TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special IV, August, 2024

INSIGHTS INTO THE YOUNG'S MODULUS OF HUMAN FINGER SKIN: EVALUATING CONTACT AREA AND INDENTATION CREEP BEHAVIOUR

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Abstract: *The study focuses on the properties of human finger skin, utilising the CETR-UMT2 setup to enhance human-machine interactions and ergonomic designs. The research comprises two main sections: measuring the contact area with cylindrical bronze indenters of varying diameters under different forces and investigating indentation creep behaviour to calculate Young's Modulus. The findings show a non-linear response of skin stiffness to increased forces, supporting previous studies. The second part, employing a Hertzian contact model, determines Young's Modulus of finger skin to be approximately 310 kPa, in line with existing literature. The study concludes with a direct relationship between skin deformation and applied force, and an inverse relationship with indenter diameter.*

Key words: *human skin, contact area measurement, hertzian contact model, young's modulus.*

1. INTRODUCTION

Skin is a complex, multifunctional organ that covers the entire surface of the body. To facilitate body movements, the skin must be flexible enough to undergo large deformations in all directions and yet return to its original shape. These functions require a wide range of mechanical properties. The skin's structure can be divided into three layers. Starting from the outside, the skin can be divided into the epidermis, dermis, and hypodermis. The average total surface area of the skin is 1.8 m^2, with an average thickness of 1.2 mm and a weight of 4.2 kg. The ratio of surface area to thickness is about 150,000 [1]. Mosteller calculates the skin's area as approximately 2 m^2 [2]. Richard revises previous measurements to 25 m^2, justifying his calculation by the fact that the skin is not a flat surface but contains structures such as hair follicles or sweat gland openings that significantly increase the epithelial surface [3]. The anatomical structure of the human fingertip is presented in Fig. 1.

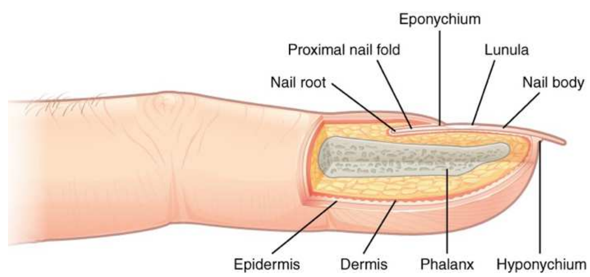

Fig. 1. Anatomical Structure of the Human Fingertip [4]

The main motivation of the presented study is to contribute to enhancing the design of devices that interact with human skin by providing a detailed understanding of skin's mechanical behavior under various forces.

2. EXPERIMENTAL SETUP

Experimental models were developed for the CETR (Bruker) UMT-2 stand, a stand that allows the evaluation of force and positioning at very low speeds. The CETR UMT-2 Microtribometer (Universal Mechanical Tester) is one of the most used tribometers both in the academic environment and in the industrial sector. It can measure, with the help of modular sensors, forces between 1mN and 2000N, with a resolution between 10μN and 100mN. The experimental setup is depicted in Fig. 2, below.

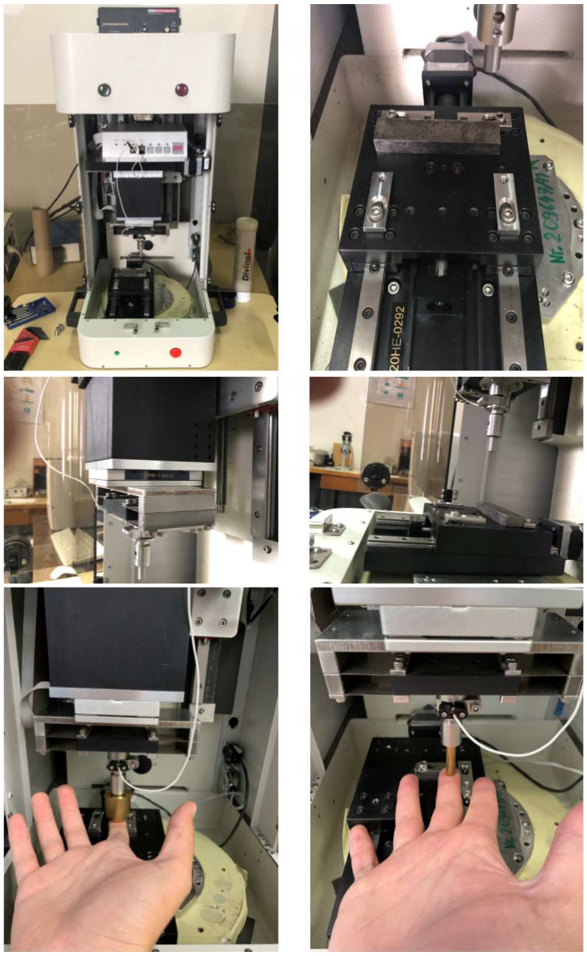

Fig. 2. Experimental setup

The finger was fixed on the translation table of the tribometer to minimise measurement errors caused by body movement or potential reactions to the machine's movements during the measurement.

All experiments were carried out at an ambient temperature of 21±2°C, with a relative humidity of 55±5%, on a single male subject aged 28 years. Before testing, the subject was acclimatized, and before each test, the hands were washed with soap and water, and the tested finger was wiped with medicinal alcohol. At least three relevant measurements were performed. The statistical variation coefficient, defined as the ratio between the root mean square deviation and the average of the values, is under 10%.

3. EXPERIMENTAL SETUP AND CONTACT AREA DETERMINATION

To determine the contact area between the finger and a rigid indenter, the CETR-UMT2 experimental stand was used. The contact area was determined with the help of three cylindrical bronze indenters with spherical ends and diameters of 8 mm, 12 mm, and 28 mm at three different forces (1.5 N, 3 N, and 5 N). The testing method was divided into five steps. The first step involved dipping the indenter in ink and wiping off the excess. The second step involved loading the contact area from 0N to the tested force over a duration of 10 seconds. For the third step, the force was maintained for a period of 5 seconds, and the fourth step involved retracting the indenter to the initial starting height. The last step consisted of the actual measurement of the contact area with a calliper, the contact area was presumed to be an ellipse. Below, in Fig. 3, the method is presented.

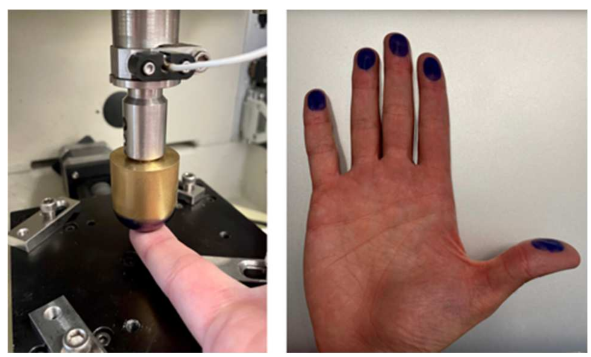

Fig. 3. Method to measure contact area.

The data were processed with the help of the native CETR-UMT Test Viewer postprocessor of the experimental rig and exported in text format to be manipulated using Excel.

Table 1

Contact Area values for human fingers.

		Contact Area for indenters (mm^2)		
Finger	**Force (N)**	**8 mm**	**12 mm**	**28 mm**
Thumb	1.5	51.60	90.48	163.58
	3	58.94	102.10	186.92
	5	65.69	109.42	205.98
Index Finger	1.5	44.67	78.46	125.54
	3	52.61	90.28	151.31
	5	58.61	92.94	169.16
Middle Finger	1.5	49.62	80.93	136.50
	3	56.06	88.97	156.62

	5	61.42	94.86	172.38
Ring Finger	1.5	47.12	83.88	124.05
	3	54.66	93.02	144.26
	5	59.89	96.25	157.24
Little Finger	1.5	43.50	75.34	107.42
	3	51.33	81.65	122.96
	5	56.55	86.55	138.04

The data are presented in graphic form in Fig. 4-7, below. In Fig. 4, the experimental data are compiled to compare the evolution of the contact area for all indenters. It can be observed how the obtained values are more closely grouped as the diameter of the indenter used is smaller.

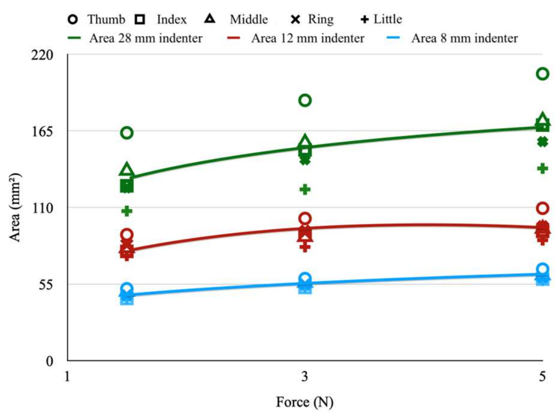

Fig. 4. Contact Area for all three indenters.

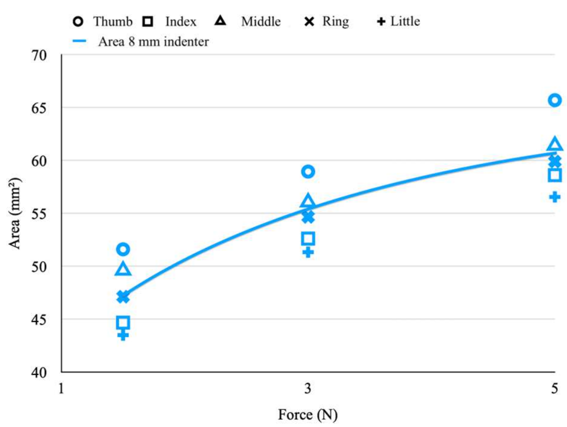

Fig. 5. Contact Area for 8 mm indenter.

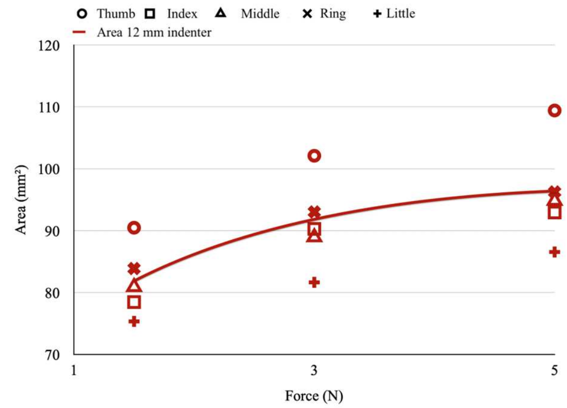

Fig. 6. Contact Area for 12 mm indenter.

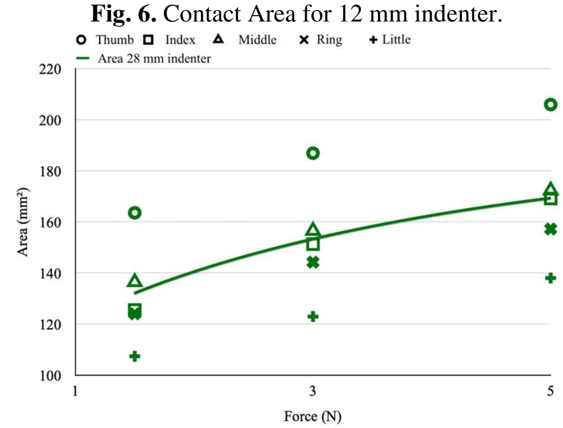

Fig. 7. Contact Area for 28 mm indenter.

From the measurements, it can be concluded that the contact area is directly proportional to the force applied, but the increase is not linear. The variation of the contact area in relation to the applied force observed in experiments is correlated with the conclusions obtained by [5], which states that the mechanical response of human skin to an external force is nonlinear, and the stiffness of the contact increases with the increase of the applied force. Figure 8 exemplifies the loading phases at the skin level.

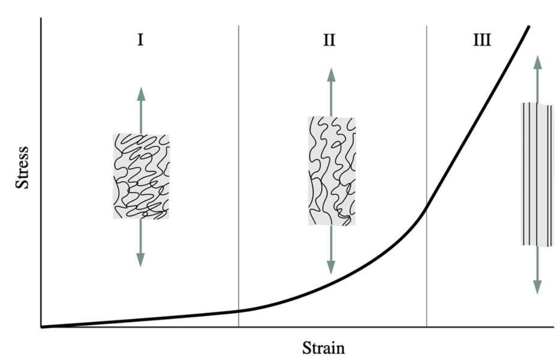

Fig. 8. Schematic diagram of a stress-strain curve for skin. [6]

The stress-strain behavior of many soft tissues, as depicted, markedly differs from that of hard tissues or other engineering materials. Furthermore, Figure 8 illustrates the process of collagen fibers aligning themselves in response to the increase in stress levels.

4. EXPERIMENTAL STUDY FOR MEASURING CREEP BY INDENTATION AND DETERMINING YOUNG'S MODULUS FOR HUMAN FINGER SKIN

Before developing a theoretical model to describe a tissue, it is beneficial to determine the general mechanical properties of that tissue. Due to the fibres within the tissue that tend to have preferred directions, depending on the part of the body where experiments are conducted, soft tissues exhibit predominantly anisotropic behaviour. The mechanical behaviour of human skin can be measured by evaluating the skin's response to various applied forces through tests such as stretching or tensile testing, applying normal loads on the skin or indentation testing, suction or aspiration tests, or torsion tests. To determine the creep characteristic of the skin at the level of human fingers, a series of tests were conducted using the CETR stand. The tests conducted in the experiment used the indentation method and were performed on a single subject, on all fingers of one hand, using three cylindrical bronze indenters with spherical ends with diameters of 8 mm, 12 mm, and 28 mm at two different forces (3N and 5N). The indenters can be considered perfectly rigid in relation to human skin. The tests were carried out in 3 steps. The first step consisted of lowering the indenter and loading the contact over a period of 30 seconds to the desired force, the contact detection force was set at 0.5 N, which is also the actual starting point for recording measurements. The second step involved maintaining the force constant for a period of 30 or 120 seconds with recording the vertical position of the indenter, and the third step consisted of unloading the contact over a period of 30 seconds and returning to the initial position.

The graph below presents the three studied phases of the creep phenomenon and are representative of all the studied values. The left side of Figure 9, below, shows the loading phase of the contact between the human finger and the rigid indenter. An increase in stiffness with loading can be observed. In the contact initiation phase with loads up to 1 N (approximately the first 5 seconds), (phase marked as I in Figure 8), large deformations occur in relation to the applied force, the tissue has a linear mechanical response, and the elastin fibres within the skin have not yet stretched enough to bear the applied load. In the next phase of loading with loads between 1 and 2 N (approximately the 5-15 second interval from the start of the trial) (marked as II in Figure 8), it can be observed how the elastin fibres begin to progressively take on the load, this being the main reason for the nonlinearity of the stress-strain relationship. In the last phase of loading, a return to a linear character of the stress-strain relationship can be observed, a phase in which the fibres that make up the skin are sufficiently stretched, and the material becomes progressively more rigid.

For determining the equivalent elasticity modulus for human finger skin, the classical Hertzian sphere-sphere contact model was chosen. The elasticity modulus for bronze was set at 100 GPa. Poisson's coefficients of 0.31 for bronze, according to the material datasheet, and 0.5 for skin [7] were selected; typical values for biological materials range between 0.25 and 0.85 [8], [9]. A Poisson ratio of 0.5 is characteristic of incompressible materials, indicating that the material does not change volume when subjected to mechanical stress. In the context of human skin, which is largely composed of water and behaves similarly to an incompressible material, assuming a Poisson ratio of 0.5 means that during the indentation tests, the skin deforms primarily through shape change rather than volume change.

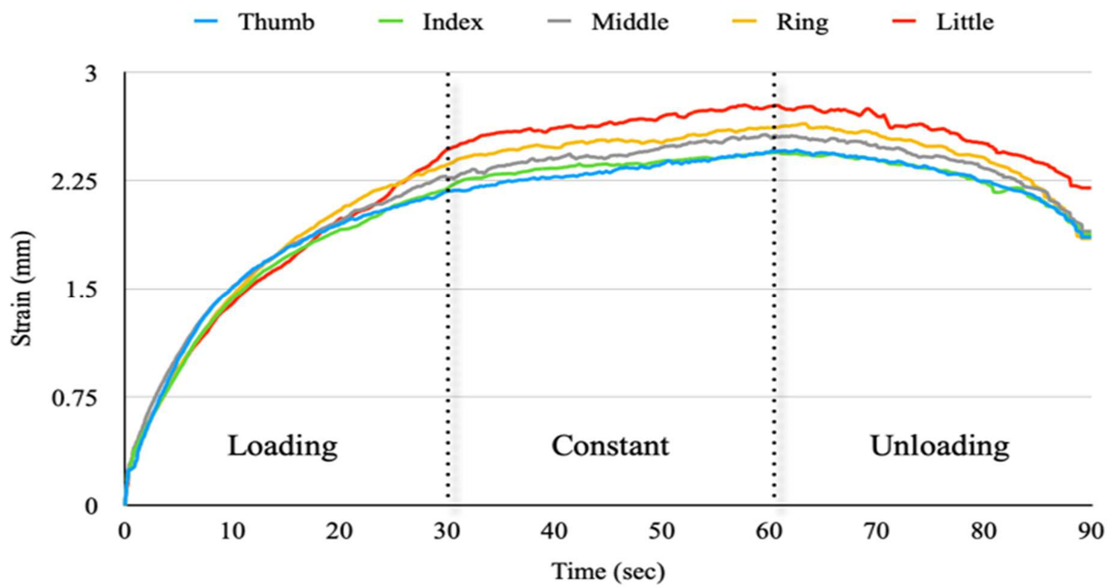

Fig. 9. Representative Complete Cycle — 8mm Indenter, 3N Force.

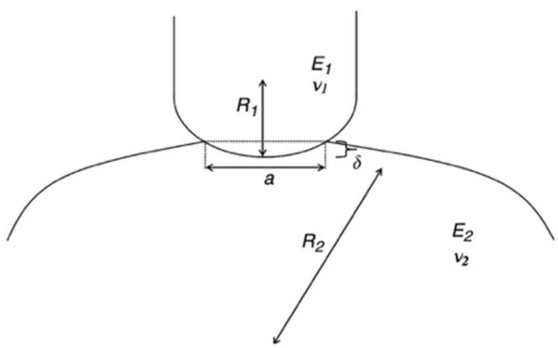

Fig. 10. Schematic Representation of the Model Used for Sphere-Sphere Type Contact Between the Indenter (Radius R_1, Young's Modulus E_1, and Poisson's Coefficient ν_1) and the Human Finger (Radius R_2, Young's Modulus E_2, and Poisson's Coefficient ν_2)

In Figure 11, below, the elasticity modulus calculated using Equation 1, below, for all five fingers of a hand, from a loading force of 0.5 N to 3 N, the loading being carried out over a period of 30 seconds, is presented.

$$\frac{1}{E_{equivalent}} = \frac{1-\nu_{indenter}^2}{E_{indenter}} + \frac{1-\nu_{skin}^2}{E_{skin}} \quad (1)$$

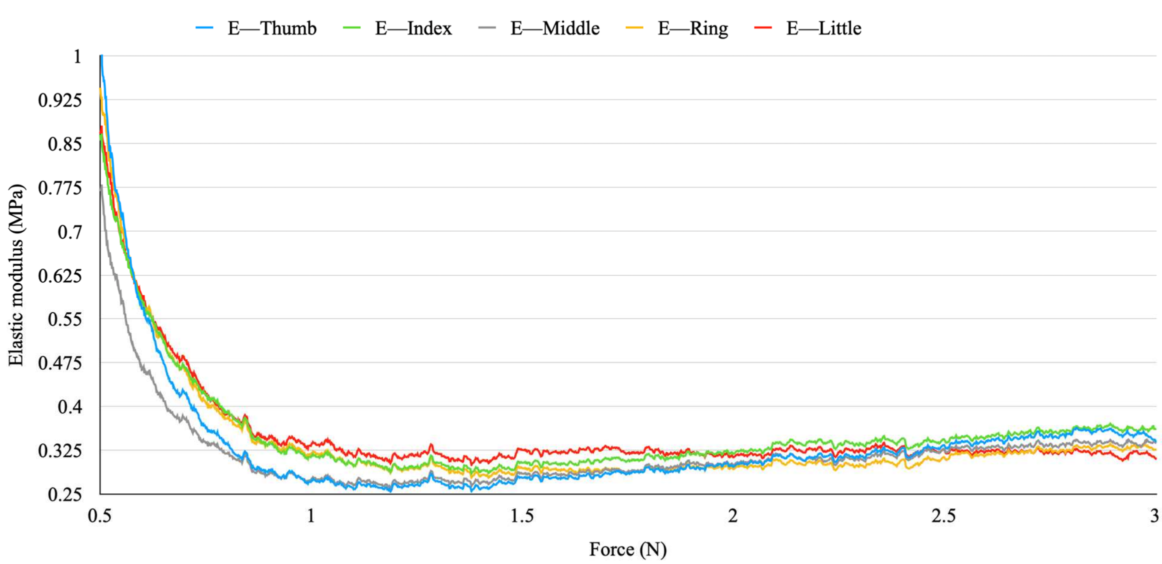

Fig. 11. Elasticity Modulus Calculated for Human Finger Skin — 8mm Indenter.

An average value of 310 kPa was recorded after the contact stabilised. In the first phase, from 0.5 to 1 N, an initial elasticity modulus value around 1 MPa can be observed. The calculated values for the presented experiments are close to those shown in Table 3, In Vivo Measurements of Young's Modulus. The differences are caused by the testing method and the applied force. The challenge in accurately measuring the elasticity modulus lies in the fact that the skin is attached to the substrate, and there is no possibility to remove the substrate effects in in vivo testing. In the literature, to test and evaluate the skin alone, methods have been tried both to use as small a force as possible (in the order of millinewtons) with very small diameter indenters (microindentation), with results for the elasticity modulus between 1 and 2 MPa [10], as well as larger diameters of indenters (4-16 mm) with results between 70 and 330 kPa [11], values very close to those calculated for the experiments presented above. The average values for the other experiments performed are found in Table 2 below. It can be observed that the calculated values are relatively closely grouped (310-351 kPa) and do not differ much in relation to the applied force or the diameter of the indenter. The variation can be explained by the difference between the experimental values obtained for the penetration depth of the indenter relative to its diameter.

Table 2

Calculated Values of the Elasticity Modulus

Indenter diameter (mm)	Force (N)	Young's Modulus (kPa)
8	3	310
	5	314
14	3	326
	5	329
28	3	338
	5	351

Table 3

In Vivo Measurements of Young's Modulus

Author	Young's Modulus	Location	Measurement technique	Other data
[12]	11.1-20 kPa	Forearm/leg	Indenter (20 mm)	
[13]	0.42 MPa	Forearm	Torsion (25 mm)	Young skin
	0.85 MPa			Old skin
	2.1 MPa	Back		Stratum Corneum
[14]	0.13-0.17 MPa	Forearm	Suction (2 mm)	
	0.20-0.32 MPa	Forehead		
[15]	0.153 MPa	Forearm	Suction (6 mm)	
[16]	0.02-0.1 MPa	Forearm	Torsion (8,7 mm)	
[17]	18-57 MPa	Forearm	Suction	
[18]	1.1-1.32 MPa	Forearm	Torsion	

Many studies have aimed at the experimental determination of Young's modulus for human skin through indentation. Due to the nonlinear mechanical response of human skin, this method can simplistically be used strictly to compare different methods of measuring the elasticity modulus since there is no measurement standard, or it can be used to compare the elasticity modulus of several volunteers. Table 2 above also exemplifies the dependence of the elasticity modulus on the penetration depth, with the skin increasing its average value for the elasticity modulus with depth. All these observations lead to the conclusion that Young's modulus alone cannot fully describe the nature of deformations that occur at the skin level, as the skin is a complex, anisotropic, stratified material, but it is a property that can help understand the deformation phenomena that occur. The study conducted presented a repeatable, robust method of testing human skin through the in vivo method. From the literature, in vivo and ex vivo indentation measurements show significant differences between the two skin tissues, so the presented method cannot be used to compare results obtained on in vivo and ex vivo skin.

5. CONCLUSION

This study on the Young's Modulus of human finger skin, focusing on contact area and indentation creep behaviour, provides practical insights into the skin's biomechanical properties. Utilising the CETR-UMT2 setup, the research aimed to better understand how skin responds to mechanical forces, particularly in terms of deformation and recovery.

The results indicate a direct relationship between the force applied to the skin and the contact area, revealing that skin stiffness increases in a non-linear manner with the increase in force applied. This finding is consistent with prior research, confirming the skin's complex response to stress. By employing cylindrical bronze indenters with varying diameters, it was able to accurately measure the skin's response across a range of forces.

The calculation of Young's Modulus, which was found to be approximately 310 kPa using the Hertzian contact model, aligns with existing literature.

The creep behaviour study further demonstrated the skin's anisotropic properties, showing how it deforms over time under constant force. This aspect of the research sheds light on the skin's dynamic properties, highlighting its initial rapid deformation and subsequent stiffening over time.

By providing a clearer picture of how skin interacts with external forces, the research supports the development of more comfortable and effective human-machine interactions.

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Contribuții asupra modulului de elasticitate al pielii degetelor umane: Evaluarea ariei de contact și comportamentului la fluaj prin indentare

Studiul se concentrează pe proprietățile pielii degetelor umane, utilizând standul experimental CETR-UMT2. Cercetarea include două secțiuni principale: măsurarea ariei de contact cu ajutorul unor poansoane cilindrice din bronz de diferite diametre sub acțiunea forțelor și determinarea comportamentului la fluaj prin indentare pentru a calcula modulul de elasticitate. Rezultatele arată un răspuns neliniar al rigidității pielii cu creșterea forțelor aplicate, susținând studiile anterioare. Partea a doua, folosind un model de contact Hertzian, s-a determinat Modulul lui Young al pielii degetelor. S-au obținut valori de aproximativ 310 kPa, în concordanță cu literatura existentă.

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