Bioengineering
and
the Skin

Bioengineering and the Skin

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Introduction

R. MARKS

Biology has become a 'numbers game'. The advantages of being able to grade changes in tissue, submit results to statistical analysis and accurately record biological phenomena make measurement essential. This is as true for the various disciplines in applied biology as it is for the more esoteric aspects of the subject. Regrettably, skin biologists until recently had not seized the opportunities that the availability of their tissue of interest afforded and fell behind in the exploration of measurement techniques. Probably this resulted in part from the mistaken sentiment that 'to see is to know'. It also originated from the complexity of the skin which, as a closely interwoven mixture of tissue types, makes assessments technically difficult. However, we are optimistic about the future.

The International Society for Bioengineering and the Skin was formed in Cardiff in July 1979 in response to the wishes of the delegates who had attended the first International Symposium on the subject in Miami in 1976 and the second in Cardiff 3 years later. This volume is the proceedings of the Cardiff meeting. We believe that it demonstrates the brave efforts and variety of new ideas that characterise the studies of scientists who realise the importance of blending the physical sciences with skin biology.

The authors' individual contributions vary in their presentation. Some are formal scientific papers, some descriptions of apparatus or techniques and some contain reviews or appreciations of particular subjects. We decided to permit this variation and not edit heavily for the sake of uniformity, as we believed that the different styles were more appropriate to the various subjects. We trust that this will not irk and will make the book more readable.

The contributions have been grouped into four sections: (1) preliminary considerations; (2) mechanical properties; (3) measurements of function and dimension; and (4) thermal, acoustic, optical and electrical properties. Inevitably there is some overlap, but we thought it useful to impose some order for ease of referral.

Preliminary Considerations

1

Experiments and analyses: a retrospect

R. M. KENEDI and T. GIBSON

SUMMARY

Retrospective evaluation highlights the shortcomings of present-day efforts in analyses, particularly in clinical applicability. The load-deformation behaviour of the soft tissues is non-linear and time dependent, and it now seems clear that present attempts to describe the biomechanical behaviour of such living entities in terms of the mathematical concepts and techniques used for non-biological materials have failed.

A reorientation to alternative formulations requiring more effective collaboration between experimentalists and mathematicians than before is necessary to produce genuine progress. Hopefully this will go hand in hand with the re-establishment of the clinical problems of the human patient as both the start and the ultimate aim of all research.

PREFACE

The last two decades have seen wide acceptance of biomechanics as a pertinent and necessary part of any study of the diagnostic and therapeutic problems of the human patient.

The expansion of the relevant literature describing the experimental and analytical enquiries undertaken is reminiscent of the transformation (in the comic strip turned television programme) which produced the Incredible Hulk from its inoffensively insignificant alter ego. Correspondingly the records of the biomechanics of tissue, and in particular, that of skin, in their multifarious aspects have become intimidating in their extent[1,2]. Yet if one uses as a form of 'outcome measure' identifiable benefit to the human patient, the accomplishments of all this activity appear less than modest.

International meetings are regarded as opportunities for exchanging information and for presenting new material for the admiration (or criticism as the case may be) of one's peers; they should perhaps be used also as forums of retrospection, hopefully leading to redirection of research and development effort if that is adjudged to be desirable.

The writers, having been part of this explosive development of tissue biomechanics, particularly in its early phases, now propose to indulge in just such retrospection on two fronts: firstly in a *broad* sense to reconsider advances in biomechanical characterisation and modelling of tissue; and secondly in *specific* contrast to re-present some overlooked work of the Viennese anatomist Langer[3] of direct pertinence to the present discussion. The rediscovery, translation and publication in English of this 19th century masterpiece is the work of one of the writers of this paper (Gibson).

BIOMECHANICAL CHARACTERISATION AND MODELLING OF SKIN

There is now virtually no disagreement, certainly in a qualitative sense, on the characterisation of the structures and mechanical behaviour of skin as determined by *experiment*.

Subsurface human skin is regarded as a multicomponent microstructure consisting of intertwined networks of collagen, elastic and nerve fibres, small blood vessels and lymphatics, covered by a layer of partially keratinised epithelium and transfixed at intervals by hairs and the ducts of sweat glands. The networks are surrounded by interstitial fluid containing a varying amount of mucopolysaccharide ground substance, and all are mobile in this semi-fluid environment. As all tissues are living organs, biological effects can occur in addition to other influences of time dependence during tests modifying the properties being measured[2,4].

Regarding the *surface* of human skin, recent work[5] is effectively exploring the topography on the microscale with a clinically applicable replication technique.

The following are the main 'experimental' findings.

The load–deformation response on the macroscale shows a decrease in deformation with increase in load, the curve being concave to the load axis. The lateral (passive) deformations are comparable in magnitude with the direct (active) deformations.

Time dependence is apparent, creep, stress relaxation and other similar effects having been reliably established on the macroscale. Hysteresis (i.e. non-coincidence of the loading and unloading curves) is present and behaviour is thus non-elastic. Preconditioning, that is the establishment of a steady-state load–deformation response, after cyclic repetition of a given load or deformation programme appears to apply to all tissues, certainly *in vitro*. Its relevance to *in vivo* behaviour is less clear. Anisotropy is important and is particularly demonstrated by the variation in magnitude of the initial deformation at low loads, which is direction dependent. Skin, *in vivo*, is in a state of tension: the 'resting or residual' tension which varies both in direction and magnitude throughout the body.

All mechanical characterisations are environment dependent.

Generally, reliable experimental (and/or test) data are available under both uniaxial and biaxial, *in vivo* and *in vitro* conditions[1,6].

The use of the experimental data available to model tissue *analytically* has taken several forms.

The empirical curve fitting of results has mostly used exponential forms[7–10], and its latest version consists of two-term relationships to express the 'biphasic' nature of the experimental data. The second term in such relationships expresses the behaviour of the material (tissue) at high stress levels, the first term 'remedying' the situation at lower stress levels.

Since the bulk of the test data corresponds to uniaxial loading, with some restricted biaxial (no cases of triaxial) loading, numerous attempts have been made in the past two decades to generalize the concepts for the three dimensions of the real world. The aim of this is to[10,11] ... facilitate data collection and analysis; derive three-dimensional stress–strain history laws under finite deformation and unify the results of different types of experiments such as static, ... dynamic, ... stress relaxation, creep, hysteresis and cyclic fatigue[7].

Most of these attempts have been based on strain energy formulations and have on the whole been unsatisfactory. The reasons for this lack of success are many and lie essentially in the need either to simplify so as to obtain a *generalized* functional form of solution or to introduce numerics for *specific* cases and consequently lose any semblance of generality.

Thus elastic concepts are used to describe non-elastic behaviour, for example by restricting consideration only to the load increasing part of the data and excluding unloading paths; isotropy is assumed in analysing patently anisotropic results and incompressibility is postulated alongside results quoted to show the existence of compressibility[2].

In fact the present state of development of *analyses* may be explained by the fact that reality is sacrificed for mathematical expediency. An increasing number of analytical solutions are being produced under such constraining assumptions that they cannot be applied to matters of clinical importance (which presumably provided the motivation for their production). The somewhat depressing prospect that now faces biomechanical analysts is seeing their mathematically elegant, but in real terms over-simplified, solutions completed and *not* finding problems to which they may satisfactorily be applied.

To plunge, in Dickensian terms, further into the 'dismals', it might perhaps also be salutary to contrast the numerous investigations of the many researchers (including the writers') carried out in the period 1960 to date with the work of an individual, presented to the Viennese Imperial Academy of Science over 100 years ago.

KARL LANGER AND HIS LINES

Langer, born in Vienna in 1819, was Professor of Anatomy at Joseph's Academy in Vienna. His work was not only concerned with descriptive morphology but also, and perhaps even primarily, with function. 'Langer's Lines – known to every surgeon – partly resulted from his major study on the functional anatomy of skin. One of the writers of this paper (Gibson), in a search to unearth Langer's original paper, rediscovered not one but four papers, all presented to the Imperial Academy of Science in Vienna during April and November 1861 and forming the records of a complete study of the directional variations of the structural properties of human skin. The complete work translated, edited and annotated has now been published (Gibson, 1978)[3], and the following extracts (at times paraphrased) have been selected as of particular pertinence to the present discussion.

'*The cleavability of the cutis* – A round-bodied awl when thrust through the skin produces not a round stab wound but a linear cleft. If the clefts are placed as closely as possible they show a definite relationship to each other in the various parts of the body, defining by their sequential orientation lines which *are an expression of the fibre pattern of the skin.* Microscopic study showed tightly grouped fibres interwoven in bundles and arranged in the form of a three-dimensional lattice work. The fibres themselves are partly wavy and partly curly. The cleft orientation is dependent on the fibre arrangement; the stab clefts are widening the inter-fibre bundle spaces in the lattice, at times enlarged by actual tearing of the fibre bundles themselves.

'*Skin tension*'–When the skin is incised the wound gapes; this 'retractile' property means that the skin around the wound shrinks as the incision widens. Broadly, wound retraction is minimal when skin is incised along the lines and maximal when the incision is oriented at right angles to them. There are two major causes of skin (resting) 'tensions': *the contents and thus the degree to which the skin container is filled*-physiological and/or pathological, muscle and fat masses, water accumulations, pregnancy etc; and *the movement of joints* – a close relationship between the possible skin tensions and joint mechanics can be assumed.

'*The elasticity of the cutis*' – Langer cut a large number (100's) of cadaveric skin specimens (approximately 25 × 10 cm) along and transverse to the lines. The specimens were then tested in uniaxial tension under careful time control: 'In order to allow for the extension which continued after the weight was applied and obtain extension values which were as uniform as possible for the individual periods of loading, the loads were allowed to operate for identical time intervals, in some experiments for 2 minutes, in others 5. Further I allowed 2 minutes to elapse after each loading before a new weight was applied'. He then plotted his load–extension diagrams and commented that: 'skin does not stretch proportionally with applied load, indeed the amount of extension grows steadily smaller so that the course of progressive extension cannot be represented by a straight line but by a curve'. Langer also identified the existence of residual stretch after reloading but found 'virtually' total recovery (to about 1–3 mm in 25 mm) after leaving the unloaded specimens overnight in a moist environment. From his results he concluded that: 'the total amount by which a strip of skin lengthens (under tension) is the result of three factors: smoothing out of the curled fibres, rearrangement of the weave of fibres and extension of the fibres themselves. Obviously the uncurling of the fibres and at least part of the rearrangement of the network will take place during the first phase of extension'. He stipulated anisotropy: 'the difference in extensibility between the longitudinal and transverse strip is mainly an expression of the non-homogeneous nature of the tissue, i.e. the meshwork