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Rapid and Non-Invasive Skin Viscoelasticity Measurement via Indentation and Relaxation

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1. Introduction

Human skin is composed of multiple layers, including the epidermis, dermis, and hypodermis, each with distinct thicknesses and mechanical properties, resulting in complex viscoelastic behavior. These biomechanical properties are fundamentally determined by structural components such as collagen, elastin fibers, and the hydration status of the tissue. Changes in skin viscoelasticity are strongly associated with physiological conditions including aging and hydration, making the analysis of skin viscoelasticity important for clinical diagnostics and cosmetic evaluations of human skin [1].

Conventional techniques for measuring skin properties, such as optical imaging or electrical impedance methods, often suffer from inaccuracies caused by surface contamination such as makeup and skincare products. To address these limitations, we developed a novel, non-invasive mechanical device that performs rapid skin viscoelasticity assessments through indentation method. By applying a generalized Maxwell model and expressing the relaxation response via a second-order Prony series, the device enables precise quantification of dermal and hypodermal mechanical properties [2]. This method allows for the characterization of the mechanical properties of the multilayered skin, enabling potential applications in personalized skincare strategy and the diagnosis of skin disorders.

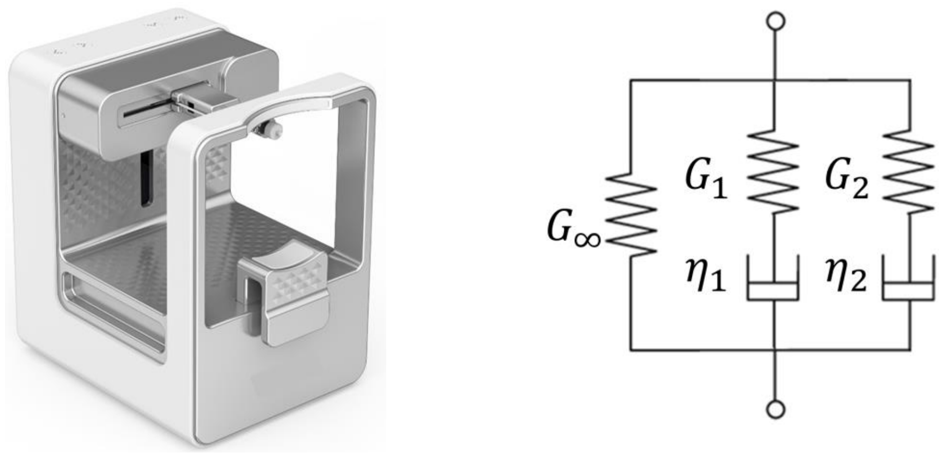
2. Materials and Methods

The developed device consists of a precision linear actuator coupled with a high-sensitivity load cell to perform mechanical indentations on the skin surface (Figure 1-a). During each test, the indenter was displaced to a preset depth at a constant speed, ensuring minimal dynamic effects. The relaxation force was recorded over time after reaching the target displacement.

The force relaxation response was modeled using a second-order Prony series representation of the generalized Maxwell model (Figure 1-b). In the case of a spherical indenter, the force relaxation behavior can be expressed as:

$$F(t) = \frac{8\sqrt{R}}{3} d^{\frac{3}{2}} (G_\infty + G_1 e^{-\frac{t}{\tau_1}} + G_2 e^{-\frac{t}{\tau_2}}),$$

where R is the radius of the spherical indenter, d is the indentation depth, G_∞ is the equilibrium modulus, G_1 and G_2 are relaxation moduli, and τ_1, τ_2 are relaxation time constants. Two distinct relaxation time constants(τ_1, τ_2) along with two relaxation moduli (G_1, G_2), and the equilibrium modulus (G_∞) were extracted to characterize the dermal and hypodermal contributions to the skin's viscoelastic behavior [3].



(**a**) (**b**)

Figure 1. (a) Skin viscoelasticity measurement device; (b) Second-order Prony series representation of the generalized Maxwell model.

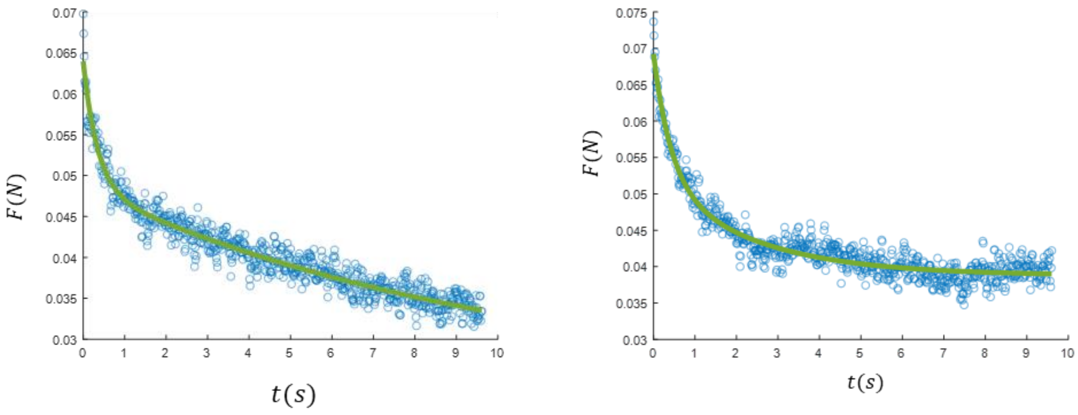
All experiments were performed on in vivo human subjects under controlled hydration and dehydration protocols. A total of 28 participants (ages 23–45, including both male and female subjects) were recruited for the study. Hydrated conditions were induced by applying a moisture pack to the skin for a set duration, while dehydrated conditions were achieved by exposing the skin to ambient air for a predetermined time. Measurements were conducted in a temperature- and humidity-controlled environment to minimize external variability.

3. Results

3.1. Hydrated, Dehydrated Skin Comparison

The force relaxation responses of hydrated and dehydrated skins are shown in Figure 2. Experimental results showed that hydrated skin exhibited a greater overall decay in force compared to dehydrated skin, indicating enhanced viscoelastic relaxation behavior.

To further evaluate elastic properties, G_1, G_2, and G_∞ values were extracted from the Prony series fitting for two male subjects (ages 23 and 25). These results are summarized in Table 1. It was observed that with increased skin hydration, G_1 and G_2 values increased, indicating an enhancement in the viscous response of the skin, while G_∞ decreased, suggesting a reduction in the overall modulus and a softening of the skin.



(**a**) (**b**)

Figure 2. Force relaxation responses for (a) hydrated skin and (b) dehydrated skin of 28 human participants.

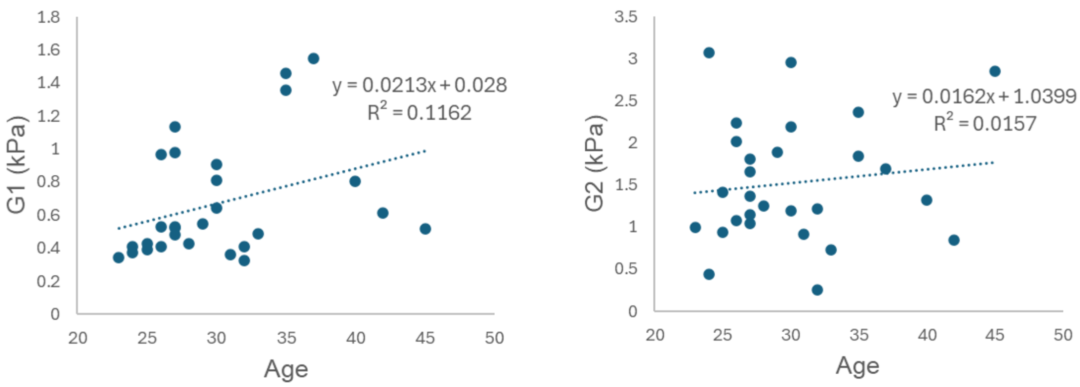
Table 1. Prony series elastic moduli for two subjects before and after hydration.

Subject (Age)	Condition	G_1(kPa)	G_2(kPa)	G_∞(kPa)
23	Dehydrated	0.89±0.17	1.49±0.36	1.82±0.31
	Hydrated	0.99±0.23	1.75±0.34	1.53±0.25
25	Dehydrated	0.57±0.11	1.06±0.27	1.71±0.20
	Hydrated	0.82±0.13	1.10±0.27	1.10±0.24

3.2. Age and Skin Viscoelasticity Relationship

An additional study was conducted across 28 male and female participants (ages 23–45) to examine the relationship between age and skin viscoelastic properties.

Figure 3 shows the correlation between age and various viscoelastic parameters G_1 and G_2. The analysis revealed a trend of a slight increase in G_1 and G_2 values with age. This result might suggest increased skin viscosity with aging; however, it should be noted that the sample size may still be insufficient to establish a definitive trend, and further studies with larger populations are needed.



(**a**) (**b**)

Figure 3. Correlation between age and skin viscoelastic parameters: (a) G_1 and (b) G_2.

4. Discussion

The results (Table 1 and Figure 2) demonstrate that hydration significantly influences the viscoelastic properties of the dermis, as evidenced by the increase in G_1 and G_2 and the decrease in G_∞ following hydration. These findings uncover the role of water content in enhancing collagen fiber flexibility and reducing tissue stiffness.

The analysis of the relationship between age and skin viscoelasticity (Figure 3) revealed a slight increase in G_1 and G_2 values with age, suggesting a potential enhancement in skin viscosity with aging. However, it should be noted that the sample size may still be insufficient to establish a definitive trend, and further investigations with larger participant groups are necessary to confirm these observations. This suggests that maintaining skin hydration could be an effective strategy for preserving skin mechanical properties over time.

Compared to optical or electrical measurement techniques, the mechanical indentation-relaxation approach proved robust against surface contamination, ensuring consistent and reliable data. These advantages position the device as a promising tool for non-invasive skin assessments in both clinical and cosmetic contexts.

Future work will extend these findings by applying the methodology to broader in vivo studies and longitudinal tracking of skin health.

5. Conclusion

In this study, we successfully developed a rapid, non-invasive device capable of quantitatively assessing skin viscoelasticity through mechanical indentation tests. Our system, based on a generalized Maxwell model and Prony series analysis, demonstrated high sensitivity and reproducibility in distinguishing between hydrated and dehydrated skin conditions. The significant variation in dermal elasticity parameters with hydration validates the device's capability to detect subtle changes in skin.

These findings imply the potential of our device as a valuable tool in dermatological research, cosmetic product evaluation, and clinical diagnostics. Future work will extend the application of this technology to broader studies of skin aging aiming to establish personalized strategies for skin health management based on skin viscoelastic properties.

6. References

[1] J. Park et al., "Characterizing viscoelastic properties of human melanoma tissue using Prony series," *Frontiers in Bioengineering and Biotechnology* **11**, 1162880 (2023).
[2] S. J. M. Yazdi et al., "Characterization of the viscoelastic model of in vivo human posterior thigh skin using ramp-relaxation indentation test," *Korean Journal of Rheology* **30**, 293-307 (2018).
[3] E. Barrientos et al., "Optimal discrete-time Prony series fitting method for viscoelastic materials," *Mechanics of Time-Dependent Materials* **23**, 193-206 (2019).