Mechanical Properties of Excised Human Skin

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Abstract—**In this study we have investigated in influence of location, gender and orientation on the deformation characteristics of 55 samples of human excised skin. Uniaxial tensile tests were carried out at a strain rate of $0.012 s^{-1}$ on excised human skin from the back. The deformation characteristics of skin (Ultimate Tensile Strength ($P<0.0001$), Failure Strain ($P=0.0177$), Young's Modulus ($P<0.0076$), Initial Slope ($P=0.0375$) and Strain Energy ($P=0.0101$)) were found to be dependent upon the orientation of specimens with respect to the Langer's Lines. The location of specimens on the back was also found to have a significant effect on the Ultimate Tensile Strength ($P = 0.0002$), the Young's Modulus ($P=0.0017$) and the Strain Energy ($P=0.005$).**

Keywords— **Skin, Langer's Lines, Histology**

I. Introduction

Skin is an anisotropic material. That is, its mechanical behaviour is not the same in every direction. This phenomenon has been noted as far back as the 19th century by Karl Langer[1] who mapped the natural lines of tension which occur within the skin. The lines are created by puncturing the skin with a circular device. The wounds then assume an elliptical shape and by joining the major axes of the ellipses a system of tension lines can be drawn as shown in Figure 1. These lines are known as Langer's Lines or Cleavage Lines. In 1892 Kocher[2] first realized the surgical significance of the Langer's Lines and observed that incisions made along these lines will cause little or no scarring, whereas incisions transverse to them will gape and lead to unsightly scars. In 1941 Cox re-investigated the cleavage lines of the skin[3]. This was the first piece of original work on the Langer's Lines since their discovery. Cox identified differences between the cleavage lines he observed and those of Langer's. Later these lines would be distinguished from the Langer's Lines as the Cox lines. Unlike Langer, Cox investigated the cleavage line pattern for excised human skin also. It was found that the line pattern remained unaltered leading Cox to conclude that the lines of increased tension must produce intrinsic structural changes to the skin. Skin sections were made in two planes, one parallel to the cleavage line and one at right angles. Cox claims those sections at right angles to the lines showed a marked preponderance of connective and elastic tissue fibres cut transversely, while those cut parallel show the fibres running longitudinally. Cox however, failed to describe the extent of the microscopical investigation.

Early tensile tests carried out by Ridge and Wright[4] in 1966 suggest that the deformation characteristics of skin are dependent upon specimen orientation with respect to these Langer lines. Recent work conducted by Liang and Boppart[5] using a technique known as Optical Coherence Elastography indicates a large difference between the Young's Modulus of skin parallel and orthogonal to Langer's Lines.

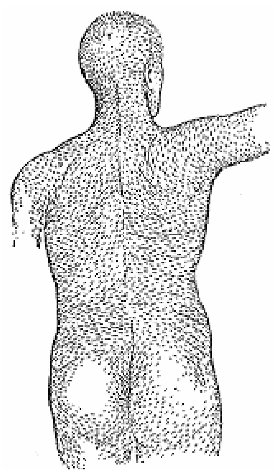

Fig. 1 Langer's Lines of the back

II. Materials and Methods

A. Specimen Preparation

Tensile tests and specimen preparation were carried out in INRETS, Lyon, France. Skin was excised from seven cadavers (three male, four female). The average age of the subjects was 89 ± 6 years and none had any related skin diseases. Only the skin from the back of the body was available for use. This was excised from the body with a scalpel. Each sample of skin was cut into a dog bone shape specimen using a custom made die and any underlying adipose

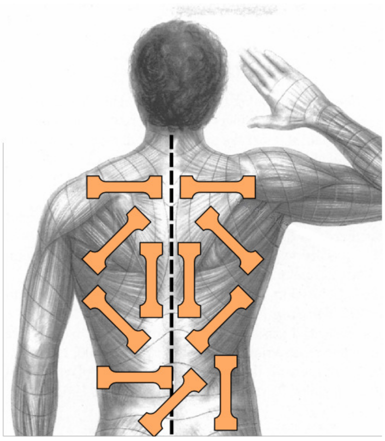

Fig. 2 Orientation of samples procured from the back

tissue was then carefully removed with a scalpel. The thickness of the skin after removal of adipose tissue was measured using Venier Callipers and the mean thickness was 2.56±0.39mm. It was observed that skin removed from the lumber area of the back contained more adipose tissue than other areas. Consistent with other investigations it was observed that both shrinkage and expansion of the specimens occurred [3, 4, 6]. It is believed that this is due to the release of the resting tension within the skin. Specimens were obtained in various orientations, shown in Figure 1, to attempt to correlate them with the direction of Langer lines. Each test specimen was sprayed with black spray paint so as to create a random speckled pattern, required for the use of Digital Image Correlation. The skin was stored in moistened paper and refrigerated at 4^{o}C until it was ready to be tested. A total of 55 samples were successfully tested.

B. Tensile Tests

Tensile tests were performed using a Universal Tensile Test machine. Samples were clamped using specially designed anti-slip clamps due to the tendency of samples to slip in grips. The strain was calculated using a cable actuated position sensor. The velocity of the cross-head was 50mm/minand the strain rate was 0.012 s^{-1}.Tensile load was measured with a 1 kN piezoelectric load cell. Each tensile test was videoed two Dalsa Falcon 1.4M100 digital video cameras at twenty frames/second. This was to record any abnormal behaviour during the experiments and also for the use of Digital Image Correlation (DIC). DIC was incorporated as an alternative method to measure deformations and was performed using Vic2D ® Software (Version 2009 - Correlated Solution, Inc.). A grey base layer of spray paint was applied to the specimen followed by a random speckled pattern with black spray paint. This random speckled pattern is required for the system to track the deformation.

C. Optimization

Data fitting of our experimental data was performed to assist in the selection of a suitable constitutive model for human skin. A MATLAB routine available in the Optimization Toolbox called lsqcurvefit was used for this purpose. Two isotropic non-linear elastic constitutive models were fitted to the stress-stretch curves obtained through the tensile tests and were assessed individually. The Fung model[7] is shown in Equation 1 and the Gent model[8] is shown in Equation 2.

$$s_{11}^{F} = \mu e^{b\left(\lambda_1^2 + 2\lambda_1^{-1} - 3\right)}(\lambda_1 - \lambda_1^{-2}) \quad (1)$$

$$s_{11}^{G} = \frac{\mu J_m}{J_m - \lambda_1^2 - 2\lambda_1^{-1}}\left(\lambda_1 - \lambda_1^{-2}\right) \quad (2)$$

Where S is the nominal stress, λ_1 is the stretch and μ is the initial shear modulus. b is a parameter associated with the strain stiffening effect whereas J_m is a parameter associated with limited chain extensibility.

D. Statistical Analysis

A statistical analysis of the experimental results was carried out using the General Linear Model procedure in SAS 9.1 (SAS Institute Inc., USA). A multivariate analysis of variance followed by the Tukey-Kramer post-hoc test were utilized to determine the influence of gender, orientation and location of the various test samples. Significance levels for all tests were set to $p < 0.05$. When performing this test a normal distribution is assumed. To ensure our data set followed a normal distribution a Lilliefors test was performed using the *lillietest* function in MATLAB R2007b.

III. RESULTS

For each tensile test performed a force-displacement curve was obtained. The nominal stress was then calculated by dividing the force by the undeformed cross sectional area of the specimen. The stretch ratio was calculated by dividing the deformed length of the specimen by the original length. In this way Nominal Stress Vs Stretch Ratio graphs were plotted for each specimen. A number of characteristics from these curves were identified as descriptive parameters. They are illustrated in Figure 3.

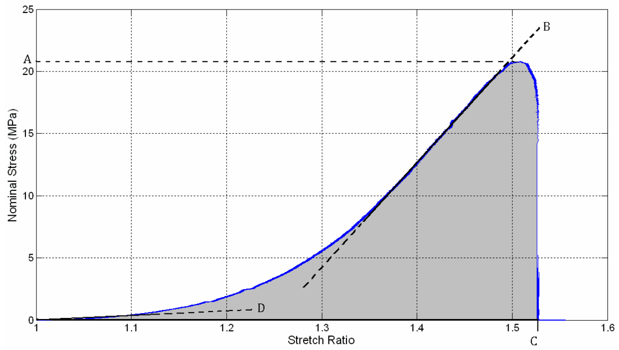

Fig. 3 Typical stress-stretch graph for experiments. The ultimate tensile strength is the maximum stress until failure and is indicated by A. The Elastic Modulus is the slope of the linear portion of the curve shown by B. The failure stretch is the maximum stretch obtained before failure, shown by C. The initial slope is the slope of the curve at infinitesimal strains and is shown by D. The strain energy is the energy per unit volume consumed by the material during the experiment and is represented by the area under the curve.

A. Influence of Orientation

The influence of specimen orientation on the mechanical behaviour of samples was investigated. It was found that the global orientation (that is, whether the samples were vertical, horizontal or at 45°) of the specimens did not have a significant effect on the mechanical behaviour. However, the influence of orientation with respect to the Langer Lines was found to have a significant effect. Specimens were classed as being parallel, perpendicular or at 45° to the Langer's Lines by comparing specimen orientation to known generic orientations of Langer Lines.

Figure 4 is an example of three stress-stretch curves representing adjacent samples in three different orientations. This graph depicts the anisotropic behaviour of skin very well. The different responses of the three different specimens can be clearly identified.

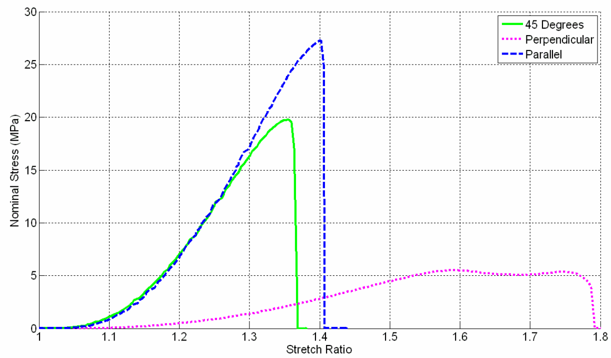

Fig. 4 Typical stress-stretch graph for experiments

A multiway analysis of variance found that orientation with respect to the Langer's Lines has a significant effect on the Ultimate Tensile Strength (UTS) ($P<0.0001$), the Strain Energy ($P=0.0101$), the Failure Stretch ($P=0.0177$), the Elastic Modulus ($P<0.0076$) and the Initial Slope ($P=0.0375$). A further simple effects analysis for orientation revealed the Estimated Marginal Means for each of the parameters listed above. These results are tabulated in Table 1 below.

Table 1 Estimated Marginal Means of orientation with .respect to Langer's Lines

Orientation	Parallel	45°	Perpendicular
UTS (MPa)	22.67	23.94	12.56
Strain Energy (MJ/m^3)	3.27	4.13	2.43
Failure Stretch	1.63	1.49	1.55
Elastic Modulus (MPa)	84.76	93.28	58.20
Initial Slope (MPa)	1.63	1.31	0.98

B. Influence of Location & Gender

When results were grouped into three locations (Upper Back, Middle Back and Lower Back), the multiway analysis of variance also found the location of specimens to have a significant effect on the UTS ($P=0.0002$), the Strain Energy ($P=0.005$) and the Elastic Modulus ($P=0.0017$), but not on the Failure Stretch nor the Initial Slope.

The influence of gender on the aforementioned parameters was also investigated. It was found to be a significant factor for the Failure Stretch ($P=0.0077$) and for the Initial Slope ($P=0.0026$) only.

C. Optimization

It was found that the Fung model performed better under tensile conditions with an average R^2 value of 97.5% as compared to 95.8% for the Gent model. The average values obtained through curve fitting for the Fung model were $\mu = 8.1\pm3.9$ MPa, $b = 3.2\pm0.9$. The average values obtained for the Gent model were $\mu = 10.1\pm4.5$ MPa, $J_m = 0.7\pm0.2$.

It was found that the orientation with respect to the Langer's Lines had a significant effect on the value of μ for both the Fung ($P<0.0001$) and the Gent ($P<0.0001$) model.

IV. DISCUSSION

As discussed by Holzapfel[9] there are a number of issues involved with tensile tests. Despite these short comings it was decided to perform in vitro tensile tests over in vivo testing for a number of reasons. Firstly, in vitro tests provide simple stress strain relationships that can be modeled and quantified easily. Secondly, in vitro testing allows histology to be carried out, which was also carried out as part of this study. Lastly, for the application of the this work in a further study into the mechanics of stabbing incidents, we are interested in failure of skin, and in vitro testing makes it possible to test until failure.

It has been shown that the UTS, strain energy and Elastic Modulus vary depending on location. However only skin from the back was available for testing and so these results only cover a small region. Although previous studies have also shown that the properties of skin are dependent upon specimen location[10, 11].

All subjects were between the ages of 81-97. This meant that no comparisons based on the age of subjects could be performed. Other studies have however investigated the influence of age on the mechanical properties of skin and it has been well documented that the extensibility of skin decreases with age[10-12].

It is important to note that both the Fung and Gent models are isotropic models and that they performed well considering their simplicity. It was shown that the parameters are dependent upon the orientation of the specimen. This illustrates that to fully describe the mechanical behaviour of skin anisotropic models must be used.

Thus far, it has only been possible to examine our data with respect to the perceived orientation of Langer Lines. However, there is variability in the directions of Langer Lines between subjects and no universal pattern of maximum tensions exist[13]. Currently, the orientation of the Langer Lines cannot be identified with certainty unless the skin of a whole cadaver is punctured. With histological data it would be possible to assess the experimental data with respect to the orientation of collagen fibres. This would be vital information for those wishing to model skin as an anisotropic material. With this information it would also be possible to confirm whether or not the Langer's Lines have an anatomical basis.

V. CONCLUSIONS

Some mechanical properties of excised human skin have been evaluated through tensile testing. The mean Ultimate tensile strength was 21.5±8.4MPa. The mean Strain Energy was 3.6±1.6MJ/m^3. The mean Elastic Modulus was 83.3±38.9 MPa. The mean initial slope was 1.18±0.88 MPa and the mean Failure Stretch was 54±17%. It has been shown that the orientation with respect to Langer Lines has a significant effect on the deformation characteristics of skin, including the Ultimate tensile strength ($P<0.0001$), strain energy (P=0.0101), failure strain (P=0.0177), initial slope (P=0.0375), and Young's Modulus (P=0.0101).

Through curve-fitting values were obtained for the parameters associated with the Fung and Gent models. For the Fung model; μ = 8.1±3.9 MPa, b = 3.2±0.9 and for the Gent model μ = 10.1±4.5 MPa, J_m = 0.7±0.2.

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REFERENCES

1. K. Langer, "On the anatomy and physiology of the skin," British Journal of Plastic Surgery, vol. 17, no. 31, pp. 93-106, 1978.
2. T. Kocher, Chirurgische Operationslehre, 1892.
3. H. T. Cox, "The Cleavage Lines of the Skin," British Journal of Surgery, vol. 29, no. 114, pp. 234-240, 1941.
4. M. D. Ridge, and V. Wright, "The directional Effects of skin. A bioengineering study of skin with particular reference to Langer's Lines," J Invest Dermatol., vol. 46, no. 4, pp. 341-346, 1966.
5. X. Liang, and S. A. Boppart, "Biomechanical Properties of In Vivo Human Skin From Dynamic Optical Coherence Elastography," Biomedical Engineering, IEEE Transactions on, vol. 57, no. 4, pp. 953-959.
6. L. H. Jansen, and P. B. Rottier, "Some mechanical properties of human abdominal skin measured on excised strips," Dermatologica, vol. 117, pp. 65-83, 1958.
7. Y. C. Fung, "Elasticity of soft tissues in simple elongation," American Journal of Physiology, vol. 213, pp. 1532-1544, 1967.
8. A. N. Gent, "A new constitutive relation for rubber," Chemistry and Technology, vol. 69, pp. 59-61, 1996.
9. G. A. Holzapfel, and R. W. Ogden, "On experimental testing methods for characterizing the mechanical properties of soft biological materials such as arterial tissues," Journal of Biomechanics, vol. 39, no. Supplement 1, pp. S324-S324, 2006.
10. R. C. Haut, "The Effects of Orientation and Location on the Strength of Dorsal Rat Skin in High and Low Speed Tensile Failure Experiments," Journal of Biomechanical Engineering, vol. 111, no. 2, pp. 136-140, 1989.
11. T. Sugihara, T. Ohura, K. Homma et al., "The extensibility in human skin: variation according to age and site," British Journal of Plastic Surgery, vol. 44, pp. 418-422, 1991.
12. H. G. Vogel, "Age dependence of mechanical and biochemical properties of human skin," Bioengineering and the skin, vol. 3, pp. 67-91, 1987.
13. I. A. Brown, "A scanning electron microscope study of the effects of uniaxial tension on human skin," British Journal of Dermatology, vol. 89, no. 383-393, 1973.

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