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Dynamic Tensile Properties of Human Skin

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Abstract The mechanical properties of skin are important for a number of applications including surgery, dermatology, impact biomechanics and forensic science. Studies have shown that the anisotropic effects of skin have been linked to sample orientation with respect to contour lines of tension, i.e. the Langer's lines. There have been numerous studies undertaken to calculate the influence of Langer's lines on the mechanical properties of human skin at quasistatic strain rates; however, it is relatively unknown what occurs at dynamic speeds. This study conducts a number of dynamic mechanical tensile tests to investigate the influence dynamic speeds have on the mechanical properties of human skin. The testing protocol involves uniaxial tensile tests at three different dynamic speeds, 1m/s, 1.5m/s and 2m/s, performed using an Instron tensile test machine. A total of 33 tests were conducted on 3 human cadavers aged 85, 77 and 82. Samples were excised at specific locations and orientations with respect to the Langer's lines. The purpose for this was to recognise the significance that location and orientation have on the mechanical properties of human skin. The mean ultimate tensile strength (UTS) was 27.2±9.3MPa, the mean strain energy was 4.9±1.5MJ/m^3, the mean elastic modulus was 98.97±97MPa and the mean failure strain was 25.45±5.07%. This new material data for human skin can be applied to constitutive models in areas such as impact biomechanics, forensic science and computer-assisted surgery.

Keywords Soft tissue, Langer's lines, Dynamic speeds, Tensile properties

I.   INTRODUCTION

Human skin is a highly complex biological material acting as the interface between the body and the environment. It provides insulation, regulates body temperature, offers a form of protection to inner organs and is therefore necessary for human existence and survival. The complexity of skin is due to the fact that it is multi-layered material comprised of three main layers, the epidermis, dermis and hypodermis. The epidermis which is the outermost layer is the dominant factor when determining the properties of the skin such as the tensile strength of skin, depending on the size and degree of crosslinking of the collagen framework [1]. At rest, the fibres appear orientated in a random fashion; however, once a load is applied, the fibres stretch parallel to the load direction. Initially, elastin fibres are thought to stretch in a linear fashion and, as the load further increases, the collagen fibres re-orient in order to carry a greater proportion of the load (figure 1). This occurs in the toe region of a stress-strain curve. As the load increases, a transition from low to high stiffness occurs and is known as the strain stiffening effect where fibres become over stretched and begin to rupture until failure occurs [2]. A typical stress-strain curve illustrating this soft tissue behaviour at quasistatic speeds can be observed in figure 1. This two-layer composition means skin has distinct and particular mechanical properties. It is heterogeneous, anisotropic, viscoelastic and shows a non-linear stress-strain relationship [3].

A major contributor to the anisotropic nature of skin is due to the discovery of natural lines of tension which occur within the skin. These specific lines of tension are known as Langer's lines, named after their discoverer Karl Langer in 1861. By puncturing the skin with a circular device, Langer noticed the wounds assumed an elliptical shape and therefore by joining the major axes, contours of lines can be drawn, as shown in figure 2.

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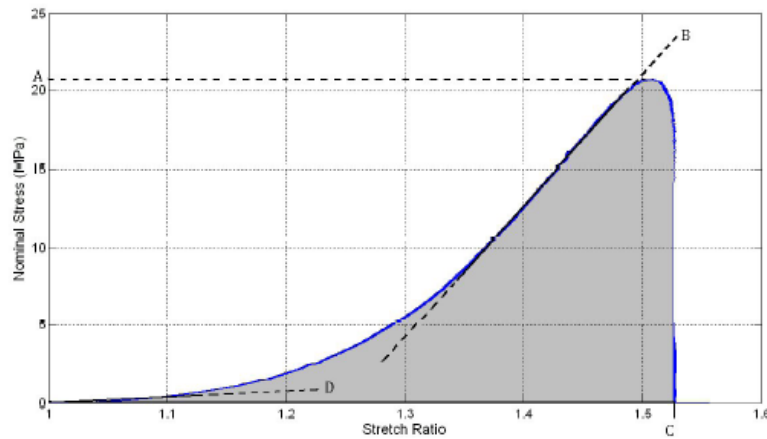
Figure 1 Typical stress-strain graph for soft biological tissue. The ultimate tensile stress, i.e. stress at failure is represented at point A. The elastic modulus, i.e. slope of linear portion of graph, is represented by B. The maximum failure stretch is represented by point C and the strain energy, i.e. toughness is represented by the area underneath the curve. [3]
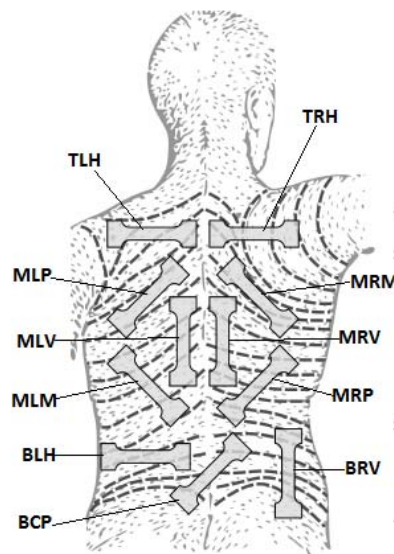

Figure 2 Specimens superimposed onto map of Langer lines (dashed lines) indicating orientation with respect to the lines [3]. T=Top; M=Middle; B=Bottom; L=Left; R=Right; C=Centre; H=Horizontal; V=Vertical.

To date there has been a number of studies using various testing methodologies carried out to discover the mechanical properties of skin at quasistatic (low level) speeds [3]-[6].These studies suggest that the deformation characteristics of skin are dependent upon specimen orientation with respect to the Langer's lines. However, research conducted to measure skin properties with respect to the subject's Langer's lines at dynamic speeds (>= 1m/s) has been very limited. Most current studies available involve *in vivo* testing. Recent work within the literature investigated the *in vivo* biomechanical properties of human skin from dynamic optical coherence elastography [7]. The study concluded that there were significant differences among measurements between directions parallel and orthogonal to Langer's lines. Other *in vivo* studies investigate the use of dynamic indentation to identify and measure the properties of elastomers and skin specimens [8]-[9]. However, no reference to a change in the material properties with respect to Langer's lines has been made.

A relatively popular *in vitro* test method is the use of the Kolsky bar, also known as a split Hopkinson pressure bar. Studies have utilised this technique on pig skin samples and have shown that pig skin exhibits rate-sensitive, non-linear behaviour whose properties vary with respect to spinal orientation [10]-[11]. Dynamic *in vitro* tensile testing on human skin is particularly rare as there are issues with tensile tests as highlighted in one particular study [12]. Firstly, as human skin is soft in nature, there is the possibility of subjecting the sample to an axial load when inserting the samples. A second issue is that the composition of the material can vary across the sample's thickness. Finally, fixation of skin samples to minimise slippage can be tricky and cumbersome; this is especially true for dynamic testing where samples are exposed to higher loading and stresses. Despite these shortcomings there are benefits to

tensile tests: they provide relatively simple stress-strain relationships which can be modelled and quantified easily. Also for this study it is of great interest to investigate the failure of skin which is possible with *in vitro* tensile tests. Work has been conducted to investigate the fracture characteristics and properties of skin during tensile testing at dynamic speeds [13]-[15]; however, comparison of skin properties with respect to Langer's lines is not investigated. This study aims to provide new material data for human skin via dynamic uniaxial tensile testing with respect to the Langer's lines.

II. METHODS

Specimen Preparation

All preparation and testing were carried out in IFSTTAR (Institut Francais des Sciences et Technologies des Transport, de l'Aménagement et des Réseaux), Lyon France. As French law allows the testing of human corpses that have been donated to science, the ethics committee within IFSTTAR approved the use of human biological tissue. Skin was excised using a scalpel from the backs of three subjects H2, I1 and J2, (two female and one male), aged 85, 77 and 82 respectively. Next specimens were cut into dogbone shapes using a customised die according to the ASTM D412 Standard for tensile testing. Eleven samples were removed from each subject as shown in figure 2 and grouped into one of six categories, depending on location (top, middle, bottom) and orientation with respect to the Langer's lines (parallel, perpendicular and 45 degrees). The samples were stored in moistened paper and refrigerated at 4˚C to maintain freshness.

Tensile Tests

Tensile tests were performed using an Instron type 8802, with a 1kN piezoresistive load cell to measure the tensile load and an acquisition frequency of 5000Hz, with the signal filtered to 750-800Hz ensuring a smooth output. The specimens were clamped using special custom made anti-slip clamps so as to counteract any slipping. Two high resolution digital video cameras were used to record each test at 5000 frames/second. This was to record any abnormal behaviour during a test and for subsequent correlation with the stress-strain data. The first set of tests, (subject H2), were performed at 1m/s. For subject I1, specimens excised from the left side of the back were tested at 2m/s and specimens excised from the right side were tested at 1m/s. This was to compare symmetry and analyse the effect of different stretch velocities on human skin. The final set of specimens (subject J2) was performed at 1.5m/s, again to analyse if the properties of skin change with a variation in stretch velocity.
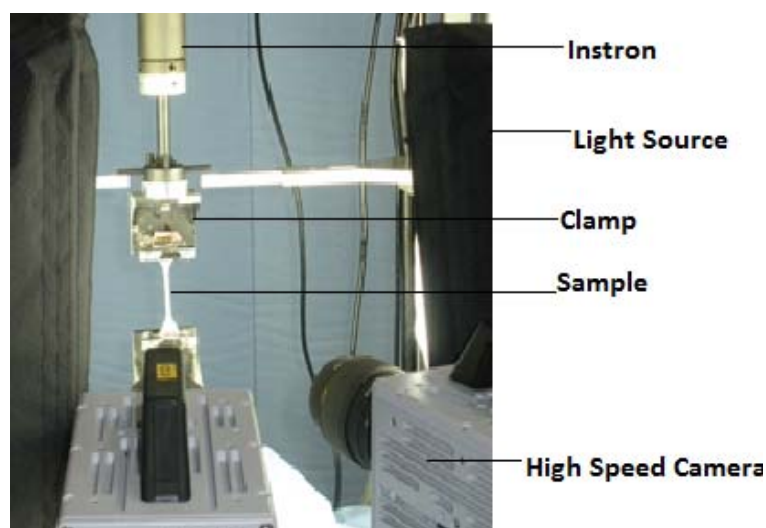
Figure 3 Test specimen clamped and positioned in Instron with two Fastcam cameras for image capture and high powered light to maintain adequate light conditions.

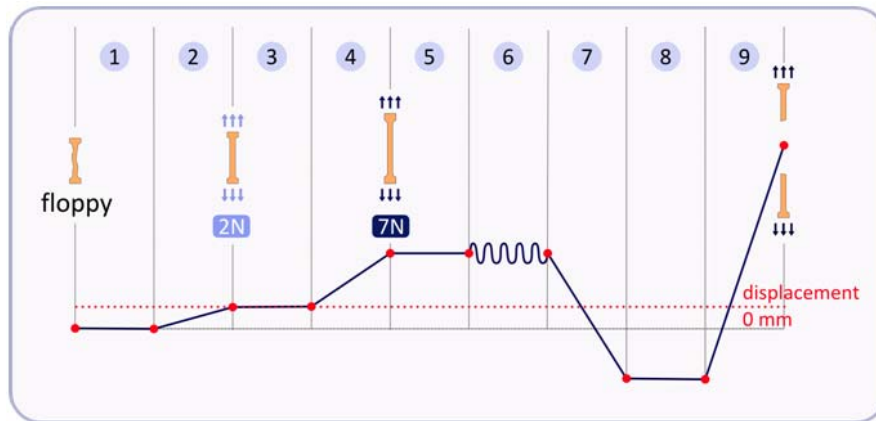The test protocol consisted of 9 steps which are illustrated in figure 4.

Figure 4 Test protocol for uniaxial tensile tests.

When the sample is placed into the clamps (step 1), it is in a floppy state. A pre-load tension of 2N which represents approximately 0.5% of the maximum load is then applied at a displacement of 0mm. This is done so as to avoid the floppy state of the sample (step 2). This tension is held (step 3) and subsequently increased to 7N in order to stretch the fibres (step 4). This tension ensures adequate stretching of the fibres without any over stretching which would otherwise cause unintentional rupturing. Once again this tension is held (step 5) and 5 cycles of amplitude ±1mm are applied to further increase and decrease the stretch of each fibre, sufficiently preconditioning the sample (step 6). Once the sample is sufficiently preconditioned, the Instron momentarily brings the sample back to a displacement of -44mm, ensuring the sample is in a floppy state (steps 7 and 8). Once step 8 is completed, the sample displacement is subsequently increased to a maximum of 110mm, guaranteeing adequate stretching and rupture of the specimen at the desired test speed.

Digital Image Correlation

In order to validate the stretch ratio, Digital Image Correlation (DIC) is used to calculate the stretch ratio both globally and locally, discovering any sudden increases in the strain which could lead to failure of the specimen. DIC works by tracking specific makers, in this case speckled back dots from spray paint applied to the skin surface. Processed images from the two Fastcam cameras can measure 2D and 3D deformation of a material.

III.   RESULTS

For every tensile test performed, a force-displacement curve was obtained. From this, the nominal stress versus stretch ratio graphs were plotted for each specimen and a number of characteristics from these curves were identified (ultimate tensile strength, strain energy, elastic modulus and failure stretch). The nominal stress was calculated by dividing the force by the undeformed cross sectional area (width × thickness) of the specimen. The stretch ratio was calculated by dividing the current length of the specimen by the initial length ($\Delta L/L$).

Intra-subject and inter-subject variation

Due to the anisotropic nature of skin, there is always the potential for large variation in experimental results across samples. Figure 5 shows the stress-strain behaviour of six samples taken from the three subjects (H2, I1 and J2). Samples were adjacent to one another (excised from the top of the back) but in the same orientation with respect to the Langer's lines (45 degrees; TLH=Top Left Horizontal and TRH=Top Right Horizontal). Samples TLHH2 and TRHH2 were tensile tested at a velocity of 1m/s. Specimen TLHI1 was tested at 2m/s while specimen TRHI1 was tested at 1m/s, the purpose for this was to compare symmetry and demonstrate profile variation due to test speed. Specimens TLHJ2 and TRHJ2 were both tested at 1.5m/s, again this was to analyse and see if the properties altered

with a change in the rate of stretch. Due to the variation in test speeds, different profiles are produced as shown in figure 5, indicating the strain rate sensitivity of human skin.
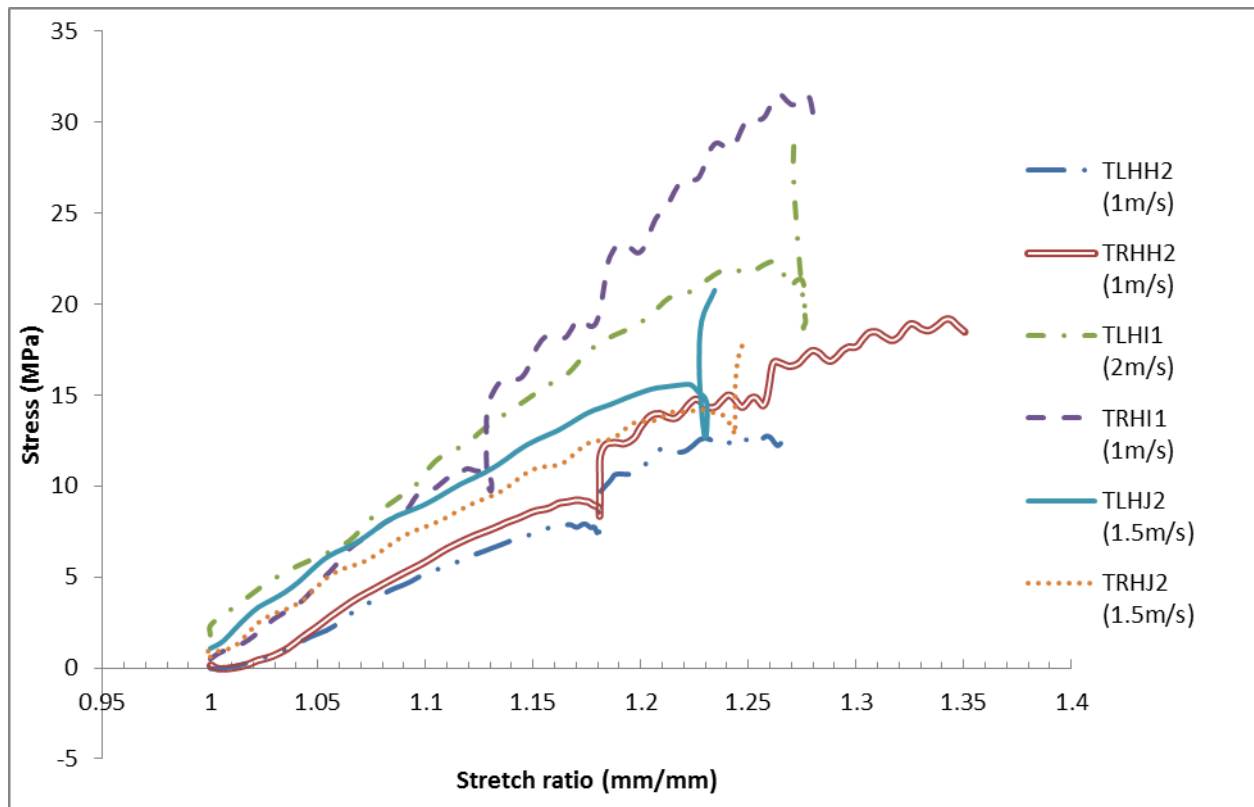

Figure 5 Stress-stretch ratio responses of adjacent samples from the upper back (TLH and TRH) with the same orientation (45˚) with respect to the Langer's lines (see figure 2), illustrating the inter-subject and intra-subject variation between adjacent samples.

3.5 Digital Image Correlation

The main feature of the DIC is its ability to calculate local strains just prior to rupture. These local strains were compared with global strain measurements obtained from the displacement sensor (DS) on the Instron. The DIC also measured the global maximum stretch of each sample by placing a virtual extensometer along the length of the sample. On comparison of results, the local stretch values obtained from the DIC were significantly higher than the overall stretch values obtained from the displacement sensor, in some cases being almost twice as high as the local strains, which has been similarly observed in the literature [13]. When plotting a distribution of local Lagrangian strains along the sample just prior to rupture, it was also observed that this magnification usually occurred over a number of areas which possibly could give rise to non-monotonic stress-strain plots.

IV.   DISCUSSION

From the results obtained, it is clear that the properties of human skin are highly dependent on the orientation and location with respect to the Langer's lines, as well as the strain rate at which the specimen is loaded. This has also been observed throughout the literature. However, on comparison of the current data to that in the literature, large variations in results can be seen. These variations are expected when experimentally testing soft biological tissue, due to the anisotropic nature of skin and because of the sensitivity of biological tissues to test conditions. The mean ultimate tensile strength (UTS) was 27.2±9.3MPa, the mean strain energy was 4.9±1.5MJ/m3, the mean elastic modulus was 98.97±97MPa and the mean failure strain was 25.45±5.07%.

An important point to note is that the elastic modulus was obtained by calculating the initial straight line portion of the slope of each graph and therefore may not be a true result but rather a guided approximation of the elastic modulus. Table 1 compares these results to those obtained elsewhere in the literature.

TABLE 1

Reference	Strain rate	UTS (MPa)	Failure Strain (%)	Elastic Modulus (MPa)	Location	Age
[3]	Quasistatic: 50mm/min	13.2-30	37-71	48.4-118.2	Back	81-79
[18]	Quasistatic: 10%/min	2-15		18.8	Abdomen + Thorax	47-86
[6]	Quasistatic: 50mm/min	7-30	31-53		Back and Abdomen (Porcine Skin)	7-8 months
[19]	Quasistatic: 0.25-10%/s	0.25-1.0	123-126	0.9-4.2	Abdomen (Porcine Skin)	
[10]	Dynamic: 1700-3500/s	0.1-0.8	16-30		Back (Porcine Skin)	9 months
[20]	Dynamic: 700-2100/s	0.16-0.4	10-40		Porcine muscle	5 months
[11]	Dynamic: 40-4000/s	25-57	40-60		Porcine Skin (Rump)	
[15]	Dynamic: 6000%/s	1.2-3.2	51.9-124.8		Dorsal Skin from Rat	1-6 months
[17]	Dynamic: 1000-5700/s	1.9-3	24-35		Porcine Skin (Jowl)	
[13]	Dynamic	5.7-12.6	27-59	19.5-87.1	Forehead and Arm	62-98
[16]	Quasistatic		16-52	0.26-0.83		15-30
Present results	**Dynamic: 1,1.5 and 2m/s**	**17.9-36.5**	**20.38-29.52**	**56.8-141.11**	**Back**	**77-85**

Table 1 Comparison of results to results in the literature. Experiments conducted on human and animal specimens both *in vivo* and *in vitro*.

When directly comparing results to similar quasistatic experimental testing conducted in the literature by [3], who also investigated the same properties of human skin (UTS, Strain Energy, Failure Stretch and Elastic Modulus) with respect to location and orientation to the Langer's lines, a number of similarities and contradictions can be seen. Results in this study show the strain energy to be lowest at 45 degrees and highest in the perpendicular orientation, which is contrary to [3]. Also from our test data, the UTS and elastic modulus is highest in the parallel direction which matches with [3], but lowest in the 45 degree orientation, contrary to [3]. Failure stretch was highest in the 45 degree Langer's lines direction and lowest in the parallel direction.

TABLE 2

Orientation wrt Langer Lines	Number of Samples Tested	UTS	Strain Energy	Failure Stretch	Elastic Modulus
45 Degrees	15	23.51±6.53	4.18±1.44	1.28±0.06	73.03±15.84
Perpendicular	9	29.82±12.77	5.7±1.5	1.26±0.04	117.14±58.81
Parallel	9	30.5±6.53	5.24±1.33	1.22±0.02	127.22±36.38

Table 2 Experimental results showing the effect of orientation with respect to the Langer's lines.

When investigating the influence of location, the strain energy, UTS and elastic modulus are highest for samples excised from the middle of the back, while samples excised from the top show the highest values for the failure stretch. When comparing influence of location with [3], only the strain energy shows comparable findings. Unfortunately no other studies in the literature focus on skin excised from the back, which makes it difficult to show any correlations. The influence of strain rate demonstrated that the UTS and the elastic modulus increased with increasing strain rate, again comparing well with the literature [11], [17]. It is also shown that the failure stretch increases with an increase in test speeds; this trend contradicts what was discovered in the literature [11]. When examining the dynamic experimental data, as expected and in accordance with the literature, the UTS and elastic modulus is lower at the quasistatic speed. On analysis of the results and comparing to quasistatic data, the failure stretch is much higher for samples tested at the quasistatic speed. It has been hypothesised in the literature that the fibres have an ability to split into thinner ones rather than failing when tested quasi-statically [14]. This splitting effect gives fibres their ability to stretch further. Secondly, according to [14], the frictional forces produced during each test is less at quasistatic speeds, meaning fibres have less stress induced on them and therefore can stretch further before rupture occurs.

Finally it is worth mentioning the variability of human skin with aging. It has been well known that the mechanical properties of skin vary with age. The most pronounced change is in the reduction of skin extensibility. This manifests itself as a shortened phase D region (figure 1) [21]. The Young's modulus remains relatively constant for all ages. The structure and organisation of old and young skin differs but the total amount of collagen and elastin remains constant [21].

V. CONCLUSIONS

This study has shown that the mechanical properties of skin have been shown to vary according to (i) the orientation of the loading direction with respect to the Langer's lines, (ii) the location on the position of the back, and (iii) the test speed. The mean ultimate tensile strength (UTS) was 27.2±9.3MPa, the mean strain energy was 4.9±1.5MJ/m3, the mean elastic modulus was 98.97±97MPa and the mean failure strain was 25.45±5.07%. However, it should be said that a limitation of this study is that skin from only 3 cadavers was tested: this provided a relatively small population of 33 test samples. Nevertheless, the presented stress-strain data and physical properties can be used to facilitate the determination of material parameters for structurally-based constitutive models for skin.

VI. ACKNOWLEDGEMENT

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