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DETERMINATION OF UNIAXIAL TENSILE BEHAVIOR OF HYPODERMIS IN PORCINE SKIN BASED ON RULE OF MIXTURES

In this study, we investigate the mechanical behavior of each skin layer, in terms of the nominal stress-strain curve by uniaxial tensile tests using specimens of porcine skin in two forms: dermis containing epidermis, and all three layers. All tests were performed under cyclic loading at the constant strain rate of 10^{-3} s^{-1} at ambient temperature. To measure the precise initial cross-sectional areas of each layer, the thickness of each skin layer was quantified by counting the number of pixels on the photo-image using image-processing software. In the tensile test, force-strain curves of the total skin and dermis with epidermis were obtained. Subsequently, a rule of mixtures was applied to determine the nonlinear mechanical properties of the hypodermis layer. In conclusion, we could define the uniaxial tensile behavior of the hypodermis, and additionally predict the weight effect of the dermis and hypodermis layers in the tensile test.

Keywords: Porcine skin, Skin layers, Visco-hyperelastic, Constitutive model

1. Introduction

The skin has a complex structure consisting of three primary layers (epidermis, dermis, and hypodermis) and many fibers (collagen fibers and elastic fibers) such as composite materials. It is responsible for preventing the body from external influences such as external forces. Hence, characterizing the skin's mechanical behavior in terms of its structure. A reliable constitutive model and its precise calibration for skin mechanics are necessary for an accurate computer simulation of the mechanical deformation of materials and structures [1-5]

Many researchers have studied the mechanical properties of the skin by conducting a variety of experiments such as uniaxial, torsion, and indentation tests in in-vivo and ex-vivo conditions. Among them, the tensile test is the most popular method to detect mechanical properties such as the stress – strain relationship, as this test can be performed in both in-vivo and ex-vivo conditions. To obtain a reliable description of the mechanical behavior of the skin, the structure of all its layers must be considered. However, some researchers have performed the tensile tests by considering only the dermis and epidermis instead of all three layers, because the dermis influences the tensile strength dominantly owing to its composition of elastin and collagen fibers [6-10].

According to the literature [1], the hypodermis is attached beneath the dermis and serves to connect the skin to the fascia underlying the bone and muscle. The boundary between the hypodermis and dermis may be difficult to distinguish, but is strictly part of the skin structure. Moreover, it has variable thicknesses throughout the body (e.g., head, abdomen, arm, finger, etc.). In these parts, this layer acts mechanically to resist external influences. Therefore, during mechanical testing, the consideration of all skin layers is essential.

Likewise, many researchers have modeled the mechanical behavior of the dermis and epidermis as constitutive equations. Further, all skin layers are well known for their nonlinear mechanical properties. However, some researchers have performed studies to derive the modulus of elasticity such as the Young's modulus, while others have performed nonlinear properties only on the dermis and epidermis not considering hypodermis [1-10].

The aim of this paper is to determine the uniaxial tensile behavior of the hypodermis (*H* layer) under tensile loading using the rule of mixtures related to the force-displacement relationships of the dermis (*ED* layer) containing the epidermis and the total skin layer. Porcine skin samples with all three layers (total layer) and the *ED* layer were prepared and subjected to uniaxial tension loading at a quasi-static strain rate.

2. Experimental

Porcine skin was obtained from a white Yucatan minipig, 100 days old, with a weight of approximately 10 kg. Large samples of porcine skin were carefully extracted from the abdomen such that the fat was removed. This was achieved by a Korean company (Optipharm co., LTD). The specimens were cut in a di-

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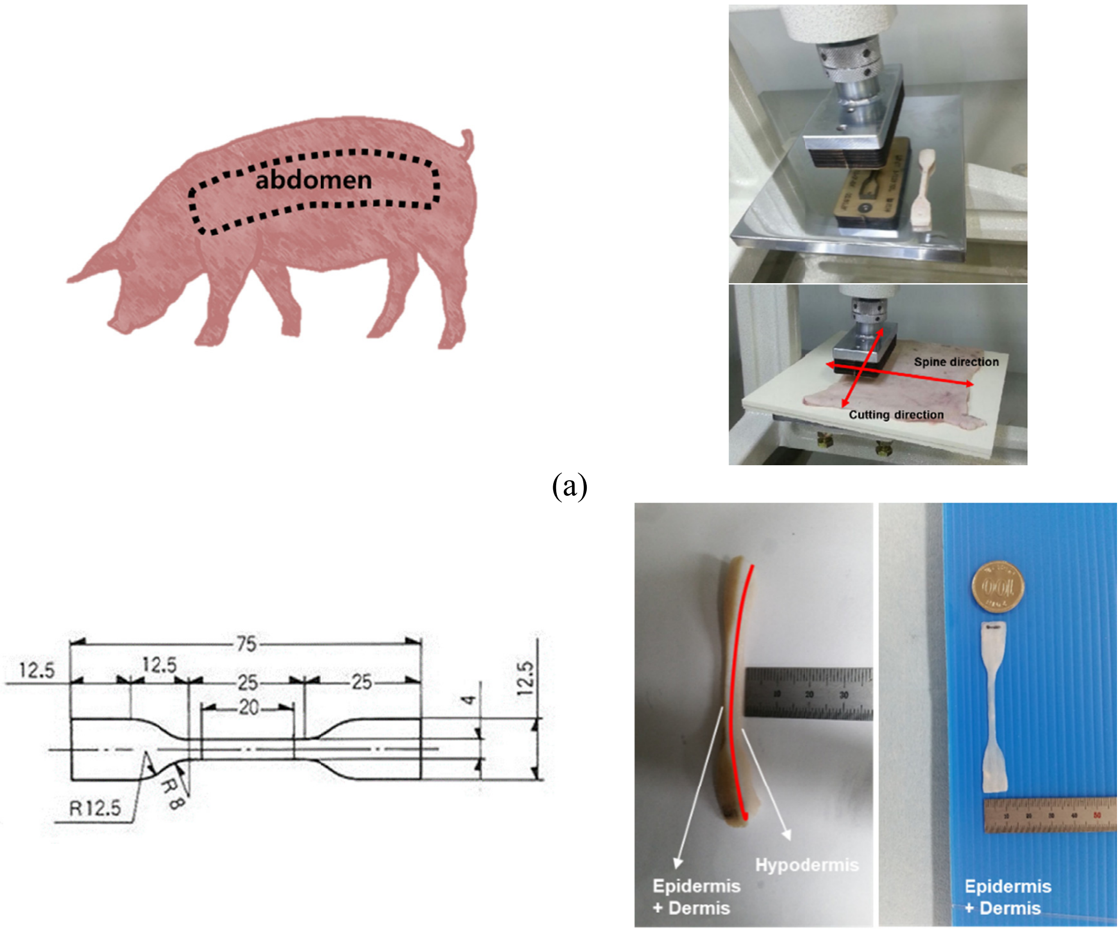


Fig. 1. (a) Portion and methods to extract tensile specimens in the direction and cutting, (b) Dimensions of the specimen, and (c): two types of specimen

rection perpendicular to the porcine spine, as shown in Fig. 1(a), and by a punch device made according to the dimensions of the DIN 53504 standard of rubber, as shown Fig. 1(b). In this study, two types of specimens were prepared, as shown in Fig. 1(c): (1) Dermis (*ED*) containing epidermis without hypodermis, (2) All three skin layers (total layer containing epidermis, dermis, and hypodermis).

For all tests, the specimens were packaged in vacuum to maintain the skin freshness. Moreover, to measure the thickness of each layer, povidone (purchased at a local stationary store) was applied onto the sidewall of the specimen before beginning the tensile test. Tensile testing was performed using a universal tester (Model 5848, Instron, Buckinghamshire, UK). According to a previous study [7], the quasi-static cyclic tensile test was performed on skin specimens (three *ED* layers and three total layers) at a constant strain rate of 10^{-3}/s. In order to predict the precise nominal stress of each skin layer (*ED* layer and *H* layer), the thicknesses for calculating the initial cross-sectional area on the specimens of three *ED* layers and three *H* layers in the total skin were measured using image-processing software (Image J). Subsequently, we applied the rule of mixtures to determine the mechanical behaviors of the *ED* layer and *H* layer. Based on this theory, the tensile behavior of the skin composed of three layers can be obtained by combining the volume fraction and tensile properties of the *ED* layer and *H* layer as follows:

$$\sigma_{total\ skin} = \sigma_{ED} V_{ED} + \sigma_H V_H \tag{1}$$

where σ_{total} skin, σ_{ED}, and σ_H indicate the tensile stresses of the total layer, *ED* layer, and *H* layer, respectively. V_{ED} and V_H are the volume fractions (%) of the *ED* layer and *H* layer, respectively. Because the length of each layer in volume is the same based on equation (1), we can express it as follows:

$$\sigma_{total\ skin} = \sigma_{ED} \frac{A_{ED}}{A_{Total}} + \sigma_H \frac{A_H}{A_{Total}} \tag{2}$$

$$\sigma_{total\ skin} A_{Total} = \sigma_{ED} A_{ED} + \sigma_H A_H \tag{3}$$

$$F_{Total\ skin} = F_{ED} + F_H \tag{4}$$

where A_{total}, A_{ED}, and A_H indicate the cross-sectional areas of the total layer, *ED* layer, and *H* layer, respectively. $F_{total\ skin}$, F_{ED}, and F_H are the tensile forces of the total layer, *ED* layer, and *H* layer, respectively.

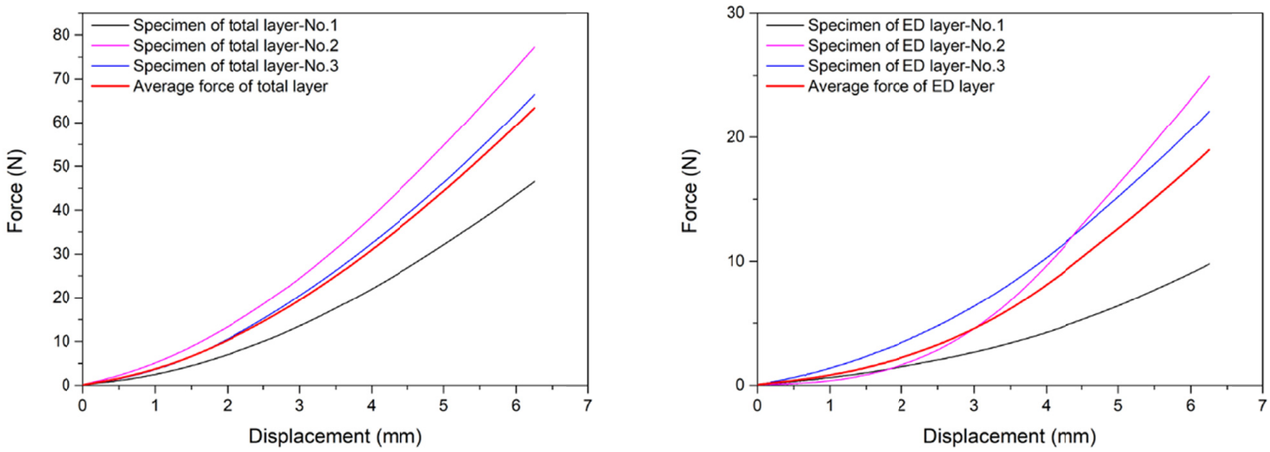
We could identify the mechanical property of the *H* layer using the average F_{Total} and the average F_{ED} obtained from conducting the tensile test on the specimens of the total layer and *ED* layer of the skin specimen. Further, we determined the weight effect of the *ED* layer and *H* layer at the same tensile strain while performing the tensile test.

3. Results and discussion

In this study, quasi-static tensile tests were conducted on two types of skin specimens (total layer and *ED* layer) extracted from a sample of the abdomen that was cut along the same direction (perpendicular to porcine spine) and according to the same geometry.

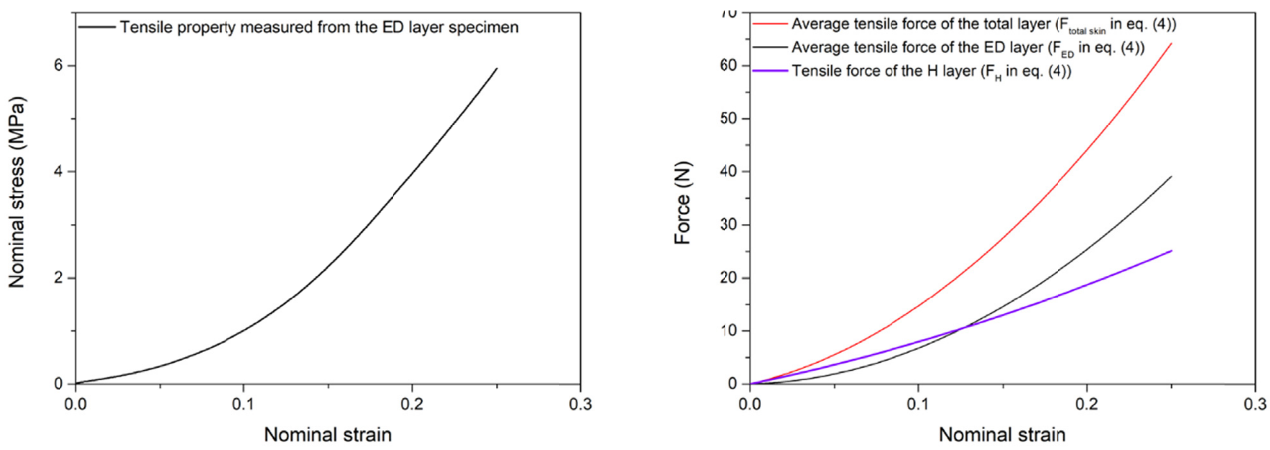
Figure 2 shows the force-displacement relationships of (a) the total skin layer, and (b) the dermis containing the epidermis of the abdomen porcine skin. These curves were represented from the first loading cycle of the tensile test. According to previous studies [6-7], the J shape is classically divided into three regimes related to the microstructure, such as elastin fibers and collagen fibers in the dermis. Although the specimens were extracted from same anatomical body region such as the abdomen of the pig, the force-displacement curves are slightly different. Thus, the average force-displacement curve was calculated for each type of specimen (the total layer and the *ED* layer). The average curve will be used for defining the mechanical property of the hypodermis.

In the case of the tensile-force-displacement curve for the ED layer, the nominal stress-strain can be converted from the force-displacement curve because only one layer exists in the initial cross-sectional area. In contrast, the nominal stress-strain relationship of the total layer cannot be converted from the force-displacement curve because it contains each layer that is responsible for resisting against the tensile force. This means that it is difficult to determine the initial cross-sectional area of the composite material. Therefore, as shown in Fig. 3(a), the nominal stress-strain curve (tensile property) of the *ED* layer was determined using an initial cross-sectional area of the *ED*



(a) (b)

Fig. 2. Force-displacement curves of (a) the total layer and (b) the ED layer in quasi-static tensile tests. The average force is calculated to define the mechanical property of the hypodermis



(a) (b)

Fig. 3. (a) Tensile property of the *ED* layer without the hypodermis for utilizing the rule of mixtures. (b) predicted tensile force-strain curve (solid violet line) of the hypodermis according to the difference between tensile forces of the total layer (solid red line, F_{total} skin in eq. 4) and the *ED* layer (solid black line, FED in eq. 4) in force relationships using the rule of mixtures

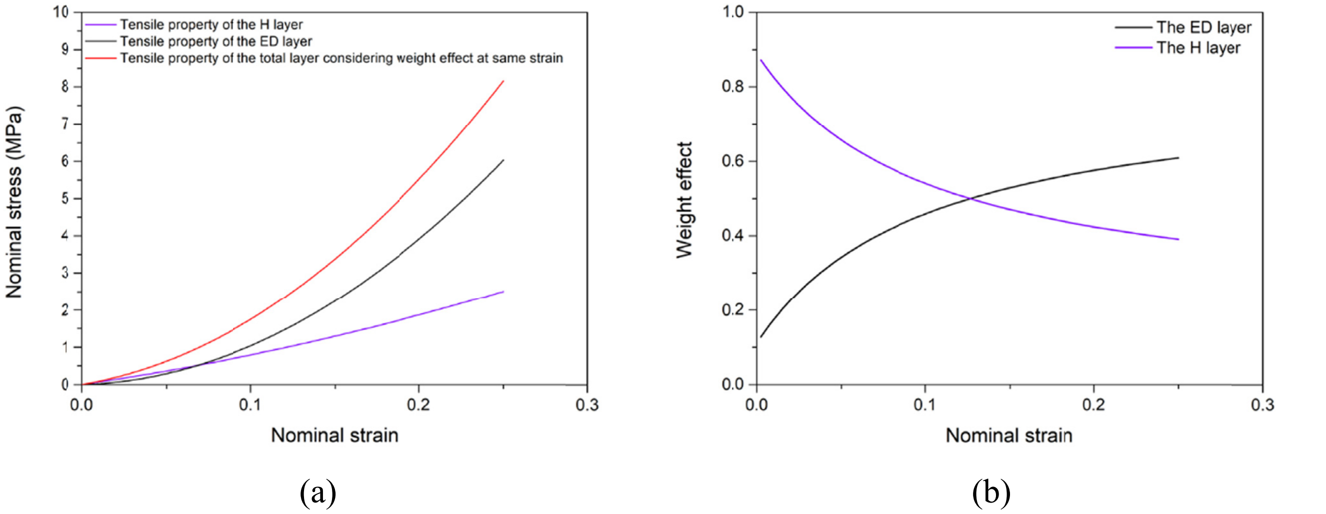


Fig. 4. (a) Tensile property of specimens of the *ED* layer (solid black line), H layer (solid violet line) and total layer (solid red line). The tensile property of the total layer was predicted using results of Fig. 4(b). (b) weight effect is calculated as the ratio between the *ED* layer and *H* layer at same strain

layer using thickness measured from image processing, and was subsequently applied to the force relationships related to the rule of mixtures. We calculated the force of the ED layer in the total skin layer using the multiplication between the average force and initial cross-sectional area. Subsequently, it was substituted into equation (3) as F_{ED}. Because F_{total} skin is known, the mechanical behavior of the *H* layer can be calculated, as shown in Fig. 3(b).

As shown in Fig. 4(a), the mechanical property for the tensile strain of the *ED* layer is determined. Further, that for the H layer is also defined based on the rule of mixtures, and the mechanical property for the tensile strain of the total layer is predicted using the weight effect between the *ED* layer and *H* layer, as shown in Fig. 4(b). Here, weight effect means the force ratio of between the *ED* layer and the H layer with each strain during tensile test. As shown in the nominal stress-strain curves in Fig. 4(a), similar to the dermis, the hypodermis also governs the tensile property of the total skin layer. In addition, according to the results of Fig. 4(b), with the increase in strain, the role of the *ED* layer becomes more important, whereas the role of the *H* layer becomes less significant.

4. Conclusions

The uniaxial tensile behavior of porcine skin with three primary layers was investigated under quasi-static cyclic uniaxial loading conditions. In addition, we measured the thicknesses of two skin layers (the *ED* layer and the *H* layer) using image processing for calculating the precise initial cross-sectional area of each skin layer. Hence, we obtained the mechanical property of the hypodermis layer in the tensile test using the rule of mixtures. The result showed that the mechanical property of the hypodermis of porcine skin was influenced by the tensile test. Overall, although the dermis was reported to exhibit the dominant role of resistance against tension, the hypodermis was also an important layer in the tensile test. The results from this study would facilitate in the construction of a constitutive model for each skin layer in biomechanical fields.

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