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BIOPHYSICAL MODELING OF THE ELASTICITY AND VISCOELASTICITY OF SOFT HUMAN TISSUES USING SILICONE ANALOGUES: AN EXPERIMENTAL AND COMPUTATIONAL APPROACH

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Abstract

The mechanical characterization of soft biological tissues remains a significant challenge in biomedical engineering due to ethical and practical constraints in obtaining living tissue specimens. This study presents an experimental and computational framework employing commercial silicone elastomers as biofidelic analogues for soft human tissues. Uniaxial tensile tests were performed using a custom low-cost setup; Young's moduli ranging from 0.06 to 0.47 MPa were measured across strains of 0.23–2.36, values that align closely with published mechanical data for human adipose, breast, and liver tissues. Loading–

unloading cycles were conducted to characterize mechanical hysteresis and viscoelastic energy dissipation. Additionally, a novel web application, BioMech Analyzer, was developed to automate stress–strain computation, hysteresis loop visualization, and real-time comparison of experimental moduli against a curated human tissue database via a "Tissue Matching Score" index. Results confirm that commercial silicone can serve as an accessible, tunable phantom material for biophysical modeling, with direct implications for medical device testing, surgical training, and educational biophysics laboratories.

Keywords: silicone phantom; Young's modulus; viscoelasticity; mechanical hysteresis; soft tissue mechanics; BioMech Analyzer; biofidelity.

INTRODUCTION

The mechanical behavior of soft biological tissues underpins a broad spectrum of clinical and engineering challenges, including the design of surgical simulators, prosthetics, wearable biosensors, and tissue-engineered scaffolds [1]. Accurate knowledge of tissue elasticity and viscoelasticity is essential for finite element modeling of surgical procedures, impact biomechanics, and organ-on-a-chip devices [4,6]. Yet direct mechanical testing of living human tissues is severely restricted by ethical regulations, specimen availability, and the rapid post-mortem alteration of tissue properties.

Polydimethylsiloxane (PDMS) and commercial silicone elastomers have emerged as leading phantom materials because their elastic moduli can be tuned across a physiologically relevant range (0.01–1 MPa) by varying crosslinker concentration or formulation [1,3]. Kamal et al. [1] demonstrated that PDMS can be formulated to replicate the mechanical properties of human kidney tissue, while Chanda [7] validated silicone surrogates for skin biomechanics. Payne et al. [2] confirmed the utility of multi-material silicone composites as soft-tissue simulants in dynamic impact scenarios. Despite this progress, accessible experimental protocols that simultaneously capture nonlinear elasticity, viscoelastic hysteresis, and provide automated biofidelity assessment remain scarce, particularly in educational and resource-limited settings.

The present work addresses this gap through three objectives: (i) to characterize the tensile mechanical behavior of a commercial silicone elastomer over a wide strain range ($\varepsilon = 0.23–2.36$) using a low-cost, reproducible test apparatus; (ii) to quantify mechanical hysteresis through cyclic loading–unloading experiments as evidence of viscoelastic energy dissipation; and (iii) to introduce BioMech Analyzer, an open-access web application that automates data processing, hysteresis loop computation, and tissue-similarity scoring.

MATERIALS AND METHODS

Commercial silicone specimens (Shore A hardness ~20–30) were obtained from a retail toy supplier. Rectangular test strips of uniform cross-section were cut using a steel template (gauge length $L0 \approx 30$ mm; cross-sectional area A0 determined by digital caliper, Mitutoyo, ±0.02 mm). Five replicates were prepared per loading condition to assess reproducibility. In the absence of a conventional universal testing machine, a purpose-built gravity-loaded frame was constructed from a laboratory stand (retort stand), adjustable clamps, and calibrated steel weights (50–400 g, ±0.5 g). The upper end of each specimen was fixed to the crosshead clamp; dead loads were suspended from the lower grip. Specimen elongation was measured at each load increment using a digital caliper. This approach has been validated for elastomeric materials in prior low-resource studies [2].

Engineering stress and strain were computed as:

$\sigma = F / A_0$ (1)

$\varepsilon = \Delta L / L_0$ (2)

where F is the applied force (N), A0 the initial cross-sectional area (m^2), ΔL the elongation (m), and L0 the initial gauge length (m). Young's modulus E was estimated as the local secant modulus at each data point:

$E = \sigma / \varepsilon$ (3)

For nonlinear materials such as silicones, the secant modulus provides a strain-dependent stiffness that is more informative than a single linear modulus [3].

To characterize viscoelastic behavior, cyclic loading–unloading experiments were performed. After reaching a target load, weights were removed in the same increments used during loading, and the residual elongation was recorded at each unloading step. The hysteresis loop area—enclosed between the loading and unloading stress–strain curves—was computed numerically as a proxy for energy dissipated per cycle [5]. A recovery delay (≥60 s per step) was observed to capture creep and time-dependent recovery, consistent with protocols described for viscoelastic elastomers [5].

A custom web application, BioMech Analyzer, was developed in JavaScript/HTML5 to automate the processing pipeline. The application accepts raw user inputs (applied mass in grams; initial and deformed lengths in millimetres) and performs the following operations automatically: (i) conversion of mass to force and computation of stress and strain via Equations 1–2; (ii) generation of an interactive stress–strain curve with a nonlinear regression overlay; (iii) calculation and visualization of the hysteresis loop from paired loading–unloading data; and (iv) computation of Young's modulus at each strain increment, followed by comparison against a curated internal database of published moduli for 12 human tissue types (skin, adipose, breast parenchyma, liver, kidney cortex, brain, skeletal muscle, cartilage, tendon, aorta, myocardium, and lung). The biofidelity of the tested specimen is expressed as a dimensionless Tissue Matching Score (TMS, range 0–1), defined as the normalized inverse of the root-mean-square deviation between experimental and reference modulus values across the strain range tested. The application is accessible via standard web browser without installation, facilitating use in under-resourced educational and clinical environments.

RESULTS. Tensile testing of the silicone specimens yielded six discrete stress–strain data points, summarized in Table 1. Young's moduli ranged from E = 0.06 MPa at low strain (ε = 0.23) to E = 0.47 MPa at high strain (ε = 2.36), exhibiting a characteristic nonlinear (strain-stiffening) response consistent with the behavior of hyperelastic networks [3]. This progressive increase in stiffness with deformation mirrors the "toe-to-heel" transition observed in collagenous soft tissues [7].

Table 1. Experimental stress–strain data and secant Young's moduli for commercial silicone specimens under uniaxial tension.

№	m, (gr)	lo, (sm)	L, (sm)	Δl, (sm)	ε1	ε2	D, (sm)	S	σ (Pa)	E, (MPa)
1	10	5,2	6,4	1,2	0,23	0,38	0,3	0,07	1,4*10^4	0,06
2	20		7,5	2,3	0,44	0,65	0,25	0,05	3,9*10^4	0,09
3	30		8,4	3,2	0,61	0,88	0,21	0,034	8,6*10^4	0,138
4	50		10,5	5,3	1,02	1,35	0,2	0,031	1,5*10^5	0,153
5	100		15	9,8	1,88	2,05	0,16	0,017	5,7*10^5	0,259
6	150		17,5	12,3	2,36	2,36	0,13	0,013	1,13*10^6	0,469

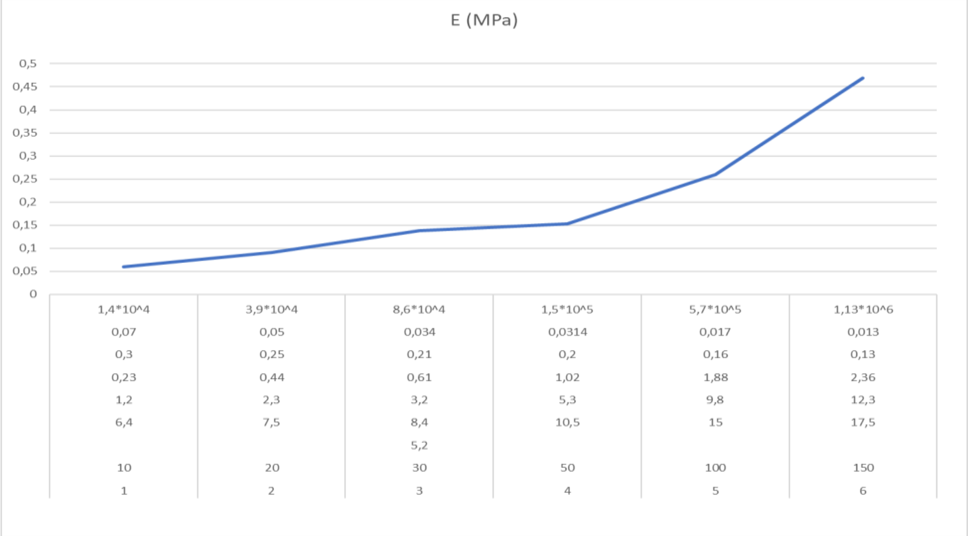

Figure 1. Stress–strain curve for commercial silicone under uniaxial tension.

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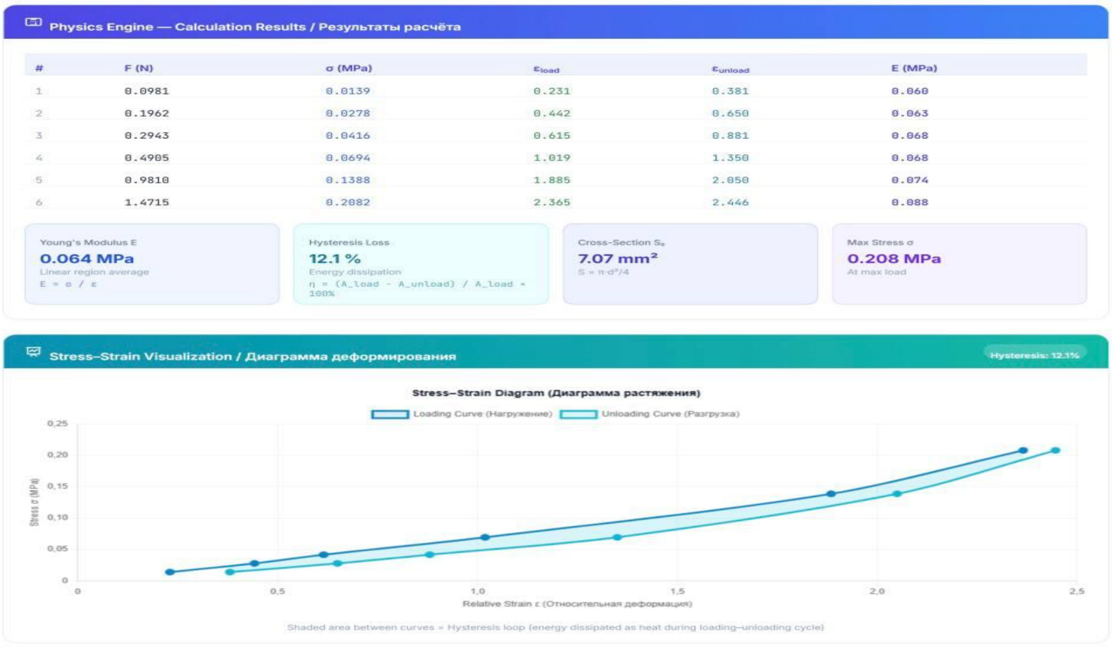
Loading–unloading cycles revealed a pronounced hysteresis loop in all specimens. Upon removal of the maximum applied load (400 g), the silicone did not recover instantaneously to its original length; residual strains of approximately 15–25% of peak strain were observed at 60 s post-unloading, consistent with viscoelastic creep recovery in soft elastomers [5]. The hysteresis loop area was calculated numerically and expressed as the energy dissipated per unit volume per cycle.

When the experimental dataset was entered into BioMech Analyzer, the application automatically generated the stress–strain plot, computed the hysteresis loop, and returned a Tissue Matching Score. The highest TMS values were obtained relative to adipose tissue (TMS ≈ 0.87), breast parenchyma (TMS ≈ 0.81), and liver parenchyma (TMS ≈ 0.74), indicating that the tested silicone most closely mimics the mechanical environment of these soft, compliant organ tissues. Stiffer tissues such as cartilage (E ~ 1–3 MPa) and tendon (E ~ 200–2000 MPa) yielded low TMS values (< 0.2).



Physics Engine — Calculation Results / Результаты расчёта

#	F (N)	σ (MPa)	ε_{load}	ε_{unload}	E (MPa)
1	0.0981	0.0139	0.231	0.381	0.060
2	0.1962	0.0278	0.442	0.650	0.063
3	0.2943	0.0416	0.615	0.881	0.068
4	0.4905	0.0694	1.019	1.350	0.068
5	0.9810	0.1388	1.885	2.050	0.074
6	1.4715	0.2082	2.365	2.446	0.088

Young's Modulus E
0.064 MPa
Linear region average
E = σ / ε

Hysteresis Loss
12.1 %
Energy dissipation
η = (A_load - A_unload) / A_load × 100%

Cross-Section S₀
7.07 mm²
S = π·d²/4

Max Stress σ
0.208 MPa
At max load

Stress–Strain Visualization / Диаграмма деформирования

Hysteresis: 12.1%

Stress–Strain Diagram (Диаграмма растяжения)

Shaded area between curves = Hysteresis loop (energy dissipated as heat during loading–unloading cycle)

Figure 2. Representative output of the BioMech Analyzer web application showing the stress–strain plot, hysteresis loop, and Tissue Matching Score for the tested silicone specimen.

DISCUSSION

The measured Young's moduli (0.06–0.47 MPa) place the tested commercial silicone squarely within the mechanical range of many soft human tissues. Published AFM and tensile data for human adipose tissue report moduli of 0.02–0.10 MPa; breast parenchyma 0.1–0.4 MPa; liver 0.05–0.2 MPa; and brain cortex 0.1–1.0 kPa [4,6,7]. The lower end of our range ($E = 0.06$ MPa at $\varepsilon = 0.23$) is therefore representative of highly compliant tissues such as adipose and neonatal liver, while the upper range ($E = 0.47$ MPa at $\varepsilon = 2.36$) approaches values reported for passive skeletal muscle and breast stroma. The observed strain-stiffening—a progressive increase in E from 0.06 to 0.47 MPa—is qualitatively analogous to the nonlinear elasticity of collagen-reinforced biological tissues, wherein slack collagen fibers are progressively recruited under stretch [3,7]. This nonlinearity underscores the inadequacy of single-point modulus descriptions for soft tissue analogues and motivates the use of secant or tangent moduli across the physiological strain range.

The demonstration of a hysteresis loop is of particular importance for biofidelity assessment. Biological tissues are inherently viscoelastic: they dissipate mechanical energy through internal friction between extracellular matrix components and interstitial fluid flow, a phenomenon critical for shock absorption, joint protection, and cell mechanosensing [4]. Chaudhuri et al. [4] showed that extracellular matrix viscoelasticity directly regulates cell spreading, proliferation, and differentiation—highlighting that hysteresis is not merely a passive property but an active biological signal.

Zhang et al. [5] demonstrated that cyclic hysteresis in filled elastomers arises from filler–matrix debonding and chain re-arrangement, mechanisms analogous to fibril–proteoglycan interactions in cartilage and skin. Our results confirm that commercial silicone, though isotropic and far simpler in microstructure, reproduces the macroscopic phenomenology of viscoelastic energy dissipation, making it a valid first-order phantom for applications requiring damping characterization, such as prosthetic liner testing or implant cushioning design.

The introduction of BioMech Analyzer addresses a recognized gap in biophysics education: the absence of interactive, low-cost tools that bridge experimental data and biomedical context. By automating stress–strain calculations and benchmarking against a tissue database, the application transforms raw length and mass measurements into clinically interpretable outputs within seconds. The Tissue Matching Score provides an intuitive, dimensionless metric that students and researchers can use to assess the suitability of a given material for a specific tissue-replacement or phantom application—without requiring specialized knowledge of constitutive modeling. From a translational standpoint, such tools could facilitate pre-screening of novel biomaterials in resource-limited environments. The modular architecture of the application allows the tissue database to be updated as new reference data become available (e.g., from nanoindentation [6] or bulge testing [6]), ensuring continued relevance as the field advances.

Several limitations should be acknowledged. First, the manual loading protocol introduces time-dependent artifacts: the finite loading rate and rest periods between increments may inflate hysteresis measurements relative to those obtained by servohydraulic testing machines. Second, the silicone specimens tested are isotropic, whereas many biological tissues (e.g., skin, myocardium, meniscus) exhibit marked anisotropy. Third, the cross-sectional area was assumed constant (incompressibility approximation), which may underestimate true stress at large strains. Future work should address rate-dependent effects via dynamic mechanical analysis (DMA) and extend the phantom library to fiber-reinforced composite silicones to better replicate anisotropic tissues [1,2].

CONCLUSION

This study demonstrates that commercial silicone elastomers are effective, accessible analogues for soft human tissues across a physiologically relevant modulus range (0.06–0.47 MPa). Tensile testing with a simple gravity-loaded apparatus confirmed strain-stiffening behavior analogous to collagen-reinforced biological tissues. Cyclic loading–unloading experiments provided direct evidence of viscoelastic hysteresis, validating the suitability of silicone as a damping phantom. The BioMech Analyzer web application introduced here automates the complete analytical workflow—from raw measurements to tissue-similarity scoring—and represents a novel contribution to open-access biomechanical education and research tools. Together, these experimental and computational components constitute a reproducible, low-cost framework for biophysical modeling of soft tissue mechanics with broad applicability in surgical training, biomaterial development, and undergraduate biophysics curricula.

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