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Topographic variations of skin biomechanics: Cadaver study

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Abstract

Aim: The skin is a multifunctional organ that covers up the entire surface of the body. Material properties such as hyperelasticity, viscoelasticity and plasticity are very important for the development of new biological materials. The main focus of this study is to investigate the biomechanical properties of the dermis and to examine how these vary according to different body parts.

Materials and Methods: Skin samples were dissected from various parts of the body. All skin samples were tested in uniaxial tension parallel to their long axis. A strength-elongation curve was obtained and the maximum strength and maximum elongation values were determined from this curve for each tensile test performed. Reaction forces and displacements were determined by software.

Results: The results of our study showed a statistically significant difference in the evaluation between the scalp, face, upper and lower extremities for elastic modulus, tensile strength and thickness. It has been observed that the elastic modulus, tensile strength and thickness values vary depending on the topographic region of the body. According to our results, the upper extremity showed the highest elastic modulus among all regions (42.70 ± 8.92 MPa). The highest tensile strength was also measured for the upper extremity skin and its value was determined as 17.72 ± 4.00 MPa.

Conclusion: Data obtained from this study may provide valuable information for modeling purposes, basic data for tissue grafts and comparison of tissue characteristics after head trauma or forensic examinations.

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Introduction

The skin is a multifunctional organ that covers the surface of the body. While maintaining its ability to return to its original status to enable body movement; it must be elastic enough to allow deformations in all directions [1]. The complexity of the skin is due to the fact that it is a multilayered material consisting of three fundamental layers (epidermis, dermis and hypodermis). When considered as a whole including the epidermal, dermal and hypodermal layer; the skin can be defined as anisotropic [2], viscoelastic [3], nonlinear and non-homogeneous [4].

The outermost layer, the epidermis, is important in determining the properties of the skin, such as tensile strength, depending on the size and degree of crosslinking of the collagen. [5]. The fibers are randomly oriented in the skin's construction at rest, and when a load is applied, the fibers run parallel to direction of road. It is thought that initially the elastin fibers are stretched in a linear way and as the applied load increases, the collagen fibers are reoriented to carry a greater load [6]. This occurs in the initial area of the stress-strain curve [4]. As the charge increases, there is an increase in stiffness, and this is known as the stress-hardening effect, in which the fibers stretch and begin to tear until rupture occurs [7]. These biomechanical properties of tissues are effective on the basis of the limit force tests applied in our study.

Material particulars such as viscoelasticity, hyperelasticity and plasticity are important for development of new biological materials. In recent years, many working groups are heading towards a better understanding of the biomechanical features of living materials [8,9]. Although it is substantial to understand tissue defects; it is also important to have information about elastic and viscoelastic features under physiological loading conditions with greater forces. Protocols for evaluating the mechanical properties of human skin tissue will provide a benchmark for creating suitable tissue-designed substitutes [6]. It is intended to produce materials to replace or restore damaged-diseased

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organs. The modified material must mimic the properties of the natural tissue it is intended to replace [10]. Materials must be able to withstand the mechanical forces they would experience when implanted in the defective area to provide the necessary anatomical shape. Therefore, the mechanical properties of the material are vital [11].

The main focus of this study is to investigate the biomechanical properties of the skin and to examine how these diversities according to different body parts. The aim of this research is to examine the elastic features of topographically different skins in cadavers using biomechanical techniques, to compare their elastic behavior and to test the mechanical similarity assumptions. The data obtained in this study can be used for biomechanical modeling purposes and can provide basic data in the biosynthesis of similar materials.

The mechanical characterization of soft biological tissues aims to determine anisotropic, nonlinear and loading history-dependent material response. This theorem was adapted to the skin which is one of the human soft tissues in our study. In this context; it was thought that the biomechanical properties of the derma such as maximum force, elasticity modulus, tensile strength, maximum elongation, and maximum strain may cause topographic differences. It was aimed to determine the biomechanical behavioral differences of the scalp, face, upper extremity and lower extremity skins by using tissues taken from human cadavers in our study. Mechanical characterization of soft biological tissues aims to determine the anisotropic, nonlinear and loading history dependent material response. In this study, it was aimed to find differences in mechanical behavior of scalp, face and extremity skins by using tissues taken from formaldehyde fixed cadavers. Mechanical differences in the skin thickness, maximum force, elastic modulus, tensile strength, maximum elongation, maximum strain values of the skin from different topographical regions of the body that we determined in our study; need to be considered in clinical studies such as skin aesthetics, skin surgical procedures and dermatological diagnosis and treatments.

Materials and Methods

Ethical approval of the study was obtained from Non-Invasive Clinical Research Ethics Committee, Kocaeli University (2019/19). The sample size of our study was limited by the number of cadavers available in Kocaeli Medical Faculty. The average age was 77.8 ± 13.12; 8 male and 2 female cadavers were included.

Preparation of skin samples

Skin samples were dissected separately from the regio brachii anterior in the upper extremity (Figure 1.c) and from the regio femoris anterior in the lower extremity (Figure 1.d). Samples were taken from regio occipitalis (Figure 1.b.) for scalp tissues and regio buccalis (Figure 1.a) for facial skin tissues. Samples were marked in the same way with a concave plastic guide to ensure the ruptures were centered and for the standard. Skin thicknesses were measured using a Vernier caliper. Buffered formaldehyde (10%) was used during cadaver perfusion to protect protein degradation. In addition, cadavers are kept in formaldehyde tanks, which are tried to be kept constant between 6-7%.

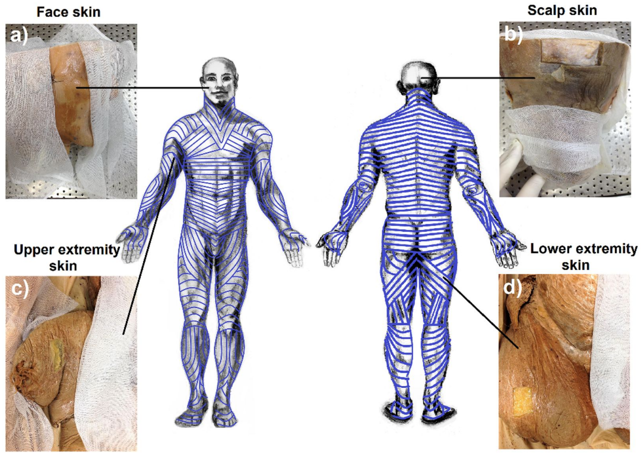

Figure 1. Skin tension lines (Langer's lines) and skin samples taken from different topographical regions; a) Face skin sample from regio buccalis b) Scalp skin sample from regio occipitalis c) Upper extremity skin sample from regio brachii anterior d) Lower extremity skin sample from regio femoris anterior.

Biomechanical tensile test

All skin samples were tested at room temperature (22°C), in uniaxial tension parallel to their long axis. Tensile tests were performed for the skin samples and the charge was measured with a 20 kN load cell. A preload stress of 7-9 N was applied, representing approximately 5% of the maximum load when the displacement was 0 mm, to release the skin samples from their relaxed state. For the tensile test, the samples were tested at a displacement speed of 10 mm/min until rupture. A decrease of at least 30% of the maximum force was considered as rupture. A strength-elongation curve was obtained and the maximum strength and maximum elongation values were determined from this curve for each tensile test performed. Reaction forces and displacements were determined by software. Nominal stress and strain graphs were drawn for each sample and the ultimate tensile strength, elastic modulus and maximum elongation properties were defined.

Calculation of biomechanical parameters

A stress-strain curve was obtained for each tensile test performed. The ratio of strain versus nominal stress was determined for each sample. The 'nominal stress' was calculated by dividing the force by the undeformed cross-sectional domain (width x thickness) of samples. The strain was calculated by dividing the current length of the sample by the initial length ($\Delta L/L$). In this way, graphs of nominal stress (MPa) (y-axis) versus strain (mm/mm) (x-axis) were drawn and final tensile, strength, elastic modulus properties were defined from these curves. By determining the slope (m) in the region where the curve is linear, the elasticity modulus value was obtained for each sample.

Statistical analysis

Statistical analysis was performed using SPSS.20 (IBM SPSS Inc., Chicago, IL, USA) package program. The data was obtained by measuring the maximum force, elasticity modulus, tensile strength, maximum elongation and maximum strain properties of the skin. Convenience sampling which is a non-probable method was used in study. In the comparison of the data of the samples, non-parametric Kruskal Wallis test was used because the data did not show normal distribution except for maximum elongation and maximum strain. Anova analysis was performed for the normally distributed maximum elongation and maximum strain data. P values of 0.05 or less were considered statistically significant. Correlation analysis was performed to understand the relationship between maximum force, elastic modulus, tensile strength, maximum elongation, maximum strain and thickness.

Results

The averages of the thicknesses of the skin samples and the averages, standard deviations, minimum and maximum values of the biomechanical parameters obtained from the force-elongation and stress-strain graphs are shown in Table 1.

Typical stress-strain plots show the viscoelasticity of skin tissue after tensile testing (Figure 2). The highest tensile strength was measured for the upper extremity skin and its value was determined as 17.72 ± 4.00 MPa. The tensile strength was determined as 10.10 ±3.17 MPa for the lower extremities, 5.09 ± 3.10 MPa for the scalp and 3.84 ±2.02 MPa for the facial skin.

As can be seen in Table 2; it was determined that there was a significant difference in the evaluations made between the groups for the elastic modulus, tensile strength and thickness. A significant difference was found between the 'elastic modulus' of scalp-upper extremity skins (p=0.011) and facial-upper extremity (p=0.024) skins ($p<0.05$). It was found that there was a significant difference between the 'tensile strength' of scalp-upper extremity (p=0.009)

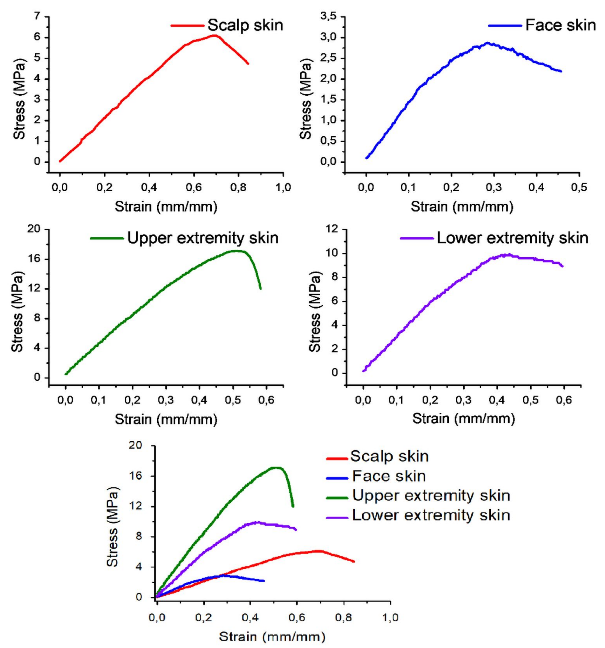

Figure 2. Stress-strain curves for scalp, face, upper extremity, and lower extremity skins.

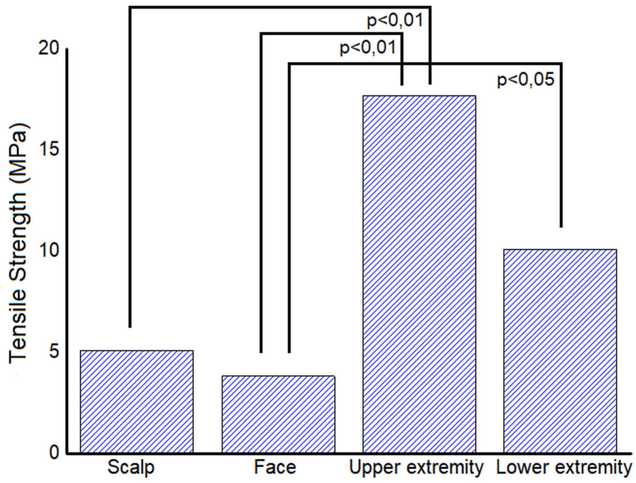

Figure 3. Tensile strength values for skin samples.

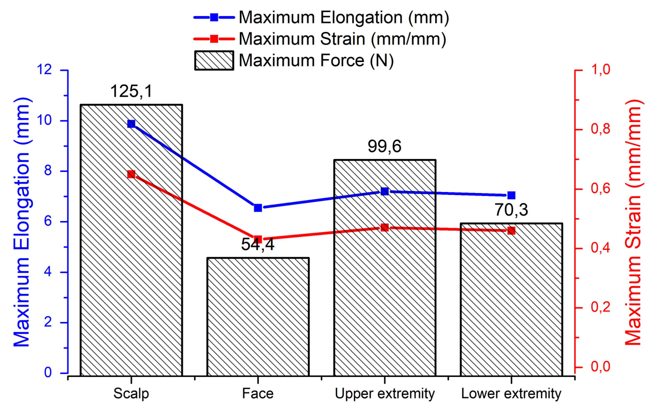

Figure 4. Comparison of maximum force, maximum elongation and maximum strain values for skin samples.

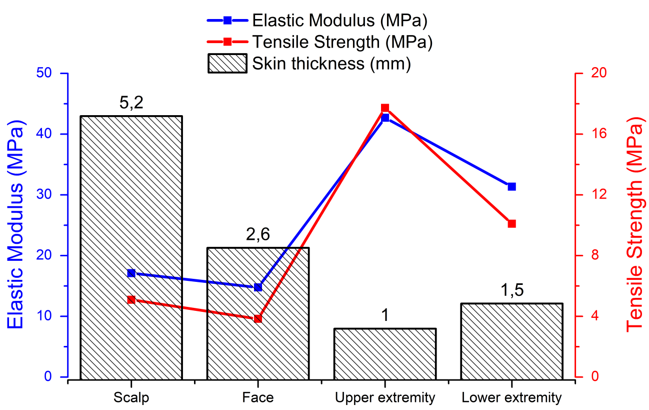

Figure 5. Comparison of elastic modulus, tensile strength, and skin thickness values for skin samples.

Table 1. Biomechanical parameters of skin samples (Mean ±Standard Deviation (Minimum value; Maximum value)).

	Scalp skin	Face skin	Upper extremity skin	Lower extremity skin
Biomechanical	Mean ±SD	Mean ±SD	Mean ±SD	Mean ±SD
Parameters of Skin	(Min; Max)	(Min; Max)	(Min; Max)	(Min; Max)
Maximum Force	125.10 ±95.30	54.40 ±45.70	99.60 ±27.70	70.30 ±19.20
(N)	(21; 355)	(19; 160)	(69; 123)	(53; 91)
Elastic Modulus	17.11 ±17.40	14.77 ±16.52	42.70 ±8.92	31.33 ±1.12
(MPa)	(5.90; 59)	(6.20; 23.80)	(37.50; 53)	(30.50; 32.60)
Tensile Strength	5.09 ±3.10	3.84 ±2.02	17.72 ±4.00	10.10 ±3.17
(MPa)	(1.05; 12.10)	(1.40; 8)	(13.80; 21.80)	(6.70; 13)
Maximum Elongation	9.87 ±7.29	6.55 ±2.94	7.20 ±1.98	7.04 ±3.41
(mm)	(1.77; 22.95)	(2.26; 11.09)	(5.01; 8.86)	(3.44; 10.23)
Maksimum Strain	0.65 ±0.48	0.43 ±0.19	0.47 ±0.13	0.46 ±0.23
(mm/mm)	(0.11; 1.53)	(0.15; 0.73)	(0.33; 0.59)	(0.22; 0.68)
Skin Thickness	5.20 ±2.39	2.60 ±1.17	1.00 ±0.00	1.50 ±0.58
(mm)	(2; 9)	(1; 4)	(1; 1)	(1; 2)

Table 2. Comparison of P-values for elastic modulus, tensile strength, and skin thickness between groups.

Biomechanical Parameters	Skin Samples	P value
Elastic Modulus	Scalp skin - Face skin	0.718
	Scalp skin - Lower extremity skin	0.063
	Scalp skin - Upper extremity skin	0.011
	Face skin - Lower extremity skin	0.113
	Face skin - Upper ekstremity skin	0.024
	Lower ekstremity skin - Upper ekstremity skin	0.579
Elastic Modulus	Scalp skin - Face skin	0.458
	Scalp skin - Lower extremity skin	0.088
	Scalp skin - Upper extremity skin	0.009
	Face skin - Lower extremity skin	0.028
	Face skin - Upper ekstremity skin	0.002
	Lower ekstremity skin - Upper ekstremity skin	0.471
Skin Thickness	Scalp skin - Face skin	0.028
	Scalp skin - Lower extremity skin	0.005
	Scalp skin - Upper extremity skin	p<0.001
	Face skin - Lower extremity skin	0.251
	Face skin - Upper ekstremity skin	0.067
	Lower ekstremity skin - Upper ekstremity skin	0.567

skins, facial-upper extremity ($p=0.002$) skins and facial-lower extremity ($p=0.028$) skins ($p<0.05$), (Figure 3).

According to the correlation analysis (Table 3); there is a statistically significant ($p<0.01$), moderate-positive correlation between maximum force and tensile strength. There is a statistically significant ($p=0.01$) strong positive correlation between maximum force and maximum elongation. According to the data obtained, it is seen that the maximum elongation increases as the maximum force increases (Figure 4).

It was determined a statistically significant ($p<0.01$) and strong positive correlation between the elastic modulus and tensile strength. A statistically significant ($p<0.05$), moderate negative correlation, was found between the elastic modulus and the maximum elongation. A statistically significant ($p<0.05$) and moderate negative correlation was found between the elastic modulus and the maximum strain. It was determined that statistically significant ($p<0.01$) and strong negative correlation between the of elastic modulus and skin thickness. In addition, a statistically significant ($p<0.05$) and moderately negative correlation was found between tensile strength and skin thickness (Figure 5; Table 3).

A statistically significant ($p<0.05$) and weak positive correlation was found between maximum elongation and skin thickness. It was determined that there was a statistically significant ($p=0.05$) and weak positive correlation between maximum strain and skin thickness, (Table 3).

Discussion

Understanding the biomechanical properties of skin can help predict its response to various deformations [12]. While the mechanical properties of the skin tissue are evaluated using in vivo examinations; Tensile testing protocols can be used to understand the biomechanics of excised skin [10]. Since boundary conditions for such tests can be defined, they can provide information for modeling stress-strain relationships [13]. By the way, it should be noted that embalming cadavers with formaldehyde inflects the biomechanical properties of the skin. However, exposing all tissues to similar chemical embalming is important to understand the limitations of the model and to evaluate how realistic it is. Therefore; testing the mechanical behavior and numerical limits can contribute to the literature in the related field.

In terms of elastic modulus, tensile strength and thickness; there was a significant difference in between the scalp, face, upper extremity and lower extremity (Table 2). Since the skin plays various roles in different parts of the body, there may be changes in its structure and mechanical behavior that will lead to differences [8]. Contact with the external environment and use according to the purpose can cause

Table 3. Correlation analysis of biomechanical parameters.

		Maximum Force	Elastic Modulus	Tensile Strength	Maximum Elongation	Maximum Strain	Skin Thickness
Maximum Force	Correlation coefficient	1	-0.04	0.562	0.62	0.621	0.403
	Significance	.	0.849	0.003	0.001	0.001	0.046
Elastic Modulus	Correlation coefficient	-0.04	1	0.653	-0.452	-0.445	-0.772
	Significance	0.849	.	<0.001	0.023	0.026	<0.001
Tensile Strength	Correlation coefficient	0.562	0.653	1	0.229	0.237	-0.489
	Significance	0.003	<0.001	.	0.271	0.254	0.013
Maximum Elongation	Correlation coefficient	0.62	-0.452	0.229	1	1	0.404
	Significance	0.001	0.023	0.271	.	<0.001	0.045
Maximum Strain	Correlation coefficient	0.621	-0.445	0.237	1	1	0.396
	Significance	0.001	0.026	0.254	<0.001	.	0.05
Skin Thickness	Correlation coefficient	0.403	-0.772	-0.489	0.404	0.396	1
	Significance	0.046	<0.001	0.013	0.045	0.05	.

lifelong changes in the mechanical behavior of the skin [6]. Previous studies have shown that the characteristics of the skin depend on the body region in which it is located [14]. For instance, it was noted that the skin on the forehead was thicker, firmer and less elastic than on the ventral surface of the forearm. It has been stated that the determination of the biomechanical properties of the skin according to the regions may be important in terms of diagnosis and treatment [15]. Griffin et al. [10] similarly showed that the forehead region has a thicker skin structure than the forearm; but the elastic modulus of the forehead is lower than the forearm, emphasizing the differences in regional skin mechanics. In our study, the highest elastic modulus was observed in the upper extremity skin. (42.70 ±8.92 MPa). The facial skin has the lowest elastic modulus among all regions (14.77 ±6.52 MPa). In this case, the upper extremity skin undergoes less elastic deformation under force than the facial skin. The highest tensile strength was also measured for the upper extremity skin (17.72 ±4.00 MPa), while the lowest tensile strength was found for the facial skin (3.84 ±2.02 MPa). The upper extremity skin showed the highest resistance to force; facial skin exhibited the least resistance for the tensile test. In our study, it is seen that upper and lower extremity skins have better biomechanical properties in terms of tensile strength/elasticity compared to other regions. Scalp, face, upper and lower extremity skins were used in this study; restricting the regional categorization to the regio occipitalis, regio buccalis, regio brachii anterior, and regio femoris anterior.

It is known that in the intrauterine development of the skin, the scalp develops earlier than other parts of the body [16]. It was measured that the scalp thickness was higher than the other regions in our study. In the correlation analysis, it is seen that the increase in skin thickness causes a decrease in the modulus of elasticity (Figure 5).
Collagen is the main component that provides the skin's resistance to stretching. Elastin fibers play a role in maintaining elasticity, but have little effect against deformation and tearing of the skin [17]. The mechanical behavior of the skin depends on the structure and density of collagen fibers in the dermal layer [5]. The response of the skin is related to the collagen content and it has been stated that collagen is mainly responsible for the tensile strength of the skin [18]. Various studies on animal skins have shown that the denser the collagen matrix, the higher the ultimate tensile strength [19]. Biomechanical measurement of skin by in vivo techniques has not been fully standardized. In vitro biomechanical tests similar to our study, provides comparable and reproducible methods for skin [20]. When examining the structures that affect the biomechanical values in the examination of dissected human skin tissues; it has been shown that a denser collagen matrix in human skin leads to an increase in the modulus of elasticity at high strain rate [21]. Therewithal, it has been pointed out that the change in skin thickness with aging is due to the molecular orientation of collagen bundles rather than a decrease in collagen content, which is confirmed by experimental results [22].

It is seen that the scalp has a thicker skin structure than the other sampled areas in the study. In our statistical analysis; it was found that there is a negative relationship between skin thickness and modulus of elasticity-tensile strength. This result is consistent with the fact that the elasticity modulus and tensile strength of the scalp are lower than the thinner extremity skins. There is a limited number of studies in the literature investigating the mechanical properties of the human scalp [23].

These studies have shown that the scalp under tension responds similarly to skin in other parts of the body, that is, when exposed to low-dimensional forces (5-15 N), the skin responds in a linear form and conforms. As the dimensional forces increased, there was a steady increase in the elastic modulus of the scalp. It has been suggested that this phenomenon is due to the presence of elastin fibers at low dimensional forces [24]. Such studies on skin biomechanics can increase the success rate in tissue engineering by highlighting the tensiometric properties of tissues. It can also contribute to better planning a reconstructive or aesthetic procedure on the skin in the clinical sciences.

Conclusion

Understanding the mechanical response of soft biological tissues is important in the development of computational tools to enable physically-based simulations in realistic applications in the medical area. This includes the planning of surgical interventions, the design of biocompatible prosthetic devices-implants and the quantitative evaluation of damaged tissues for faster healing. Our study aims to determine the mechanical characterization, anisotropic, nonlinear and material response based on loading history. The results of our study showed differences in the evaluation between the scalp, face, upper and lower extremities for elastic modulus, tensile strength and thickness. Statistically significant differences were found in elastic modulus, tensile strength and thickness values between topographic regions. According to our results, the upper extremity showed the highest elastic modulus among all regions. The highest tensile strength was also measured for the upper extremity skin and its value was determined. With this study, it has been shown that there are regional differences in the mechanical properties of different regions of the skin. Results related to these regions are indicated by the differences in elastic modulus, tensile strength and thickness values for different topographic regions of the skin, emphasizing the heterogeneity of human skin.

Our study demonstrates simple mechanical testing protocols for evaluating human skin tissue. Implementation of these protocols; it enables tissue engineered constructs to better mimic natural tissue and provides basic information about the biomechanical properties of tissues. The results from this study can supply valuable information for modeling purposes. Also, it can also contribute to the comparison of baseline data for tissue grafts and tissue properties after head injury or forensic examination.

Ethics approval

The study was obtained from Non-Invasive Clinical Research Ethics Committee, Kocaeli University (2019/19).

References

1. Ross MH, Pawlina W. Histology. Lippincott Williams & Wilkins; 2006. 934 s.
2. Stark HL. Directional variations in the extensibility of human skin. Br J Plast Surg. April 1977;30(2):105-14.
3. Pereira JM, Mansour JM, Davis BR. Dynamic measurement of the viscoelastic properties of skin. J Biomech. 1991;24(2):157-62.
4. Brown IA. A scanning electron microscope study of the effects of uniaxial tension on human skin. Br J Dermatol. October 1973;89(4):383-93.
5. Chanda A. Biomechanical Modeling of Human Skin Tissue Surrogates. Biomimetics (Basel). 23 July 2018;3(3):18.
6. Pawlaczyk M, Lelonkiewicz M, Wieczorowski M. Age-dependent biomechanical properties of the skin. Postepy Dermatol Alergol. October 2013;30(5):302-6.
7. Edsberg LE, Mates RE, Baier RE, Lauren M. Mechanical characteristics of human skin subjected to static versus cyclic normal pressures. J Rehabil Res Dev. April 1999;36(2):133-41.
8. Callejas A, Melchor J, Faris IH, Rus G. Hyperelastic Ex Vivo Cervical Tissue Mechanical Characterization. Sensors (Basel). 05 August 2020;20(16):4362.
9. Müller SJ, Weigl F, Bezold C, Bächer C, Albrecht K, Gekle S. A hyperelastic model for simulating cells in flow. Biomech Model Mechanobiol. April 2021;20(2):509-20.
10. Griffin M, Premakumar Y, Seifalian A, Butler PE, Szarko M. Biomechanical Characterization of Human Soft Tissues Using Indentation and Tensile Testing. J Vis Exp. 13 December 2016;(118):54872.
11. Nimeskern L, van Osch GJVM, Müller R, Stok KS. Quantitative evaluation of mechanical properties in tissue-engineered auricular cartilage. Tissue Eng Part B Rev. February 2014;20(1):17-27.
12. Savoji H, Godau B, Hassani MS, Akbari M. Skin Tissue Substitutes and Biomaterial Risk Assessment and Testing. Front Bioeng Biotechnol. 26 July 2018;6:86.
13. Everett JS, Sommers MS. Skin Viscoelasticity: Physiologic Mechanisms, Measurement Issues, and Application to Nursing Science. Biol Res Nurs. July 2013;15(3):338-46.
14. Sugihara T, Ohura T, Homma K, Igawa HH. The extensibility in human skin: variation according to age and site. Br J Plast Surg. September 1991;44(6):418-22.
15. Diridollou S, Black D, Lagarde JM, Gall Y, Berson M, Vabre V, vd. Sex- and site-dependent variations in the thickness and mechanical properties of human skin in vivo. Int J Cosmet Sci. December 2000;22(6):421-35.
16. Holbrook KA, Odland GF. Regional development of the human epidermis in the first trimester embryo and the second trimester fetus (ages related to the timing of amniocentesis and fetal biopsy). J Invest Dermatol. March 1980;74(3):161-8.
17. Ma L, Gao C, Mao Z, Zhou J, Shen J, Hu X, vd. Collagen/chitosan porous scaffolds with improved biostability for skin tissue engineering. Biomaterials. November 2003;24(26):4833-41.
18. Oxlund H, Andreassen TT. The roles of hyaluronic acid, collagen and elastin in the mechanical properties of connective tissues. J Anat. December 1980;131(Pt 4):611-20.
19. Lynch B, Bonod-Bidaud C, Ducourthial G, Affagard JS, Bancelin S, Psilodimitrakopoulos S, vd. How aging impacts skin biomechanics: a multiscale study in mice. Sci Rep. 23 October 2017;7:13750.
20. Edwards C, Marks R. Evaluation of biomechanical properties of human skin. Clin Dermatol. August 1995;13(4):375-80.
21. Baumann L, Bernstein EF, Weiss AS, Bates D, Humphrey S, Silberberg M, vd. Clinical Relevance of Elastin in the Structure and Function of Skin. Aesthet Surg J Open Forum. 14 May 2021;3(3):ojab019.
22. Ribeiro JF, dos Anjos EHM, Mello MLS, de Campos Vidal B. Skin Collagen Fiber Molecular Order: A Pattern of Distributional Fiber Orientation as Assessed by Optical Anisotropy and Image Analysis. PLoS One. 18 January 2013;8(1):e54724.
23. Gambarotta L, Massabò R, Morbiducci R, Raposio E, Santi P. In vivo experimental testing and model identification of human scalp skin. J Biomech. November 2005;38(11):2237-47.
24. Raposio E, Nordström RE. Biomechanical properties of scalp flaps and their correlations to reconstructive and aesthetic surgery procedures. Skin Res Technol. May 1998;4(2):94-8.