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INFLUENCE OF A SKIN TISSUE ANISOTROPY ON MECHANICAL HYSTERESIS

WPŁYW ANIZOTROPII TKANKI SKÓRNEJ NA HISTEREZĘ MECHANICZNĄ

Abstract

The mechanical properties of a pig's skin as a human skin substitute in the studies carried out *in vitro* are used in surgery and engineering design. The investigation included the uniaxial tensile test and cyclic loading-unloading tests of a swine skin. The values of dissipated energy and energy dissipation ratio for first, fifth and tenth hysteresis loop of every examined sample were obtained. In the investigation, the skin anisotropy was taken into consideration. The estimation of the influence of various levels of load on the values of the measured parameters was also made.

Keywords: mechanical properties, energy dissipation, skin, animal samples, hysteresis

Streszczenie

Właściwości mechaniczne tkanki skórnej świni jako substytutu skóry ludzkiej w badaniach *in vitro* są wykorzystywane w chirurgii i projektowaniu inżynierskim. Badania obejmowały przeprowadzenie próby jednoosiowego rozciągania oraz wykonanie testów cyklicznego obciążania-odciążenia dla skóry świni. Otrzymano wartości energii dyssypacji oraz współczynnika pochłaniania energii dla pierwszej, piątej i dziesiątej pętli histerezy mechanicznej każdej zbadanej próbki. We wszystkich przeprowadzonych badaniach uwzględniono anizotropową budowę tkanki skórnej. Oceniono także wpływ różnych poziomów zastosowanego obciążenia na wartości mierzonych parametrów.

Słowa kluczowe: właściwości mechaniczne, dyssypacja energii, tkanka skórna, próbki zwierzęce, histereza

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1. Introduction

The skin is a non-homogeneous material, which has a complicated multilayered anatomy structure. It displays viscoelastic mechanical properties and *in vivo* it is subjected to a pre-stress, which is unequal distributed on its surface. The areas of reduced tension are mapped by Langer`s lines [1–4]. Their direction is perpendicular to the long axis of muscles lying under the skin [1].

From a mechanical point of view, skin can be treated as a composite material with a highly-hierarchical structure. Due to the complex anatomy structure, skin tissue is a strongly anisotropic material. Basic mechanical properties of the skin are largely influenced by the structural arrangement and orientation of the collagen fibers [5, 6]. The viscoelastic behavior of skin tissue is shown in the hysteresis in the stress-strain relationship. Hysteresis is defined as the energy lost within the tissue between loading and unloading. Hysteresis is caused by internal friction of a material. This internal friction is responsible for dissipating mechanical strain energy to heat. When the skin is stimulated repetitively with constant load peak, the load-deformation curves shift to the right in a load-elongation diagram and the hysteretic effects diminish. By repeated cyclic, eventually a steady state is reached at which no further change will occur (the tissue is preconditioned) unless the cyclic routine is changed [7].

The description of mechanical properties of the skin is still an open question, not only from the theoretical point of view, but also from an experimental aspect. There is no one definite standard that has been established in testing skin tissue. The knowledge obtained in mechanical tests is used in dermatology as well as in traumatology and plastic surgery, especially in view of the aging and fatigue features. It is also used in the engineering design of medical robots and surgical instruments [8].

In the case of the investigation of living tissue, the availability of research material is limited, especially if the study would concern human tissues. An important limit of such tests consists of ethical considerations. Much greater freedom is characterized by investigation of animal tissues. Therefore, in many studies, substitutes are used [9, 10]. These materials have a structure and properties as similar as possible to the original. In the case of the investigation of human skin tissue, a good substitute is swine skin. It has an anatomical structure very similar to that of human skin. Pig`s skin contains dermal collagen and elastic content that is more similar to humans than other laboratory animals [11, 5]. In the literature, the most commonly used tests to characterize pig's skin are uniaxial and biaxial tensile tests and relaxation tests [12, 13]. However, the data obtained in tensile tests are often very different. This difference results from the biological variety among animals, the sensitivity of biological tissues to test and storage conditions of samples, problems with obtaining samples of identical dimensions (e.g. various thickness), as well as from the anisotropic character of the skin [14]. The Young's modulus of the pig's skin varies between 7.6 MPa and 62.6 MPa, the tensile strength varies between 2,5 MPa and 15.7 MPa [12, 15–17].

The aim of the study was an estimation of the influence of skin anisotropy and various levels of load on mechanical hysteresis under cyclic loading-unloading of swine skin.

2. Material and methods

2.1. Samples preparation

In the study, the skin from a domestic pig, which weighed ca. 110 kilograms and was 6 months old, was used. Firstly, patches of skin from the back were extracted. The skin and adipose tissues were separated. Rectangular samples, in the same geometric dimensions: 100 mm in length and 10 mm in width, were made. There is no standard for testing skin tissue and literature review showed that e.g. the width of sample can be in the range between 5 and 12,7 mm [12, 18]. Therefore, the geometry size of skin samples was selected according to PN-EN ISO 527-2. Specimens were taken in three directions: parallel, perpendicular and at an angle 45 degrees (oblique) to the backbone (Fig. 1). The average thickness of the samples was 2,27±0,19 mm.

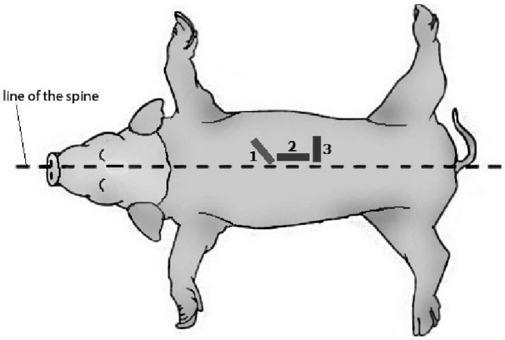

Fig. 1. Direction of samples taken from swine`s back (1 – oblique, 2 – parallel, 3– perpendicular) in relation to the backbone line

In order to better store the biological material, the specimens were frozen at the temperature of –18°C and defrosted in the period of 1 hour at room temperature before the test.

2.2. Research methods

The mechanical properties under static tension were determined with the use of the MTS Insight 50 testing machine. The samples were mounted using flat clamps and they were extended at the speed of 5 mm/min. The measurement base of the sample was 50 mm. Each set of samples for tension testing (the samples divided according to the direction of their taking) contained a minimum of 5 samples. The determined values of mechanical parameters: Young's modulus (E_1 in the first phase of elongation, E_2 in the second phase of elongation), the tensile strength (UTS) and the strain at break were shown as the average values with a standard deviation (X ± SD).

Repeated loading cycles were made for three levels of load: 30 N, 65 N and 100 N and for three directions of the taken samples. The applied tensile load was within the elastic limit of the skin. The test was made with the use of MTS Insight 50 testing machine. The loading as well as the unloading was conducted at a constant rate of 5 mm/min. Initial sample length was $l_0 = 50$ mm.

The cyclic loading-unloading tests consisted of 10 loading-unloading cycles. Three hysteresis loops for each level of load were registered (first, fifth and tenth). On the basis of the received data, the force-elongation characteristics were obtained. These curves were used to calculate dissipated energy (the area of loop) and energy dissipation ratio (dissipated energy/energy during loading) in each loading cycle. Also, examples of strain versus time curves were shown, and on their basis values of residual strain were calculated. Eighteen samples were taken, two samples for each set of research direction and load level. The calculated values of energy of dissipation, energy dissipation ratio and residual strain were shown with a standard deviation.

3. Results

The anisotropy of the skin tissue had a considerable impact on its mechanical parameters. The research shows that the best mechanical parameters characterized samples taken parallel to the spine. The lowest values were obtained for the perpendicular samples (Tab. 1).

Table 1

The average values of obtained mechanical properties

Research direction (to the backbone)	Maximum force [N]	UTS [MPa]	Strain [%]	Young`s modulus E_1 [MPa]	Young`s modulus E_2 [MPa]
perpendicular	242.42±81.93	10.61±3.18	43.39±8.60	2.35±0.28	35.53±3.97
parallel	522.70±95.91	22.06±3.31	45.16±3.68	2.46±0.35	72.28±6.56
oblique (45°)	484.26±55.66	21.18±2.32	44.32±5.91	2.39±0.27	63.89±8.75

As a result of the cyclic loading-unloading tests of the swine skin tissue, stress-strain characteristics for the three various load levels (30 N, 65 N, 100 N) and with respect to skin's anisotropy were obtained (Fig. 1 to 3).

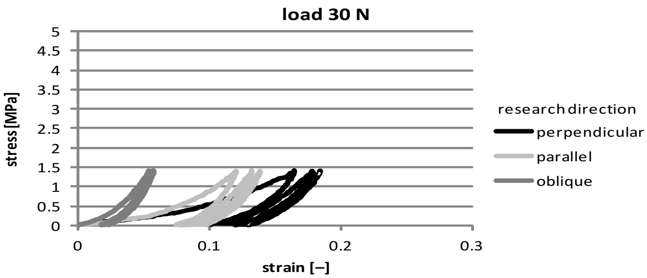

Fig. 2. Comparison of hysteresis loops (1st, 5th and 10th) obtained under load of 30 N for three directions of samples taken

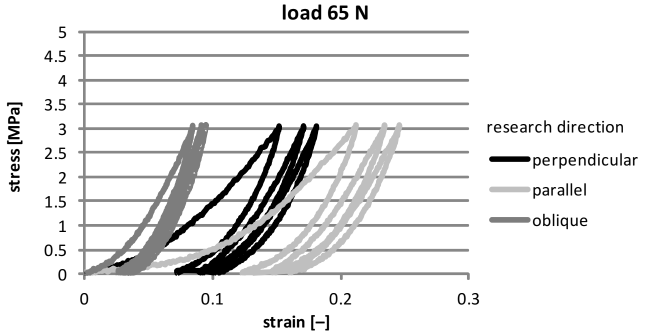

Fig. 3. Comparison of hysteresis loops (1st, 5th and 10th) obtained under load of 65 N for three directions of samples taken

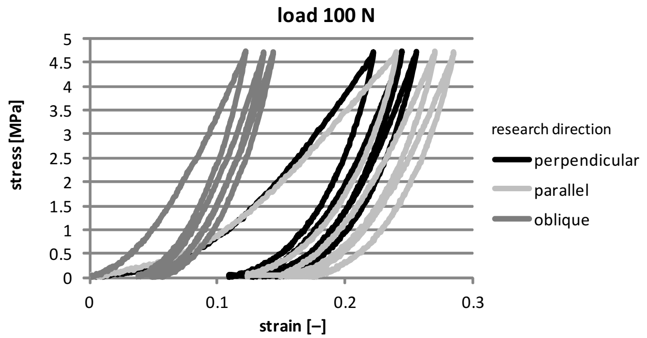

Fig. 4. Comparison of hysteresis loops (1st, 5th and 10th) obtained under load of 100 N for three directions of samples taken

The maximum value of the stress reached at the load of 30 N was 1.42 MPa (peaks of each hysteresis loops). For the last, tenth loop, the value of the maximum strain was 18.4–18.6% for perpendicular samples, 12.1–13.8% for parallel samples and 4.8–5.8% for oblique samples (Fig. 2). When the load of 65 N was used, the maximum value of the stress was 3.08 MPa. Instead, the value of the maximum strain for the last loop was in the range of 18.1–18.7% (perpendicular samples), 24.6–25.2% (parallel samples), 9.5–10.7% (oblique samples). The application of load of 100 N resulted in obtaining maximum stress with a value of 4.73 MPa. The values of the maximum strain for the tenth loop were 24.8–25.5% for the perpendicular samples, 25.4–28.4% for the parallel samples and 14.3–21.5% for the oblique samples.

In Figs. 2 to 4, difference between the area of the first hysteresis loop and the following loops have been seen. At every examined load level and research direction, the first hysteresis loop had a definitely higher value of the surface area than other loops. The values of the surface area of each registered loop were calculated and shown as energy of dissipation in Figs. 5 to 7. The highest value of the energy dissipated was observed in the first cycle of loading-unloading test (in the first hysteresis loop) for all directions of the taken samples. An increase of the number of loading cycles caused a decrease of the value of dissipated energy. The percentage reduction of these values was presented in Tab. 2. For perpendicular samples under the load of 30 N, the average value of energy dissipation for the first loop was 56.79±0.81 mJ. The average value of the energy dissipation for the first loop for parallel samples under the load of 30 N was 31.72±3.94 mJ. The smallest differences between each loop were shown for oblique samples. The average value of energy dissipation for the first loop (under the load of 30 N) was 8.7±0.91 mJ.

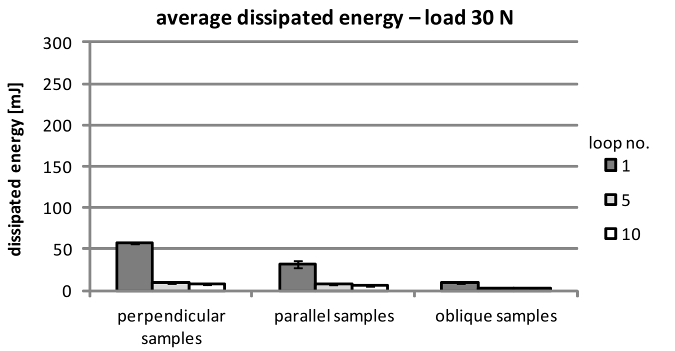

Fig. 5. Values of dissipated energy under the load of 30 N

Under the load of 30 N, for the perpendicular samples the value of dissipated energy was the highest (Fig. 5). At this load level, parallel samples exhibited less ability to energy dissipation. Oblique samples obtained the worst result. The level of applied load (30 N) corresponded to the first phase of elongation test, in which elastin fibres are mainly responsible for the stretching mechanism. At this stage, collagen fibers remain folded, so their contribution in energy absorption is negligible [19, 20]. Therefore, in the case of low value of load, participation of more oriented collagen fibers in parallel samples had no effect on energy dissipation. At larger loads, parallel samples absorbed more energy than perpendicular and oblique samples (Fig. 3 and 4). This may results from the fact that most of the collagen fibers are arranged longitudinally to the line of the spine of animals and energy supplied to the skin is partly dissipated by collagen fibers during their ordering in the direction of the applied force [18].

The highest value of the energy has been dissipated during investigation of parallel samples. For the first loop, the average value of energy dissipation for parallel samples was 124.95±9.89 mJ. For perpendicular samples, the average value of dissipated energy in the first loop (under the load of 65 N) was 92.72±1.44 mJ. The smallest differences between each loop for oblique samples can be seen. The average value of energy dissipation for the first loop was 35.38±2.60 mJ.

For perpendicular samples, in the first loop, the average value of energy dissipation was 189.98±14.13 mJ. The greatest values of dissipated energy for parallel samples can be seen. The average value of this parameter, at this load level (100 N), for the first loop, was 198.29±72.53 mJ. The smallest values of energy dissipation were for oblique samples. In the first loop the average value of this energy was 125.48±45.02 mJ. In the case of the highest value of applied load as well as parallel and oblique samples, the large spread of the average value of energy dissipation can be seen. These results may be caused by differences in the specimens' thickness or the area of the taken specimen, and requires testing with the use of a larger number of samples.

Table 2

Differences of values of energy dissipation between loops under the load of 30 N

Research direction	Loop no.	Percentage reduction of values of energy dissipation (relative to the first loop)%		
		30 [N]	65 [N]	100 [N]
perpendicular	5	83.39	75.75	76.81
perpendicular	10	87.92	77.79	79.93
parallel	5	77.55	76.33	75.70
parallel	10	80.88	80.64	79.61
oblique	5	66.95	61.45	70.53
oblique	10	70.46	65.72	73.67

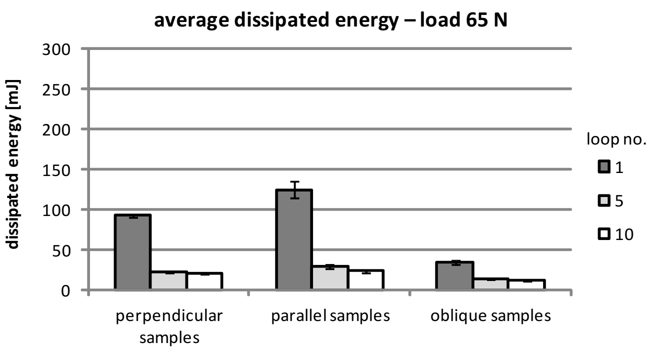

Fig. 6. Values of dissipated energy under the load of 65 N

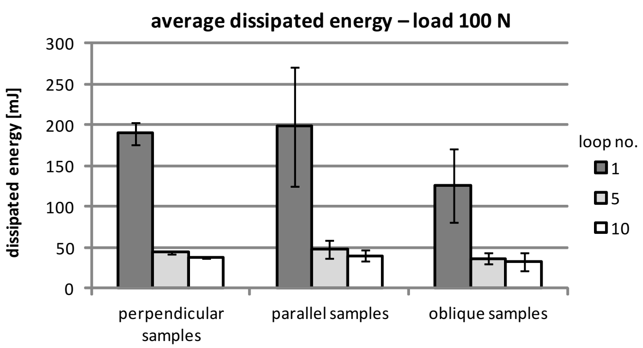

Fig. 7. Values of dissipated energy under the load of 100 N

Analyzing data from the above graphs (Fig. 5–7) relatively slight differences between values of energy dissipation for fifth and tenth loop in the margin of error can be noticed. This results from a certain stabilization of this parameter after few loading-unloading cycles.

By analyzing the obtained values of the energy dissipation ratio (Fig. 8–10), the fact that, at each load level, an increase of the number of loading cycles caused a decrease of the values of this ratio, may be seen. Differences between values of the energy dissipation ratio for fifth and tenth loop were inconsiderable. This is the result of stabilization of this parameter after few load-unload cycles.

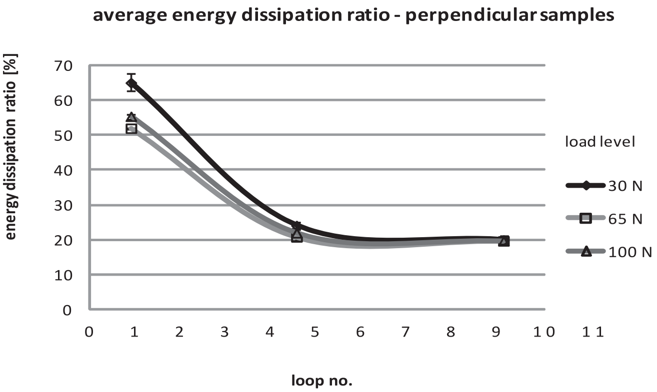

Fig. 8. Values of energy dissipation ratio under three load levels for perpendicular samples

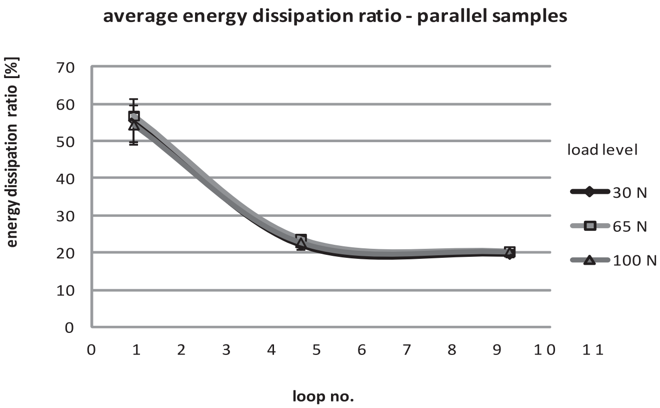

Fig. 9. Values of energy dissipation ratio under three load levels for parallel samples

In Fig. 11, examples of strain versus time curves under the load of 30 N were shown. The stages of cyclic loading-unloading can be recognized for these curves. In the loading phase, the value of strain increased and in the unloading phase, it decreased to the value of residual strain which occurred immediately after the first loading-unloading cycle. This behavior resulted from the viscoelastic nature of skin tissue. In Tab. 3, the values of residual strain for the tested samples were shown. The values of residual strain increased with the number of loading cycles (number of hysteresis loops). The highest values of residual strain under the load of 30 N were obtained for perpendicular samples and under higher loads for parallel samples. This trend was similar to that observed in the case of energy of dissipation.

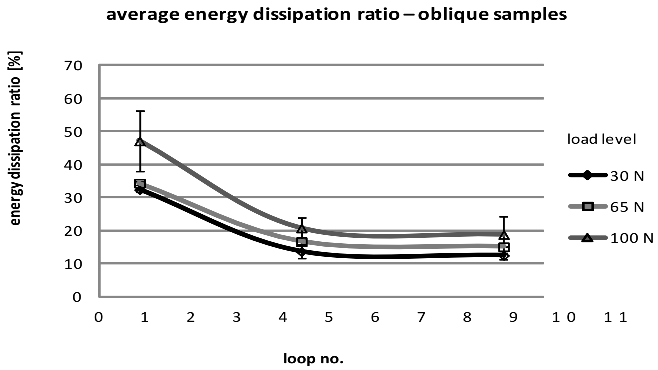

Fig. 10. Values of energy dissipation ratio under three load levels for oblique samples

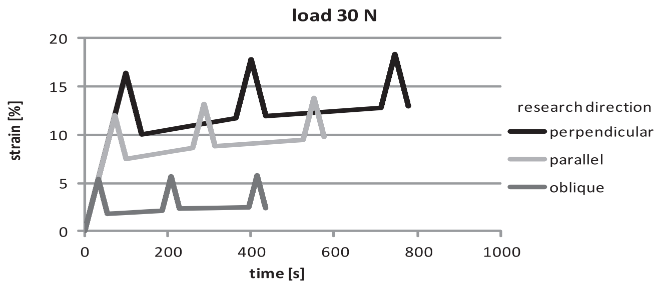

Fig. 11. Examples of strain versus time curves under the load of 30 N

Table 3

Comparison of values of residual strain for tested samples

Load [N]	Loop no.	Residual strain [%]		
		Perpendicular	Parallel	oblique
30	1	10.59±0.79	6.09±1.97	1.45±0.47
	5	12.50±0.78	7.43±1.95	1.90±0.60
	10	13.32±0.48	8.41±1.95	2.01±0.53
65	1	7.44±0.29	11.76±0.82	2.91±0.41
	5	9.50±0.41	14.59±0.27	3.60±0.39
	10	10.41±0.12	16.19±0.21	3.91±0.54
100	1	11.61±1.04	12.36±0.08	6.25±3.49
	5	14.06±0.66	15.05±0.39	7.95±4.39
	10	15.02±0.54	16.57±1.14	8.89±4.58

4. Conclusion

The results confirm that like human skin, pig skin is a highly dissipative material exhibiting non-linear mechanical behavior. Based on the research of the mechanical properties obtained in the uniaxial tensile test and cyclic loading-unloading tests of the skin tissue samples taken in three directions in relation to the swine`s backbone, the huge influence of anisotropy of the skin on its properties can be confirmed. The conducted uniaxial tensile test showed that the best mechanical parameters were obtained for the parallel samples. The lowest values were revealed by the perpendicular samples. Instead, oblique samples medium values of every obtained parameter were achieved. The mechanical parameters of the swine skin are comparable with values describing the human skin [19, 21]. This confirmed that swine skin is a good material for the substitution of human skin in vitro researches.

The test under loading and unloading showed that the skin anisotropy influenced on mechanical hysteresis. At a low load level (30 N) the perpendicular samples obtained the highest value of dissipated energy. But at a higher load level (65 N, 100 N), the highest value of dissipated energy was achieved by parallel samples. At every examined load level for oblique direction of samples taken, the smallest surface area of hysteresis loops was observed. The increase of load values resulted in a higher value of the dissipated energy for all directions of samples taken. The stabilization of the value of energy dissipation between fifth and tenth loop was shown. Similar results were obtained for dog skin by Bismuth et al. [21]. At every examined load level, the first hysteresis loop had a higher surface area than other loops. This tendency was in reasonable agreement with the results obtained by Ehret et al. [22].

Characterization of the mechanical properties of pig skin is important and allows for it to be used as an animal model for human skin disease. Skin hysteresis is especially useful to absorb the energy from high forces that may be experienced during accidental impacts.

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