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Research Paper

Strain rate and anisotropy effects on the tensile failure characteristics of human skin

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A R T I C L E I N F O

Article history:
Received 6 May 2014
Received in revised form
6 October 2014
Accepted 8 October 2014
Available online 16 October 2014

Keywords:
Human skin
Ex-vivo tensile test
Dynamic strain-rate
Anisotropy
Langer lines

A B S T R A C T

The anisotropic failure characteristics of human skin are relatively unknown at strain rates typical in impact biomechanics. This study reports the results of an experimental protocol to quantify the effect of dynamic strain rates and the effect of sample orientation with respect to the Langer lines. Uniaxial tensile tests were carried out at three strain rates ($0.06\ s^{-1}$, $53\ s^{-1}$, and $167\ s^{-1}$) on 33 test samples excised from the back of a fresh cadaver. The mean ultimate tensile stress, mean elastic modulus and mean strain energy increased with increasing strain rates. While the stretch ratio at ultimate tensile stress was not affected by the strain rate, it was influenced by the orientation of the samples (parallel and perpendicular to the Langer lines. The orientation of the sample also had a strong influence on the ultimate tensile stress, with a mean value of 28.0 ± 5.7 MPa for parallel samples, and 15.6 ± 5.2 MPa for perpendicular samples, and on the elastic modulus, with corresponding mean values of 160.8 MPa $\pm$ 53.2 MPa and 70.6 MPa $\pm$ 59.5 MPa. The study also pointed out the difficulties in controlling the effective applied strain rate in dynamic characterization of soft tissue and the resulting abnormal stress–strain relationships. Finally, data collected in this study can be used to develop constitutive models where high loading rates are of primary interest.

1. Introduction

Skin is the largest organ of the human body with an area of about $1.8\ m^2$ and an average thickness of 2 mm. In medical terms, skin can be referred to as an integument, derived from the latin *tegument* meaning cover. Indeed, skin covers the whole human body and one of its primary functions is to protect from foreign aggressions. Human skin is subjected to a variety of loading conditions during our daily motions, where it is stretched, sheared and pinched. Skin however,

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http://dx.doi.org/10.1016/j.jmbbm.2014.10.006
1751-6161/

tends to return to its initial state due to its elastic properties. Moreover, its high mechanical strength ensures it is not easily torn, and therefore, our skin protects us from tetanus, open hemorrhages, or from direct damage to underlying organs. Skin also fails due to trauma such as planned surgical incisions, gunshot wounds and penetrative wounds from stabbing attacks or can even originate internally when a bone pierces the skin.

In 1861, Langer was interested in the geometry changes of open wounds. By puncturing a cadaver's skin with a circular device, he noted that the wound transformed into an elliptic form. By joining the major axes of these ellipses, he drew a pattern of tension lines on the body: these lines are now known as the Langer lines (Langer, 1978). These early experiments illustrated the anisotropic nature of skin, but did not explain fully the mechanism involved. Indeed, the correlation between the Langer lines, the macroscopic mechanical properties of human skin and its structural basis is still under investigation (Ridge and Wright, 1966; Ní Annaidh et al., 2012a; Gąsior-Głogowska et al., 2013). Recently, Ní Annaidh et al. (2012b) have shown through the use of quantitative structural data, that the Langer lines have a structural basis. A point which had previously been alluded to but not quantitatively assessed. The current study takes place in the general context of trauma biomechanics and at strain rates relevant in automotive collisions and in sharp force injury. The collection of experimental data on human skin is an essential step in the development of a numerical model capable of predicting the rupture of skin in sharp force injury. In order to obtain experimental data relevant for this application, it is necessary to understand how skin behaves when it is dynamically loaded above its physiological range (up to rupture).

Consideration has previously been given to the effect of strain rate on the properties of skin. Dynamic testing often involves the study of the response of the skin subjected to an oscillatory solicitation (Boyer et al., 2009; Dawes-Higgs et al., 2004; Lamers et al., 2013) or to wave propagation through it (Liang and Boppart, 2010; Lim et al., 2011). These methodologies are useful to examine the *in vivo* response of skin, or to access the viscoelastic properties of the skin, but not to study the failure properties of the skin. Previous studies which *do* examine the failure properties of skin, have confined their experiments to low strain rates. Zhou et al. (2010) investigated the coupling of strain rates and temperature for tensile tests on pig skin, but strain rates did not exceed $0.1\,s^{-1}$. Similarly, Ní Annaidh et al. (2012a) conducted tensile experiments of human skin but did not exceed a strain rate of $0.01\,s^{-1}$. For intermediate strain rates, valid for automotive collisions and sharp force injury, Haut (1989), Dombi et al. (1993), Arumugam et al. (1994), or Khatam et al. (2014) performed tests on animal skins only, with Haut (1989) and Dombi et al. (1993) having also considered the orientation of samples. Shergold et al. (2006) performed tests in the range $0.004\,s^{-1}$ to $4000\,s^{-1}$ but these experiments were in compression only. To the best of the authors' knowledge, only one study has tested human skin in the intermediate range of velocities: Jacquemoud et al. (2007) used a customized tensile device based on a drop test machine and Digital Image Correlation to investigate local strain levels. Nevertheless, a clear comparison of the mechanical properties of human skin at quasi-static and intermediate velocities which considers the effect of anisotropy is still wanting in the literature. The present paper aims to provide new material data for human skin via dynamic uniaxial tensile testing with respect to the Langer lines, which can be applied to constitutive models in areas such as impact biomechanics and forensic science.

2. Materials and method

2.1. *Sample preparation*

All tests and procedures were in line with the French ethical rules and the law that allows experiments involving post mortem human subjects (PMHS) for biomedical research under the control of a medical school. The desired location and orientation of test samples was marked on the back of a PMHS with a custom made ink stamp (Fig. 1). The skin tissue was then excised in one piece from the back of the PMHS one day after death and stored at 4 °C in gauze soaked with saline solution. The skin sample included the epidermis, dermis, hypodermis and the underlying adipose tissue. Within two weeks, dogbone shape samples were cut with a custom die, following the previously marked locations. In total, 33 samples were collected. The hypodermis and underlying adipose tissue were then removed from each test sample with a scalpel. As the dermal layer appears visually distinct from the hypodermis, the removal is straight forward to perform. The mean thickness of the samples was 2.3 ± 0.4 mm. They were stored in gauze soaked with saline solution in a 4 °C storage room prior to testing. Each specimen was grouped into one of three categories: parallel, perpendicular or at 45° to the Langer lines. The orientation of the samples was determined based on anatomy sketches of Langer lines reported in the literature and on the photographs of the sample locations prior to excision.

Samples were clamped using custom designed anti-slip grips. They were cautiously positioned in the grips to limit axial preload and bending prestress. Table 1 provides the characteristic measurements of samples before testing.

2.2. *Tensile tests*

Tensile tests were performed using a servo-hydraulic machine (Instron 8802, High Wycombe, England). The tensile

Table 1 – Mean values of the specimen characteristics with standard deviation given in brackets.

	Total length (cm)	Working length (cm)	Width (mm)	Thickness (mm)
Long samples ($n=11$) *dynamic testing*	11.8 (0.2)	7.1 (10.9)	5.2 (0.3)	2.5 (0.3)
Small samples ($n=10$) *dynamic testing*	4.5 (0.1)	1.2 (0.1)	3.6 (0.7)	2.0 (0.3)
Small samples ($n=11$) *quasi-static testing*	4.6 (0.3)	1.3 (0.1)	3.5 (1.0)	2.4 (0.5)