論文の内容の要旨

論文題目　A Mechanical Approach to Wrinkle Formation in Aging Skin Based on Buckling Analysis
（座屈解析に基づく老化にともなうシワ形成機構の検討）

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Skin is the largest organ of human body, which constitutes about 16% of body weight. It serves for protection, identification, communication, and emotional expression functions. The incidence of skin problems increases with age because of changes in skin structure and a lifetime accumulation of environmental damage. Wrinkle is the primary obvious sign of anxiety in aged skin. Although skin wrinkle varies in severity, it adversely affects mental health and quality of life. Early recognition, prevention, and treatment of skin wrinkle are therefore an important element in the overall care of the middle-aged and older group.

Dermatologists describe the appearance of skin aging from two processes, that is, intrinsic and extrinsic aging processes. Intrinsic aging reflects the genetic background of individual and results from the passage of time. The characteristics of intrinsic aged skin are smooth and unblemished, with exaggerated expression line but preservation of the normal geometric pattern of the skin. On the other hand, extrinsic aging is a result from external factors such as smoking, drinking, poor nutrition, and sun exposure. Sunlight is a major problem in the skin aging process. The harmful ultraviolet wavelengths not only damage the DNA in the cell of skin, but also inhibit the repair mechanism that repair damaged skin cells. The breakdown of DNA, collagen, elastin, and other supporting molecules in the dermis leads changes in skin. Extrinsic aging appears predominantly in exposed areas of the skin such as face and arms. Coarse wrinkle, dyspigmentation, and laxity are signs associated with photoaging.

At present, the knowledge about mechanism and structure of wrinkles is partly known. Wrinkle is the skin deformation and it emerges from the combination of biological and mechanical processes. While the biological consideration of the wrinkle problem has been extremely studied, the mechanical side is still far from to be understood. Therefore, it is a challenging task to get more understanding in wrinkle and its mechanism in order to establish a suitable guideline for the applications. The present study proposed a mechanical consideration of wrinkle formation and established methodology to evaluate wrinkle property in aged skin.

Skin consists of three main layers, epidermis, dermis, and hypodermis. The epidermis is subdivided into stratum corneum and the living epidermis layers. Stratum corneum contains dead cells and is stiffer than other layers. Thus, it should be considered as an independent layer. The dermis is divided into two layers, that is, papillary dermis and reticular dermis. The papillary dermis has an undulating shape and contains moisture, loose connective tissue, and fine elastic and collagen fibers. Thus papillary is softer and more flexible than reticular dermis. Hypodermis is fat layer, which property depends on the body site, gender, and individual. From this mechanical viewpoint, the skin can be represented with five layers model.

The permanent wrinkle is initiated by the repetition of skin buckling caused by muscle contraction at the same site in the long period such as expressive wrinkle in facial skin. Thus, the buckling property is the most important factor for skin wrinkle. To establish the methodology for investigate the fundamental property of the skin, a bilayer model, in which the upper layer is thin and stiff compares to the lower layer, is employed. The skin wrinkle is interpreted as a consequence of the buckling of the upper stiff layer of this model.

The infinite expanded skin is assumed subjected to uniform compression which is induced by a muscle contraction. The problem is described as a compressed beam on elastic foundation. The linear springs, which are uniformly distributed under the beam, characterize the elastic foundation. The compressive load P applied on the beam and the compression of foundation is neglected. A unit depth is employed as a consideration for the infinite width. Each layer is assumed linearly elastic and small deformation. The linear buckling analysis of beam theory is carried out. The flexural rigidity of the beam is denoted by EI, and the spring constant of elastic foundation per unit beam length is denoted by k. The beam length is denoted by L, which is infinite and unknown in the skin problem. Young's moduli of the upper and lower layers are denoted by E_U and E_L, the thicknesses are denoted as t_U and t_L, respectively. Thus E_U is Young's modulus of beam and the spring constant equal to E_L/t_L. Let the deflection of the beam by ν, and buckling equation can be written as,

$$EI\frac{d^4\nu}{dx^4}+P\frac{d^2\nu}{dx^2}+k\nu=0. \tag{1}$$

The minimum buckling load for a periodic solution is obtained by,

$$P_{cr}=2\sqrt{kEI}. \tag{2}$$

This is realized when the beam length is satisfies

$$L=\alpha W_{cr}, \tag{3}$$

where α represent the buckling mode, and W_{cr} is the wavelength of the minimum buckling load, which is determined by

$$W_{cr} = 2\pi\sqrt[4]{\frac{EI}{k}}, \tag{4}$$

and it is referred as a specific wrinkle size in wrinkle analysis. The W_{cr} is constant value, which is obtained from material parameters. To analyze the multilayer structure of skin, the critical strain is adopted as a compared parameter instead of critical load. The critical strain is calculated from.

$$\varepsilon_{cr} = \frac{P_{cr}}{E_U t_U}. \tag{5}$$

The critical strain means resistance against the buckling. The buckling that has the smaller critical strain appears on the skin and strongly affects the formation of permanent wrinkles.

Finite element method is introduced to analyze the more realistic skin problem. To obtain the buckling property of skin, the infinite-length skin and its compression in the plane of cross section are considered. Assuming the periodicity of the buckling mode, the finite-length periodic cell model is introduced. The length L is unknown, which is identified so as to minimize the buckling strain, because this kind of constrained buckling problem has the characteristic wavelength of the buckling mode. The cell model is compressed with uniform displacement d. Introducing scaling factor λ, and the critical unknown displacement is described by λd. By using the finite element method, the eigenvalue problem for linear buckling can be described as,

$$(\mathbf{K} - \lambda\mathbf{G})\mathbf{V} = \mathbf{0}, \tag{6}$$

where $\mathbf{K}$ represents the linear stiffness matrix, $\mathbf{G}$ is the geometric stiffness and, $\mathbf{V}$ is buckling mode. The scalar factor λ is determined as the eigenvalue. The geometric stiffness matrix includes the current stress which can be represented by $\lambda\mathbf{t}$, where $\mathbf{t}$ is the stress tensor corresponding to the displacement d. Thus, G is obtained from $\mathbf{t}$.

The buckling feature depends on the length of the structure. The first critical point appears at the minimum buckling load. To obtain the optimum periodic length L_{cr} and the critical strain ε_{cr}, the first minimum buckling strain is minimized with respect to the model length L. For this minimization, starting from the tentative length $\overline{L}$, the first minimum buckling strain ε_1 is approximated in the sense of the second-order as,

$$\varepsilon_1 = \overline{\varepsilon}_1 + \varepsilon_1^{\mathrm{I}}\Delta L + \frac{1}{2}\varepsilon_1^{\mathrm{II}}\Delta L^2, \tag{7}$$

where $\overline{\varepsilon}_1$ is the current value corresponding to $\overline{L}$. $\varepsilon_1^{\mathrm{I}}$ and $\varepsilon_1^{\mathrm{II}}$ are the first- and second-order sensitivities, respectively, obtained by the finite element sensitivity analysis for the eigenvalue problem of Eq. (6). The correction ΔL is determined so as to minimize ε_1 of Eq. (7). By the iterative renewals, the model length L reaches at its optimum L_{cr}, the critical strain ε_{cr} is determined. The specific wrinkle size W_{cr} is the wavelength of the first minimum buckling mode.

Three distinct buckling stages are categorized. Stage I is stratum corneum buckling, where the stratum corneum buckles under the support of epidermis. Stage II is epidermis buckling, where stratum corneum and epidermis simultaneously buckle with the support of papillary dermis. Stage III is defined as dermis buckling, where all skin layers buckle from the support of hypodermis. The reticular dermis is not considered as the lowest layer since this layer is stiffer than the upper papillary dermis layer.

The flat skin model and aging hypothesis are proposed to demonstrate the aged – related changes of wrinkle. The realistic value of the material parameters of facial skin are employed to skin model. The stiffening of skin in each layer and thinning of epidermis are the effect of intrinsic aging. The effect of photoaging is represented by thickening of papillary dermis. It is assumed that the material parameters alter linearly with aging. The influence of epidermis aging, which is defined by changing the material parameters of stratum corneum and epidermis, is investigated and compared with the affect of dermis aging, which is characterized by alteration of material property of papillary and reticular layers.

As results, epidermis aging has much stronger influence to total aging than dermal aging. Critical strain becomes smaller, while the specific wrinkle size basically increases with aging. The wrinkle size of stage I buckling is close to the fingerprint, which is too small and not to be recognized as a wrinkle. Stage II and Stage III are similar to small and large wrinkles, respectively. In facial skin, the large wrinkle appears as an expressive wrinkle around eyes or month, and disappears with relaxation of expressive muscle in young skin. The buckling strain of the dermis buckling (stage III) is too large to predict within the framework of small deformation. The aging leads to the switch of minimum buckling mode, from stratum corneum buckling (stage I) to epidermal buckling (stage II). Mode switch drastically enlarges the specific wrinkle size. The large specific wrinkle size suddenly appears at certain middle age. The mode switch also supports the fact that the wrinkle suddenly appears with aging on similar site to the position of expressive wrinkle, where the buckling of skin is frequent repeated. This repetition of buckling enhances the opportunity to yield the large wrinkle in the aged skin and to damage the epidermal and dermal, which more significant than stratum corneum buckling in young skin. Therefore, the mode switch from stratum corneum to epidermal buckling gives rise to permanent wrinkle.

The effect of the geometrical complexity of papilla is taken into account in the skin aging model with papillae. The sinusoidal undulating is introduced to represent the interface between epidermis and dermis layers. The papillae are flattening with aging. The total aging model is proposed by considering both alteration of material properties and shape of papilla. The results show that the buckling periodic and papillary periodic are different and independent. The shape of papilla affects the wrinkle formation. The existence of papilla induces the stratum corneum buckling and prevents switching of buckling mode. Therefore, papilla prevents the appearance of large wrinkle.

In conclusion, a new methodology based on mechanical perspective has been developed for evaluation of the mechanism of wrinkle formation. The methodology treats skin as multilayer structure with different material properties and analyzes with minimum-buckling analysis in order to estimate the wrinkle properties of skin and effect of aging. The specific wrinkle size W_{cr} and critical strain ε_{cr} are a pair of quantitative measure parameters for wrinkle analysis. The proposed method is verified with skin aging models with and without papilla. We obtained a hypothesis that aged prominent wrinkle comes from the buckling mode switch of skin with aging. The epidermal aging (stage II) has strong effect on wrinkle formation. The undulating surface of papillae assists stratum corneum buckling and prevents the mode switch to epidermal buckling. Consequently, maintaining the shape of papilla is necessary for anti-wrinkle therapy.

In the cosmetic industry, collagen, elastin, hyaluronic acid, and other skin components are popular additions to anti-wrinkle creams. Putting these components in skin care products may sound convincing, however, when applied to the skin, these creams do not have much effect on the changes in appearance. Collagen, elastin, and hyaluronic acid are components in dermis layer. Our results show that dermis layer has lesser influence to wrinkle than epidermis layer. Therefore, to prevent the appearance of wrinkle, it is important to focus on epidermis layer instead of dermis layer.