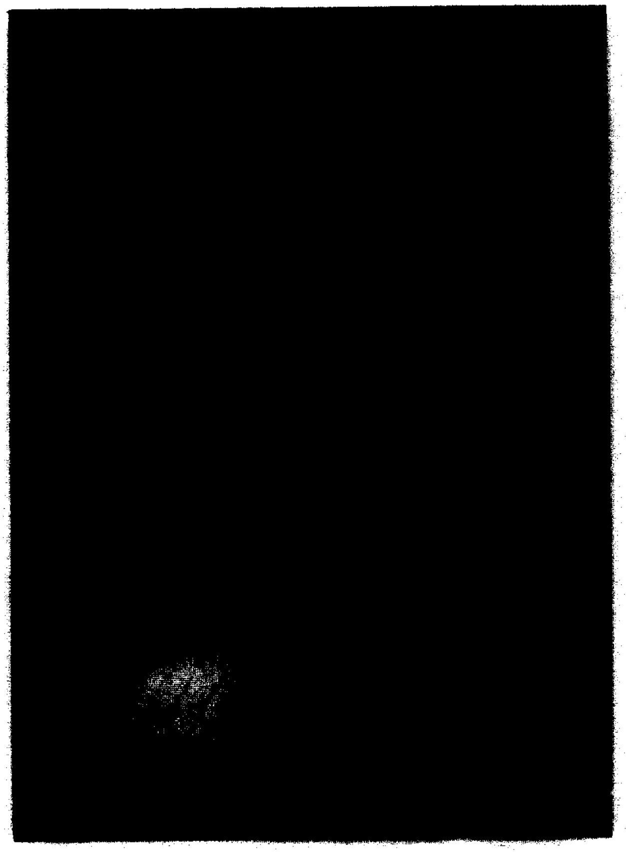

Fig. 13. A typical test situation for the rotational position servo showing the guard ring support in position.

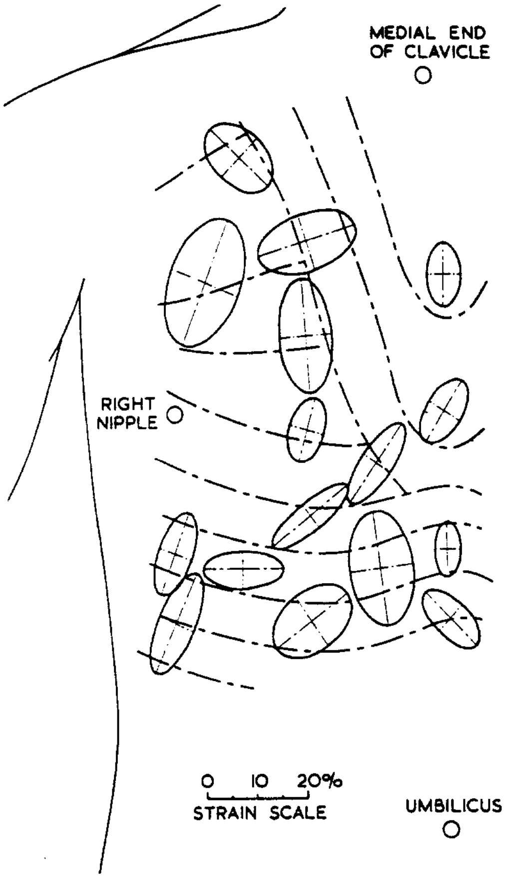

Fig. 5. Strain ellipses of the chest region—after Gibson, Stark and Evans (1969).

affected by the tensile forces is not controlled in any way. In order to overcome this problem of an indefinite test area it is necessary to place a guard ring around the test area. Such a ring would be attached to the skin and held in a fixed position so that tests could be performed inside the ring relative to the ring position. Grahame (1969) described such a system with a suction being applied to the area within the ring. This work was based on the method developed by Dick (1951) for *in vitro* tests and formulae for isotropic materials derived by Tregear (1966). A sudden decrease in pressure was applied to the skin by the apparatus and the resulting initial rise in strain was recorded by the author as a measure of the 'true elasticity' of the material. The use of the term 'true elasticity' (with its implied ability to return to a zero condition) to describe the movements of the fibrous dermal structure is rather questionable, whilst the effects of any sub-dermal adhesion tend to be emphasised by suction tests.

Vlasblom (1967) and Duggan (1967) both described devices for applying torsional loads to skin *in vivo* although neither system used a guard ring. Vlasblom quoted an 0·2 sec time constant to characterise the dynamics of his mechanical test system. Such a time constant would consequently justify a certain amount of concern as to the accuracy of his frequency response tests which he performed up to 8 Hz.

Both these torsional test systems could be characterised by Fig. 6. A voltage applied to the coils of a motor produces a torque on the motor shaft. This torque causes the shaft to turn, thus applying a torque to the skin. Eventually the shaft stops moving and the torque exerted by the skin is just equal to the torque developed by the motor coils. Under any dynamic situation then part of the torque developed by the motor coils has to be used to accelerate the motor shaft. Consequently only a fraction of the torque developed by the motor coils can be applied to the skin during any dynamic situation. Vlasblom used the measure of current drawn by the motor as an indication of the torque being applied to the skin. By means of a strain-gauged arm, Duggan recorded the actual torque applied to the skin, although this gave him no control over his two recorded quantities of torque and displacement.

Daly of the University of Washington has designed and developed a torsional test system

Fig. 6. A typical 'open-loop' test system.

with a guard ring, Tomlinson, Daly, Odland and Short (1969). The device, intended for clinical use, is constructed to give a fixed *small* sinusoidal displacement. Such a design restricts the investigations to a small portion of the physiological response range.

THE *IN VIVO* DYNAMIC INSTRUMENTATION

It is with all these problems in mind that the author set out to design and build a device that could be used to investigate fully the non-linear visco-elastic properties of skin *in vivo*. The problems encountered due to the use of an 'open-loop' test system, as described by Fig. 6, were overcome by making the device into an automatic control system.

Figure 7 illustrates the essential elements of such a system, with the important additions of a transducer to produce a voltage proportional to the output quantity and a comparator to derive the difference between the desired and actual levels. Whilst an error exists between these two levels then the error voltage derived by the comparator will drive the motor. This arrangement constitutes a 'closed-loop' control system (or servo-system).

A rotary position servo-system with a guard ring was chosen as the means of test. Such a system enabled displacement inputs of any waveform within the limits of the dynamic specifications.

The design had to meet with certain clinical as well as mechanical specifications. Since this was to be a prototype intended for purely research purposes, the size was not critical so long as it could be handled easily by one person. A dynamic response such that the actual displacement would follow the desired displacement without any phase shift or attenuation at frequencies up to 1 Hz was desired. This criteria was required to be met for amplitudes of ±5° with a maximum desired displacement of ±20° and resolution of 0·1°. From the clinical point of view there had to be no electrical parts capable of producing sparks. Any pieces of equipment in contact with the patient had to be removable for sterilisation. The maximum skin torques anticipated were thought to be less than 50 mN m. Apart from the obvious requirements such as mains isolation and earthing, then these were the major design requirements.

In order to meet with the requirement for a system that would not produce any sparks, it was necessary to choose a brushless motor. For the servo-system to be unaffected by the external torque on the output shaft (i.e. in this case produced by the skin) it was necessary to select a motor capable of producing a torque several times greater than that expected from external sources. To match these specifications an Aeroflex brushless d.c. torque-motor, TQ52W, was chosen with a maximum continuous torque of 1·5 N m. The transfer function of this motor, including the added inertias of supplementary parts in a practical design, was:

$$\frac{\Theta(s)}{V(s)} = \frac{2{\cdot}36}{s(1+0{\cdot}0065s)(1+0{\cdot}0274s)}\ \frac{\text{rad}}{\text{V}}.$$

where s = the Laplace operator

$\Theta(s)$ = Laplace transform of the angular displacement of the output shaft, $\theta(t)$

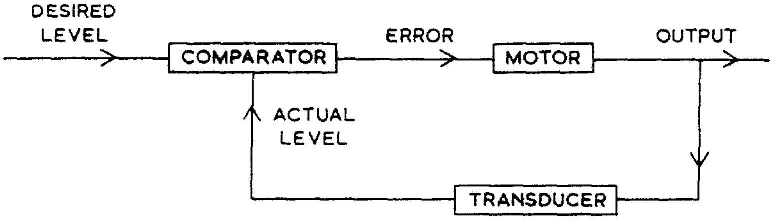

Fig. 7. Basic parameters of a 'closed-loop' test system.

$V(s)$ = Laplace transform of the voltage applied across the motor coils, $v(t)$.

It soon became obvious from a theoretical study that such a system could not satisfy the frequency response requirements on the basis of a purely proportional feedback system. A tachometer was therefore included in the initial design so as to give proportional plus derivative feedback. The resulting device with the motor, *A*, and tacho generator, *B*, is shown in Fig. 8. *A* feedback potentiometer, *C*, was connected to the motor shaft via a non-slip belt, *D*, and gears, *E* and *F* (Reliance Gear Company) with a ratio of 3 to 1 respectively. This gearing was included to give the system an angular resolution better than 0·02°. The final design was such that an external torque of 50 mN m on the motor shaft would cause a position error of less than 0·1°. A 12-way socket, *G* (Souriau Connectors) was used to supply power to the servo motor assembly. Due to electrical noise problems caused by pickup from the power supply leads, it became necessary to use a separate set of leads for the strain gauge supply and output. These four screened leads were taken into the servo via a separate socket, *H*. In this way the servo motor could be readily detached from its power supplies.

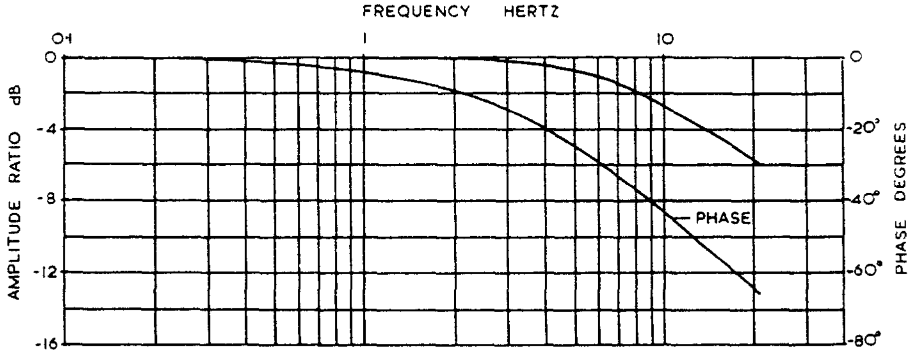

Fig. 9. Frequency response of the position servo.

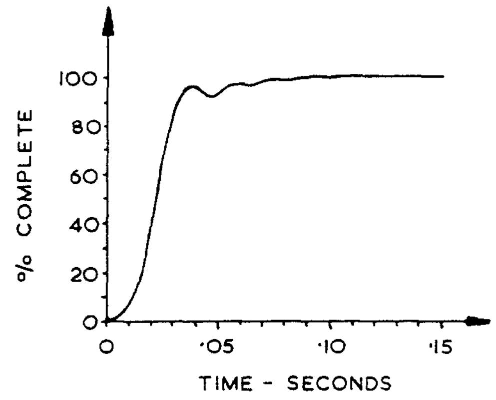

Fig. 10. Rotational step response of the position servo.

A characteristic frequency response for the system is given in Fig. 9, whilst Fig. 10 shows a typical step response of the servo recorded by an ultra violet recorder (Southern Electrics S.E.2005) using a B100 galvanometer (100 Hz natural frequency) with a damping factor of 1·0.

Torque generated by the skin under torsional strain was sensed by a flat strain gauged beam, I, Fig. 8. This beam was mounted in linear bearings so that the motor weight was not transmitted to the skin. Two 90° strain gauge rosettes (Micro Measurements, Number EA-06-125TK-350) were used to produce a full bridge circuit. The amplifying stage consisted of two FET amplifiers (Analog Devices 501B). It was necessary to use two amplifiers to achieve the desired gain, so as to maintain accuracy of measurement at the higher frequencies of operation, Fig. 11. The calibration curve proved to be linear over the range tested up to torques of 125 mN m pro-

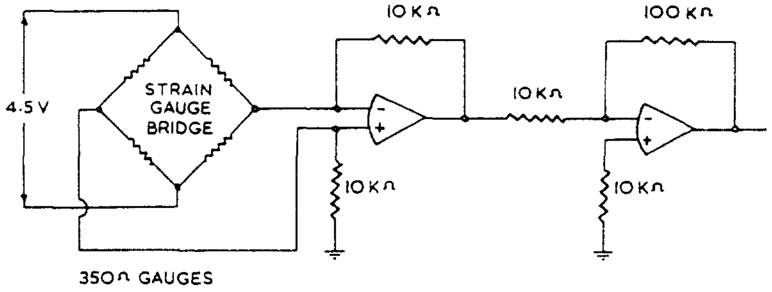

Fig. 11. Torque sensing and amplifying circuit.

ducing corresponding outputs up to 2·5 V for a bridge excitation of 4·5 V. In order to reduce noise problems, a d.c. battery (Exide L20), was used.

At the end of the torque arm was a detachable stainless steel disc to facilitate attachment to the skin (see *J*, Fig. 8). A complete view of the test set-up is given in Fig. 13, showing the torque device with the cover that supported the guard ring. The stainless steel detachable guard ring fitted into a body that ran on linear bearings.

A 15 mm dia. disc was chosen as a convenient size for the initial studies. When the guard ring was fitted, the amount of strain applied to the skin depended directly on the internal diameter of the guard ring and the displacement of the disc. Several tests proved that a guard ring of 23 mm inside diameter combined with disc displacements in the range of 6–12° gave suitable torques within a physiological range. To produce an adequate area for attachment to the skin, an outside diameter of 33 mm was chosen for the guard ring.

ATTACHMENT TO SKIN

The majority of papers surveyed had used a double-sided adhesive tape for attachment to the skin during mechanical tests *in vivo*. To further improve adhesion, in these investigations a solution of Tincture of Benzoin was applied to the skin before attaching the tape.

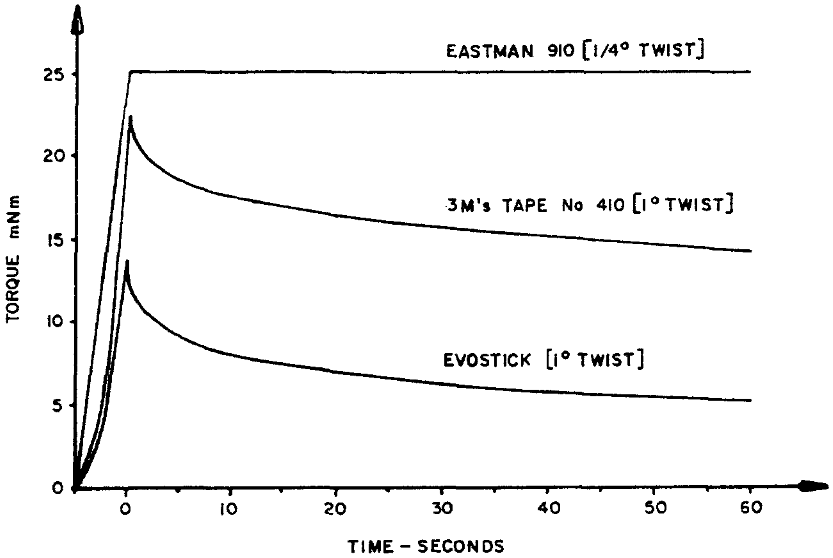

Fig. 12. Summary of tests on various adhesives for attachment to the skin.

Under these circumstances the linkage between disc and skin appeared to be exceptionally good. It was after several exploratory tests had been conducted that a certain amount of doubt arose concerning the shear properties of the adhesive layer. In order to check this adhesion, the torque device was connected to a metal sheet, rather than skin, by the adhesive tape. If the contact was perfect then any small displacement of the servo would be taken up as a twist on the strain-gauged beam. It became immediately apparent that a large amount of viscous flow was taking place in the adhesive layer. An identical test conducted with Evostick impact adhesive produced similar results. After further consideration and allergy tests, the use of Eastman 910 (a strain gauge cement) was investigated. All three tests are summarised in Fig. 12. For the curves related to adhesive tape and Evostick, the input displacement was 1° uniformly applied over a period of 5 sec and then held constant. The curve relating to Eastman 910 was produced by an 0·25° displacement in 5 sec. Exceptional amounts of stress relaxation are seen in both adhesive tape and Evostick curves whilst the Eastman 910 gave no relaxation at all. Preparation of test sites on skin first involved the shaving of any hair before applying adhesive tape several times to remove the loose layers of epidermis. A catalyst (supplied by Micro Measurements for use with Eastman 910) was applied to the skin and allowed to dry (about 1 min). Eastman 910 was painted thinly on the disc and guard ring before fixing them into the torque device. The test site was pressed lightly against the disc and guard ring, being held there for 1 min whilst the cement set. From the work completed so far, no tissue reaction has been obtained from such procedures for as many as 3 attachments to the same site.

RESULTS

A standard technique for the analysis of a visco-elastic system is based on frequency response data. In order to investigate the possibility of applying such an approach to the analysis of skin, tests were conducted by supplying the rotational servo with a sinusoidal wave form at 1 Hz. Figure 14 summarises the results of the various tests performed. The servo output was in the form of a pure sine wave—a section of such a wave is given in the latter figure. Corresponding torque responses relating to sinusoidal displacements up to ±8° r.m.s. applied to the dorsal surface of a subject's left forearm (50 mm above the styloid process of the ulna) were recorded and clearly illustrate the non-linear characteristics of human skin. For small displacements up to ±2° r.m.s. the torque output was sensibly linear, being of the same sinusoidal form as the input. Displacements above ±2° r.m.s. demonstrated the typical mechanical response of skin—a relatively low dynamic stiffness at small amplitudes rapidly increasing in stiffness as the displacement increased. Figure 14 shows how the torque response doubled in magnitude as the displacement was increased by one-third from ±6° to ±8° r.m.s.

Whenever such non-linear problems are encountered in engineering problems, the general practice is to conduct small amplitude tests about fixed amplitude levels. In this manner a complete picture of the non-linear characteristics can be built up on the basis of linear results. A typical test result obtained when applying this technique to the analysis of human skin is shown at the bottom of Fig. 14. Using a sinusoidal displacement ±½° r.m.s. applied at a steady level of 6°, an almost linear torque response was obtained (compare with the true sine wave at the top of the figure). It is, however, still apparent that the curve demonstrates a greater stiffness at the higher displacement. If the problem was no more complex than this, then an analysis of the visco-elastic properties based on such small amplitude tests would be quite valid. Due to the ability of the dermis to re-orient itself under the action of a load, it is possible to obtain completely different results

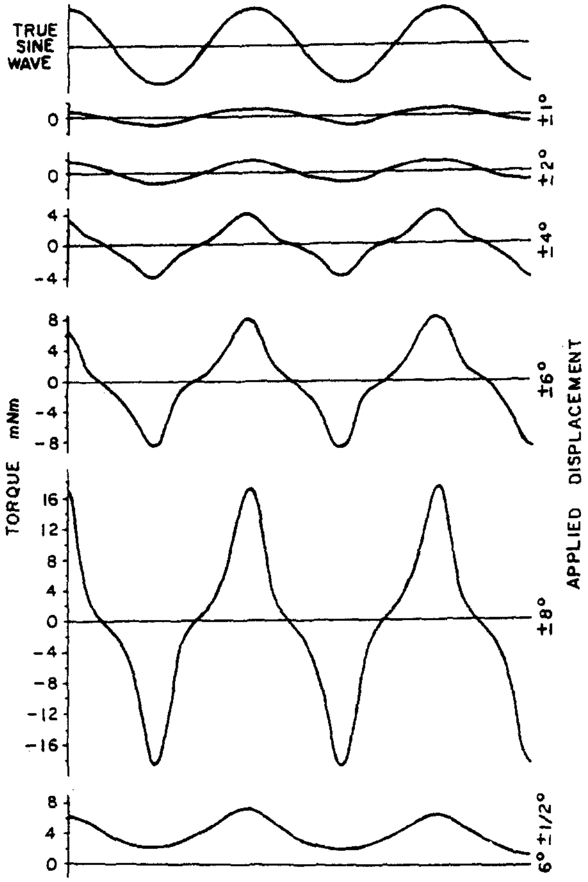

Fig. 14. A summary of the response of human skin to various levels of sinusoidal displacement at 1 Hz.

from what appears to be exactly the same test. If, after testing the skin with a sinusoidal displacement of ±½° r.m.s. about a mean level of 6°, the mean level was increased to 12° for a period of several seconds, then, returning to the original level of 6° would yield a response somewhat different from that previously obtained. This history-dependent fibre orientation is discussed in more detail and illustrated in the following sections.

In practice, a trapezoidal input waveform has been found useful in determining the clinically significant characteristics of the mechanical response of skin over the whole physiological range. A typical test sequence for such a trapezoidal (quasi-static) test is given in Fig. 15. In the sequence illustrated, a 6° displacement was uniformly applied over a period, *AB*-in this case 3sec. During a 30 sec period, *BC*, the displacement was held constant at 6° before finally being reduced to 0° over the period, *CD*, at the same rate as the period, *AB*, 2 deg/sec. A typical test result from the dorsal surface of the leg (120 mm below the head of the fibula over the belly of gastrocnemius) of a 72 year old male is illustrated with Fig. 15. Over the first 4° of the displacement, *AB*, the torque rose slowly whilst during the final 2° of the rotation a rapid torque increase was evident. This non-linear behaviour of the skin is now a well reported test result. Whilst the rotation was

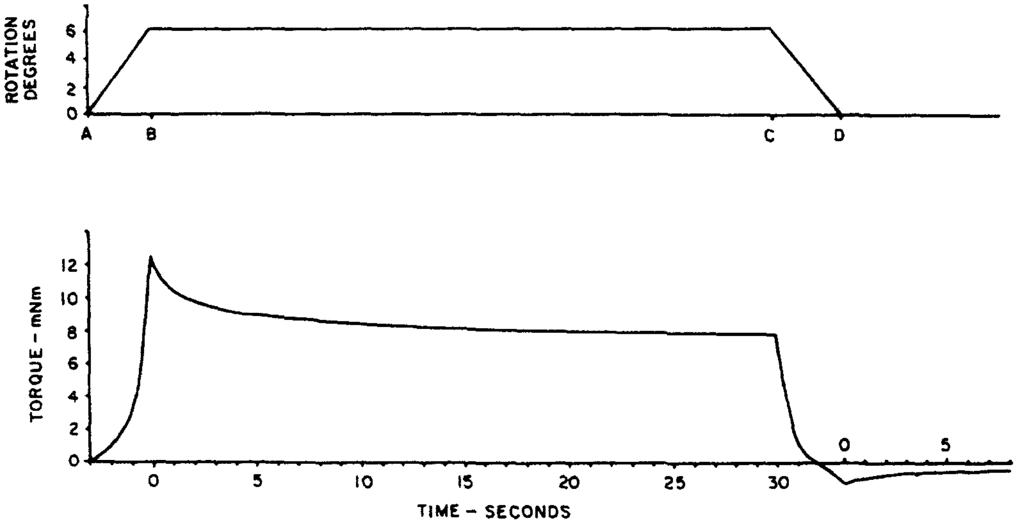

Fig. 15. The torsional response of human skin to a rotational displacement of trapezoidal form.

held constant during *BC*, there was a considerable load relaxation in the tissue—about 35 per cent. Returning the disc to its zero position over the period *CD*, initially caused a rapid torque relaxation. When the rotation ceased at zero degrees, the torque was seen to have a negative value which gradually relaxed with time. The torque did not, however, return to zero even after a period of up to 5 min. The significance of this residual torque is discussed further in the following section. Ridge and Wright (1965) have reported a similar load time relationship for quasi-static uniaxial tests on human skin *in vitro*.

A series of repeated trapezoidal rotational inputs yields further information on the tissue behaviour. The test sequence used in a specific investigation is shown in Fig. 16. A series of four identical trapezoids applied in the same rotational direction was followed by

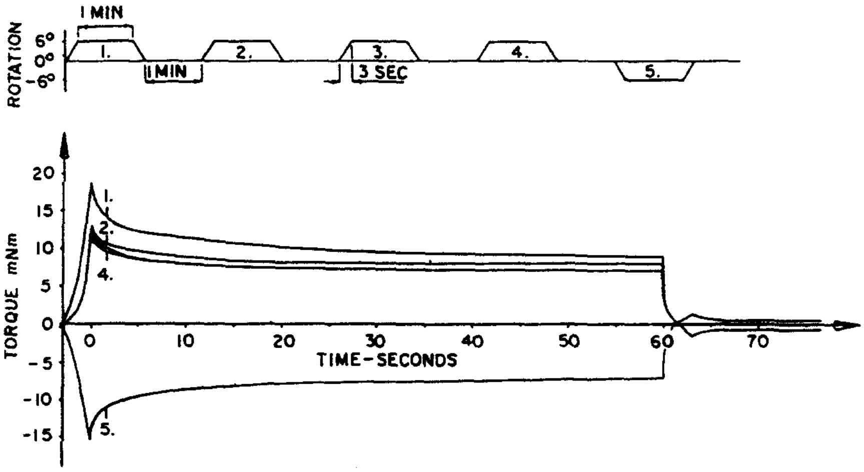

Fig. 16. The torsional responses produced by repeated trapezoidal displacements of human skin.

a further identical trapezoid but in the opposite rotational sense. The displacements were 6° applied uniformly over 3 sec and held constant for a period of 60 sec. A rest period of 60 sec was allowed to elapse before applying the subsequent trapezoid. Torque responses corresponding to these five trapezoids are shown plotted on the same time base as each other for comparison purposes. These results were obtained from the same subject and test site as for Fig. 15.

It is important to note that the loading portion of the first test showed a fairly linear increase in torque over the whole loading time of 3 sec. The second, third and fourth tests exhibited the characteristic slack in the 3 sec rotation. Peak values of these three responses were significantly lower than the first test. The fifth trapezoid applying the 6° in the opposite sense to the previous runs, showed virtually no slack in the response. This reverse test had a peak value noticeably higher than the second, third and fourth runs and almost equalled the first run. Upon return to the zero position, each run exhibited a characteristic residual torque as described in the previous section.

DISCUSSION

Careful consideration of Fig. 16, based on a knowledge of skin structure, permits a prediction of the behaviour of the dermis under load. Distortion of the fibre-fluid network of the dermis inevitably causes a certain degree of fluid shift within the test area. Such distortion could cause the displacement of fluid to the surrounding test area as well as causing accelerated drainage of the fluid by the lymph capillaries. This change in fluid content could then give rise to the difference in peak values between the first and subsequent runs. However, such a simple fluid displacement hypothesis does not account for the large peak in the reverse test of the fifth run. Similarly, the differences in the torque levels at the end of the 1 min period (prior to unloading) would not be explained by this fluid movement. Although a certain degree of fluid shift must take place during these deformations, it does not completely explain the phenomena seen in Fig. 16.

It is proposed that straining of the human dermis causes a residual orientation of some of the dermal fibres, even though the points of application of the strain are returned to their original position. Figure 17 shows how this criteria, when applied to the rotational test, explains the shape of the resulting torque curves in the repeated trapezoidal test. Diagram *A* shows an element of fibrous

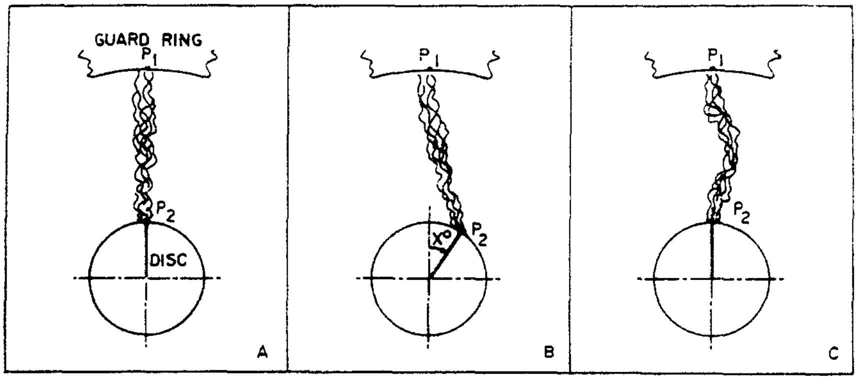

Fig. 17. Proposed behaviour of the fibrous network within the human dermis when a disc attached to the skin is moved relative to a surrounding similarly attached guard ring. A. (0°) A thin strip of the random fibrous network between disc and guard ring. B. (X°) Partial orientation of the fibres due to the disc displacement. C. (0°) Residual orientation of the dermal fibres between the disc and guard ring.

network between the disc and guard ring when the system is at zero degrees rotation. Turning the disc through an angle $X°$ causes a partial orientation of the fibre network as shown in diagram *B*. Returning the disc to the zero position causes the fibres in the vicinity of the points P_1 and P_2 to return to their original position. However, due to the characteristics of the fibrous network, there remains a partial fibre orientation in the region between disc and guard ring. Further displacements to the position of diagram *B* consequently cause lower torques for the same angle of rotation. From the situation illustrated in diagram *C*, it is quite clear that a negative rotation will yield a higher torque for the same angle than further positive displacements.

On the basis of the latter proposals, it might appear that a negative displacement following several repeated positive movements should cause a higher peak torque than the initial positive rotation. Investigation of Fig. 16 shows that this is not necessarily borne out in practice. To explain this situation it could be proposed that a certain amount of fluid was extruded from the test area by the first test. Such a fluid removal would not, however, have to take place to explain the test results. It could be argued that a fibre orientation already existed in the tissue due to the recent strain history. It is not thought relevant at this stage to labour over this point of fluid shift since the proposed residual fibre orientation is of far greater significance.

CONCLUSIONS

Residual alignment of dermal fibres due to the action of a torsional strain system would definitely appear to be indicated by the results presented. Complementary mechanical studies have indicated that such a fibre rearrangement is dependent on the magnitude of the strain applied. Excessive tension necessary in sutures to close an excised area can consequently be reduced by applying to the sides of the wound a greater force than that required to just close the wound. Maintaining this load for several seconds produces, on release, a smaller wound requiring relatively lower suture tension for closure.

The equipment described in this report is now being used in a series of clinical studies to enable the design to be simplified and so produce a compact self-contained device. A preliminary design for such an instrument is now under analysis. These clinical investigations based on the trapezoidal displacement waveform are intended to cover a broad population of subjects with normal and diseased skin conditions.

Previous workers have produced mathematical models of biological tissue based on an assortment of spurious assumptions. Since the absolute deformations of skin vary so much between individuals, any model developed is mainly aimed at proving the validity of the original assumptions. Whilst very small deformations can be assumed to be characterised by linear coefficients, skin displacements experienced under normal physiological conditions are far from such simple characterisations. Using the torsional servo system described, a complete picture of the mechanical behaviour of skin is being developed gradually on the results of small amplitude step tests over the whole physiological range.

It is hoped that from the basis of a wide variety of clinical studies a better understanding of the dynamic properties of skin can be obtained for both high and low strain rate conditions.

Acknowledgements—The work reported has been conducted in the BioEngineering Laboratories of the University of Strathclyde (Director, Professor R. M. Kenedi) and in the Plastic Surgery Unit of Canniesburn Hospital (Director, Professor T. Gibson). The author wishes to thank Professors Kenedi and Gibson for their support and guidance in this continuing work.

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NOMENCLATURE

$\theta(t)$	angular displacement of the motor shaft, rad.
$v(t)$	voltage applied across the motor coils, V
s	the Laplace operator
$\Theta(s)$	Laplace transform of $\theta(t)$
$V(s)$	Laplace transform of $v(t)$.

Torques are reported in Newton metres, N m, or in milli Newton metres, mN m i.e. 10^{-3} N m. The micrograph magnification mark is given in micro metres, μm.