A multiscale approach for nonlinear hysteretic skin elasticity evaluation by means of PM space modeling

Approche multiéchelles par espaces PM pour une caractérisation des propriétés élastiques non lineaires et hystérétiques de la peau ex vivo

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Abstract

This paper investigates the use of the Preisach-Mayergoyz (PM) space to characterize the mechanical properties of skin tissue, assess elasticity or damage and localize sources of nonlinearity potentially responsible for skin ageing, in complement to the Time Reversal based Nonlinear Elastic Wave Spectroscopy methods. Hysteresis behaviour coming from the complex loading of porcine skin tissues has been identified with a PM space statistical model, which can be expressed as weight combination of hysterons or hysteretic elasticity units (or memristors). Identifying the PM space probability density within a class of distribution mixtures by means of numerical optimization algorithms simulated annealing, fast simulated annealing and their modifications, the elasticity of porcine skin is evaluated. It is found that optimization techniques with L_2 distance and Φ-divergence measures induces a PM space with 1000 hysterons distributed along a mixture of two Guyer distributions. Parameters of the distributions and final PM spaces of porcine skin experimentally measured data are presented and analysis of data shows that PM space approach is suggested as a new tool for extracting multi-scale parameters containing information about aging of the skin, based on single units analogue to memristors.

Keywords: *Hysteresis, Elasticity evaluation, Preisach-Mayergoyz model, Distribution mixtures, Density identification, Simulated Annealing, Skin tissue.*

Résumé

Une approche multiéchelles de type Preisach-Mayergoyz (PM) est proposée pour extraire de nouveaux paramètres permettant de décrire les comportements vicoélastiques complexes et à hystérésis d'un essai de traction uniaxiale de la peau ex vivo. Le processus de traitement du signal s'inscrit dans une démarche d'extraction de paramètres multiéchelles et multiphysique de la peau dans le but d'en tirer un indicateur pragmatique et multiéchelles du vieillissement de la peau. L'exploitation des données expérimentales montre qu'un ensemble de 1000 éléments hystérétiques élémentaires, distribués selon un mélange de deux distributions de type Guyer, permet d'ajuster le comportement à hystérésis obtenues lors d'essais de traction uniaxiale de la peau. Ce résultat a été obtenu en utilisant un algorithme d'optimisation de type (fast) simulated annealing associé à la mise en oeuvre de distances de type L_2 et Φ-divergence.

Mots clés : *Hystérésis, Elasticité, Approche de Preisach-Mayergoyz, Mélange de distributions, Identification de densité, Simulated annealing, Tissu dermique.*

1 Introduction to hysteresis and signal processing

The aging and fatigue features of biomaterials are of great interest in the domain of medicine and cosmetics. The description of human skin deformation under complex stress protocol is an open problem, not only from a theoretical point of view, but also from an experimental aspect. Complementary to skin models, the usage of *ex vivo* porcine skin tissue substitute begins to bring a new aspects for validation of novel experimental methods and innovative parameter description.

The objective of studying memory properties of complex systems is motivated by the need to understand biological systems which could naturally exhibit long time behavior and memory effects and aging. Since the researches of Volterra, relatively little theoretical work has been done in the field of aging, or time-variable, viscoelastic media [1]. These highly reverberating biological media are strongly needed for experimental methods in classical medical ultrasonic imaging or Non Destructive Testing (NDT) for exploring biological tissues (skin, bones or neural cells of the brain) which exhibit memory effects. It is known that (nonlinear) memory effects, including hysteretic properties, are responsible for the aging of materials.

Hysteresis is a phenomenon occurring in ferromagnetic materials as well as in a course of deformation of some materials, which are flexible or elastic. Preisach-Mayergoyz model (PM model) of hysteresis [2] has an important place in the field of nonlinear elastic spectroscopy. During the inversion procedure of PM space identification, some optimized signal processing methods should be taken into account in order to consider relaxation effects, and the vanishing of internal loops which is also observed elsewhere. Some accurate experiments should be performed in order to obtain noiseless curves of the stress-strain relation for porcine skin tissue. Furthermore, it can be seen that the hysteresis area is increasing versus amplitude. To overcome this drawback, it is necessary to develop coded signal processing that could identify PM space statistical properties, and can be suitable for real-time identification and smart system design. For the porcine skin analysis under study, the low frequency loading protocol will be coupled to a high frequency acoustic probing device involving Time Reversal (TR) based Nonlinear Elastic Waves Spectroscopy (NEWS) localized imaging methods. Accurate analysis of nonlinear time reversal systems needs the use of new methods of signal processing [3], [4] and [5]. More fundamentally, the memory properties are an essential building locks in leaving and decision-making in biological systems. Recently, memristor have been studied in biological inspired neuromorphic circuits, with complex learning rules such as spike-timing dependent plasticity (STDP) properties [6]. This experimental study enters also in the new research area which tends to associate single hysteretic element, to the global behavior of the human brain. In biological systems, short-term memory generally lasts from second to tens of minutes ; on the contrary, long-term memory lasts from a few hours to days or weeks, sometime even to a lifetime [7].

In this study, we show that the skin leading bears a striking resemblance with memory properties of the memristor, the simple unit of the memory loss in biological systems. By stimulating the skin with repeated loading protocol, we observe an effect analogous to memory transition in biological systems with complex internal structural changes in the skin, measured with the PM space approach.

Today hysteresis and memory based modeling is one of the most interesting and challenging field of innovation in many engineering applications such as actuators [8,9], but also as components of plasma membranes in many plants, fruits, and seeds [10]. Recently, an active research has also been conducted for the modeling of nonclassical nonlinear effets in biological tissues using memory based phenomenological approaches [11]. A memristive effects could also play a significant role in the complex nonlinear properties of biomaterials, such as bone or tooth [12]. When microdamage is present in biological tissues like bone [13], high levels of nonlinearity is found, with specific nonlinear signatures such as

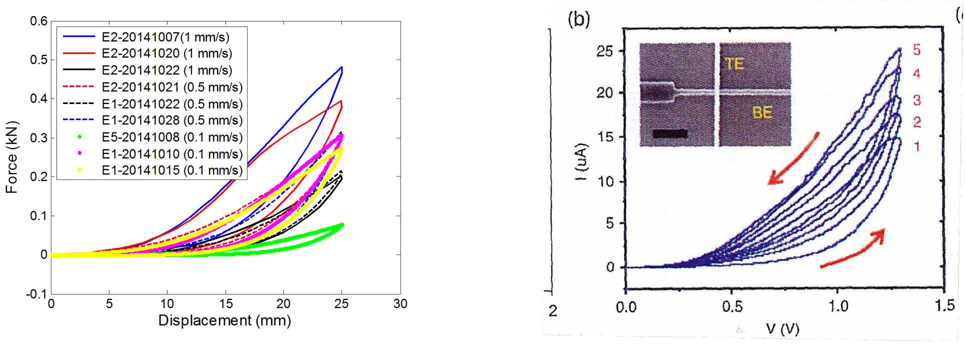

*Fig. 1. (a) Force-displacement curve characteristics of the the studied samples versus the velocity of the loadings (V =0.1; 0.5 and 1 mm/s). All samples are 100*30*2mm size (data courtesy from [3]). (b) Dynamical behavior of memristive nanojunctions : current-voltage curves are numbered sequentially showing the hysteresis loops of increasing conductivity (data courtesy from [18])*

hysteresis and tension/compression asymmetry [14, 15]. Perspectives of this approach is to associate and design electro-mechanical models, and its automatic detection system [16] in similarity with complex media such as skin, tooth, or brain which are known to exhibit multiscale memory and memristive effects [17, 18].

The analogy between the memory effects of the memristor and memory effects in the skin (figure 1) allow us to suggest the same physical origin of aging. Since the memristor is a two-terminal device whose conductance can be modulated by external inputs, its memory effects due to internal states changes can have the same properties of the internal state changes of the skin during mechanical loading. Such devices typically show hysteresis and multi-state behavior when excited by optimized excitations. Such behavior showing hysteresis has been widely reported in nanoscale devices [19].

The paper is presented as the following : the first part will concern the concept of the Preisach-Mayergoyz appoach which is the basic hypothetis of our study. The last part will present the numerical optimization used on experimental data published previously [3]. The second part will concern the comparative and complete results and discussion on porcine skin tissues. Then the conclusion will be suggested for future experimental and theoretical work.

2 PM space model and its identification using numerical optimization

Preisach-Mayergoyz model of hysteresis [2] is a tool for describing materials and systems with hysteresis behavior. The PM space model is based on the idea that a given material is composed of a large number of small elastic particles (units, cracks, etc.). These small units are called hysterons, or hesteretic elementaary unit (HEU), and can be found either in the closed state (valued by 1) or in the open state (valued as -1). Parameters P_c and P_o represent hysteron's closing and opening values under the assumption that $P_o \leq P_c$. Mathematically, the Preisach's operator $\hat{\gamma}_{P_c,P_o}$ of hysteron is expressed as follows

$$\hat{\gamma}_{P_c,P_o}(u(t)) = \begin{cases} -1, & u(t) \leq P_o, \\ 1, & u(t) \geq P_c, \\ k, & u(t) \in (P_o, P_c), \end{cases} \quad \text{(eq. 1)}$$

where $u(t)$ is an input signal and

$$k = \begin{cases} 1, & \text{if } \exists t^* : u(t^*) > P_c \text{ and } \forall \tau \in (t^*, t), u(\tau) \in (P_o, P_c), \\ -1, & \text{if } \exists t^* : u(t^*) < P_o \text{ and } \forall \tau \in (t^*, t), u(\tau) \in (P_o, P_c). \end{cases} \quad \text{(eq. 2)}$$

Applying the input signal $u(t)$, the PM space output $y(t)$ is described in the continuous case as a double integral over the PM space

$$y(t) = \int\int_{P_o \le P_c} \mu(P_c, P_o)\, \hat{\gamma}_{P_c,P_o}(u(t))\, \mathrm{d}P_c\, \mathrm{d}P_o, \qquad \text{(eq. 3)}$$

where $\mu(P_c, P_o)$ is probability function and $u(t)$ is the input signal.

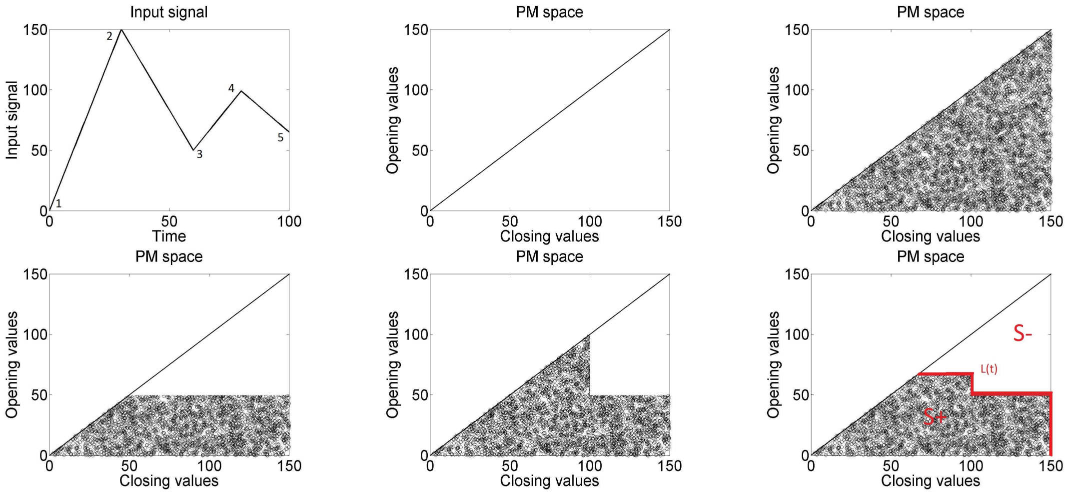

Fig. 2. Geometrical interpretation of the PM model: hysterons with the closing value under the current value of the input load have switched from the opened state to the closed state during the loading protocol; the units with lower opening values than the current input have returned to the open state during decreasing input signal

Main task in the field of PM space elasticity modeling is the identification of probability density function $\mu(P_c, P_o)$. The primary goal is to determine a density of hysterons in PM space only from the knowledge of hysteresis curve and the input signal. We make use both the fundamental statistical distributions (e.g. Exponential, Gaussian, Uniform, Weibull) and also two distributions originated from R. A. Guyer and K. R. McCall [22], [24].

Distribution Guyer 1 is defined by

$$P_c = \max \cdot r_c^{\alpha}, \qquad P_o = P_c \cdot r_o^{\beta}, \qquad \alpha, \beta \in \mathbb{R}, \qquad \text{(eq. 4)}$$

where 'max' is a maximum of input pressure, P_c and P_o are closing and opening values ($P_o \le P_c$), r_c and r_o are random numbers uniformly distributed between 0 and 1, and α, β represent parameters of the distribution.

Distribution Guyer 2 is determined as

$$P_c = \max \cdot r_c^{\alpha}, \qquad P_o = P_c \cdot r_o^{0.25+0.75\mu}, \qquad \alpha, \mu \in \mathbb{R}, \qquad \text{(eq. 5)}$$

where α, μ represent parameters of the distribution in this case.

To identify the corresponding PM space of some material only from the knowledge of an input signal and experimentally obtained hysteresis curve, we use also the statistical theory of distribution mixtures [20] better reflecting the real material structure.

We employ numerical optimization stochastic methods [21] called Simulated Annealing (SA) and Fast Simulated Annealing (FSA) optionally in combination with the blind random search together with further novel modifications for the PM space density identification, i.e. for the distribution parameters and parameters of mixture identification (see below).

Every optimization problem consists of minimizing a functional $\mathcal{F}$ systematically choosing input values from within an allowed set and computing the values of the functional. In our case the functional $\mathcal{F}$ represents deviation of calculated hysteresis curve in each iteration step from the hysteresis curve experimentally obtained. For the assessment of that deviation we use either classical L_2-distance or ϕ-divergences [23] which are more robust against either outliers or other unpredictable measurement errors. We focus on the Hellinger distance and the so called LeCam divergence.

To determine the density of hysterons in PM space we run the programme called 'PM identifier' which was developed progressively [25], [26].

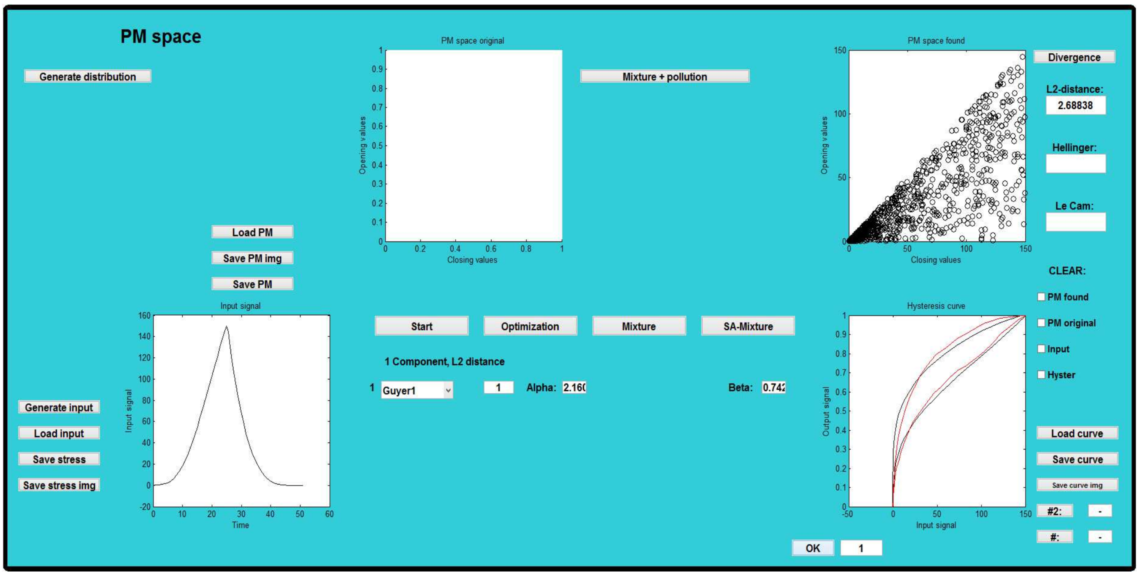

Fig. 3. An example of identification of simple PM space along Guyer 1 distribution, value of the L_2-distance is equal to 2.688

3 A comparative result on porcine skin

The experimentally measured hysteresis curves of porcine skin tissue and the input signals (see Figure 5) have been processed.

First we searched for a simple PM space (without using the distribution mixtures) by means of the simulated annealing. We tried various distributions, especially Guyer 1 and Guyer 2. An example of the identification of the simple PM space is shown in Figure 3. In this case, the corresponding red hysteresis curve is only roughly (comparatively) similar to original (black) hysteresis curve and thus the result is not satisfactory. The value of the L_2-distance is equal to 2.688 which is too large.

To solve this inaccuracy we find out the layout of hysterons in PM space by means of distribution mixtures using the Fast Simulated Annealing algorithm in order to reach significantly lower deviation from experimentally obtained hysteresis curve. We achieved the lowest L_2-distance deviation for the distribution mixture combining the Guyer 1 and Guyer 2 distribution. An example of this identification is shown in Figure 4. The PM space obtained for this distribution mixture (shown in Figure 4) is far from the simple PM space depicted in Figure 3. The first component Guyer 1 fanned out along the diagonal, i.e. representing almost elastic hysterons without hysteretic behavior. The second component is placed mainly at the bottom of the PM space, where the hysterons have small opening values. Thereby, a very surprising result was achieved and the assumption that the mixture of distributions could better reflect the real material, was confirmed.

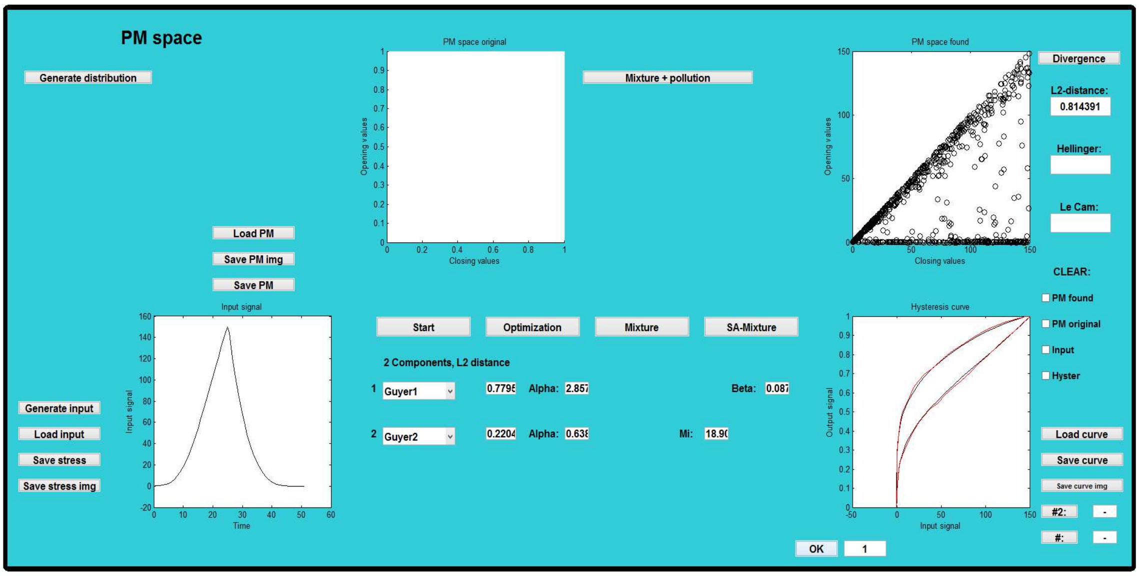

Fig. 4. An example of identification of the PM space along the mixture of Guyer 1 and Guyer 2 distribution, value of the L_2-distance is equal to 0.814

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4 Complete results on porcine skin tissue

All the PM space distributions were identified for all available measurements on porcine skin tissues. The final PM spaces for each measured hysteresis curves and related input signals are depicted in Figure 5. In all cases the optimal layout of hysterons was identified in the form of distribution mixture of Guyer 1 and Guyer 2 distribution.

Basic statistics (sample mean and deviation) of the parameters of each distribution for 1000 repetitions are shown in the tables 1, 2, and 3. In each table there are statistics of weight of distribution Guyer 1 (weight of distribution Guyer 2 is a complementary to 1), statistics of found parameters α_1, β_1 of Guyer 1 and α_2, μ_2 of Guyer 2. We also present the mean deviation L_2^* which was adjusted to the different number of evaluation points on hysteresis curve, thus the deviation L_2^* is related to single point.

	Weight λ_1	α_1	β_1	α_2	μ_2	L_2^*
Sample mean	0.58	3.05	0.33	3.10	48,10	0.04838
Sample variance	0.06497	0.36283	0.20162	0.53756	89.6481	

Tab. 1. Results of PM 1 identification

	Weight λ_1	α_1	β_1	α_2	μ_2	L_2^*
Sample mean	0.67	2.94	0.22	2.49	32.14	0.02882
Sample variance	0.08889	0.64434	0.15425	1.17302	75.6903	

Tab. 2. Results of PM 2 identification

	Weight λ_1	α_1	β_1	α_2	μ_2	L_2^*
Sample mean	0.60	2.57	0.37	2.11	22.83	0.03917
Sample variance	0.05914	0.54029	0.24979	0.75512	29.63803	

Tab. 3. Results of PM 3 identification

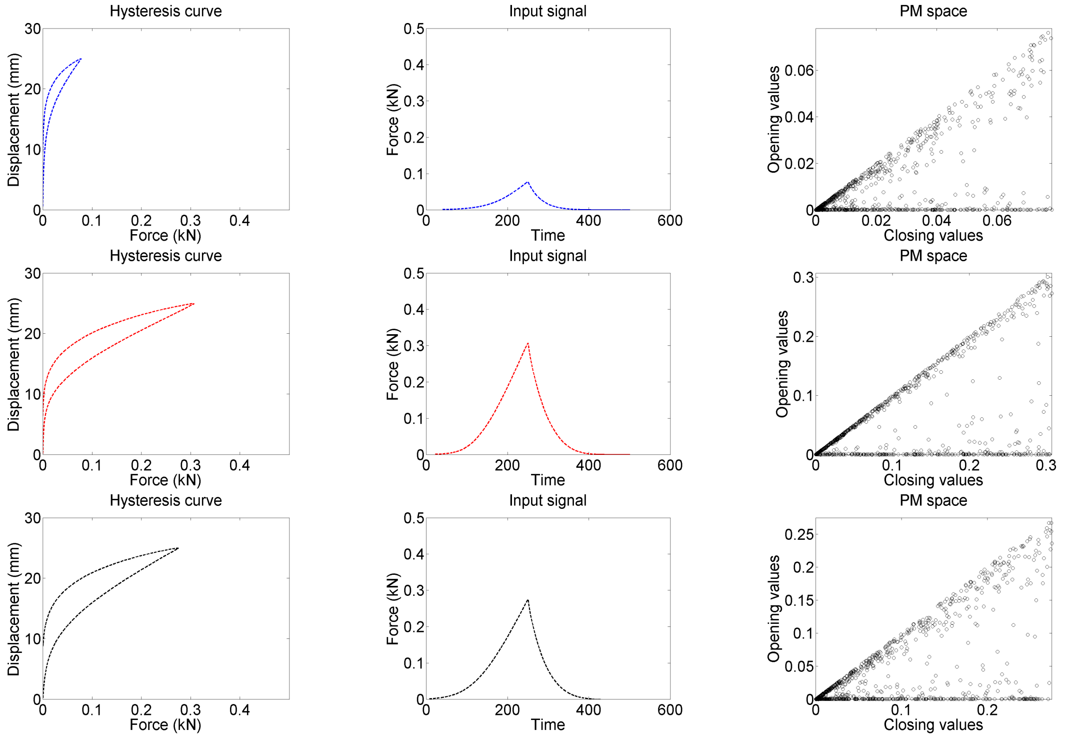

Fig. 5. The experimentally measured hysteresis curves and input signals of porcine skin tissue and final related PM spaces identifying the elasticity of porcine skin

5 Conclusion

Results of PM space density identification of porcine skin tissue by means of iterative optimization method based on minimizing the distance between the hypothetic hysteresis curve and the measured one are presented. Analysis of data coming from hysteresis behavior shows that the PM space approach could be perspective and it models more complex structures of the real materials, revealing other different biological structures in the real life around. It is shown that PM space with a $N = 1000$ HEU statistically disctributed along a mixture of Guyer 1 and Guyer 2 disctribution could approximate the mechanical viscoelasticity of the skin under uni-axial loading. The objective to extend this modern approach to the skin and the human brain, whose memory effects are currently accepted, gives this approach a promising future for modern engineering and medical biomechanical imaging.

The skin is thus an analog memory, where the analog value is stored in internal state variables (hysteretic elements) and read out by interrogating the skin plasticity during complex loading. The complex modeling of the skin behavior is extremely nonlinear in stress-strain, with negligible elastic modulus changes at low stresses, and very rapid elastic modulus changes occurring at large stresses. Our analysis therefore provide both experimental evidence and crucial analysis for describing the skin plasticity as the consequences of the hysteretic behavior of multi-scale distributed hysteretic elementary units based on single memristive element.

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