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3-Dimensional Stress Calculation of Competitive Swimwear Using Anisotropic Hyperelastic Model Considering Stress Softening

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Abstract

Three dimensional stress calculation of competitive swimwear using anisotropic hyperelastic model considering stress softening was investigated in this paper. An anisotropic hyperelastic model considering stress softening of swimwear fabrics was introduced in order to reproduce the mechanical characteristics of swimwear fabrics on the analysis. The cyclic tensile loading test was carried out to evaluate the mechanical characteristics of the swimwear fabrics. From the test results, the mechanical characteristics of swimwear fabrics show strong-anisotropy and the stiffness of the fabrics shows hardening along with the increase of stretch. Also, the test results show reduction of stiffness which depended on the maximum deformation previously reached in the history of the swimwear fabrics. From the test results, material parameters of the anisotropic hyperelastic model and the stress softening model were approximated. The theoretical calculations were in good agreements with experimental data. In addition, the pressure measurement tests were conducted to measure the pressure of swimwear tightening the cylinder. The theoretical pressure calculated by the proposed model showed similar trend of pressure measurement tests. Finally, 3-dimensional stress calculation of swimwear was conducted using the anisotropic hyperelastic model considering stress softening. The stress calculation enabled the visualization of stress distributions of swimwear. In addition, the torque generated in right and left hip joints were calculated by stress calculation of swimwear. The stress calculation investigated in this study enabled the new design of competitive swimwear considering the torque generated in hip joint.

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1. Introduction

Currently, the competitive swimwear is designed for increasing the pressure to adjust human body shape and the swimwear increases the water resistance. However, investigating the effect of the swimwear to the body during swimming in water would be difficult. Therefore, stress analysis of swimwear would be useful. Also, the swimwear fabrics show anisotropic depending on tensile direction. In addition, stress of the swimwear fabrics is softened by the maximum strain experienced in each warp and weft fibers. Therefore, analysis method considering the stress softening would be useful for design methods of competitive swimwear.

In this study, 3-dimensional stress calculation of competitive swimwear using anisotropic hyperelastic model considering stress softening was proposed. Proposed hyperelastic model was applied to calculate stress distribution of swimwear in four swimming motions, crawl, backstroke, butterfly and breaststroke. Stress softening model considering anisotropic hyperelastic model for competitive swimwear was proposed. Cyclic tensile loading tests were conducted to verify the anisotropic hyperelastic model and softening function. In addition, pressure measurement tests were conducted to measure the pressure of the swimwear using the acrylic cylinder. Finally, 3-dimensional stress calculation of swimwear was conducted to calculate the effect of swimwear on the human body during swimming. The stress calculation enabled the visualization of stress distributions of swimwear. In addition, the torque generated in right and left hip joints were calculated by stress calculation of swimwear. The stress calculation proposed in this study enabled new design of competitive swimwear considering the torque generated in each hip joint.

2. Material testing and anisotropic modeling of swimsuits

2.1. Cyclic loading tests

The cyclic tensile tests were conducted to evaluate the anisotropy and stress softening of swimwear fabrics. The materials of the test specimens were weave fiber which is consisting of nylon 73% and polyurethane 27%. Dimensions of the specimens were 120 mm length, 30 mm width, and 0.2mm thick. In addition, the fiber orientation angles of prepared test specimens were 0°, 15°, 30°, 45°, 60°, 75° and 90° to evaluate the anisotropy of swimwear fabrics. The maximum tensile displacements were 168mm, 180mm, 192mm, 204mm and 216mm which were correspond to the stretch of 140%, 150%, 160%, 170% and 180% along the specimen. 5-cyclic tensile deformations were applied to the specimens for each elongation to evaluate the stress softening of swimwear fabrics. Speed of fixing jigs was set as 1mm/sec.

2.2. Anisotropic hyperelastic model considering stress softening

In this study, the strain energy function considering stress softening proposed by Matsuda et al. (2013) was introduced as follow to reproduce the mechanical characteristics of swimwear fabrics on the analysis:

$$W = W_{iso}(\mathbf{C}) + S(I_{4 \max}^{(1)})W_{ani}(\mathbf{C}, \mathbf{M}^{(1)}) + S(I_{4 \max}^{(2)})W_{ani}(\mathbf{C}, \mathbf{M}^{(2)}) \quad (1)$$

where, \mathbf{C} is the right Cauchy-Green deformation tensor. $\mathbf{M}^{(1)}$ and $\mathbf{M}^{(2)}$ are the structural tensors. $I_{4 \max}^{(1)}$ and $I_{4 \max}^{(2)}$ are maximum elongations experienced by swimwear-fabrics. $W_{iso}(\mathbf{C})$ is the Mooney-Rivlin model proposed by Rivlin et al. (1951) and anisotropic part W_{ani} is proposed by Asai et al. (2010). Softening function $S(I_{4 \max}^{(1)})$ and $S(I_{4 \max}^{(2)})$ proposed Matsuda et al. (2013) were defined as follows:

$$S(I_{4 \max}^{(1)}) = 1 - \alpha_1 [1 - \exp\{-\gamma_1 (I_{4 \max}^{(1)} - 1)\}] \quad , \quad S(I_{4 \max}^{(2)}) = 1 - \alpha_2 [1 - \exp\{-\gamma_2 (I_{4 \max}^{(2)} - 1)\}] \quad (2)$$

where, $\alpha_1, \alpha_2 \geq 0$, γ_1 and γ_2 are the softening parameters for fabrics. The second Piola-Kirchhoff stress tensor \mathbf{S} is given by the partial differentiation of the strain energy function W with respect to the right Cauchy-Green tensor \mathbf{C} as follow:

$$\mathbf{S} = 2 \frac{\partial W}{\partial \mathbf{C}} \quad (3)$$

Material constants of Eq.2 were identified using the stiffness ratios. The relationship between nominal stress and nominal stretch was calculated theoretically using Eq. 1, Eq. 2, and Eq. 3. Material constants of Eq. 1 were identified using the cyclic loading test results (0° , 45° and 90°). Fig.1 shows the cyclic loading test results (0° , 45° and 90°) for the second time at the each maximum elongations (1.4, 1.6 and 1.8) and identification results of material parameters. The proposed model showed good agreements with experimental data in Fig.1. In addition, Fig.1 showed the stress was greatly reduced when updating the maximum elongation.

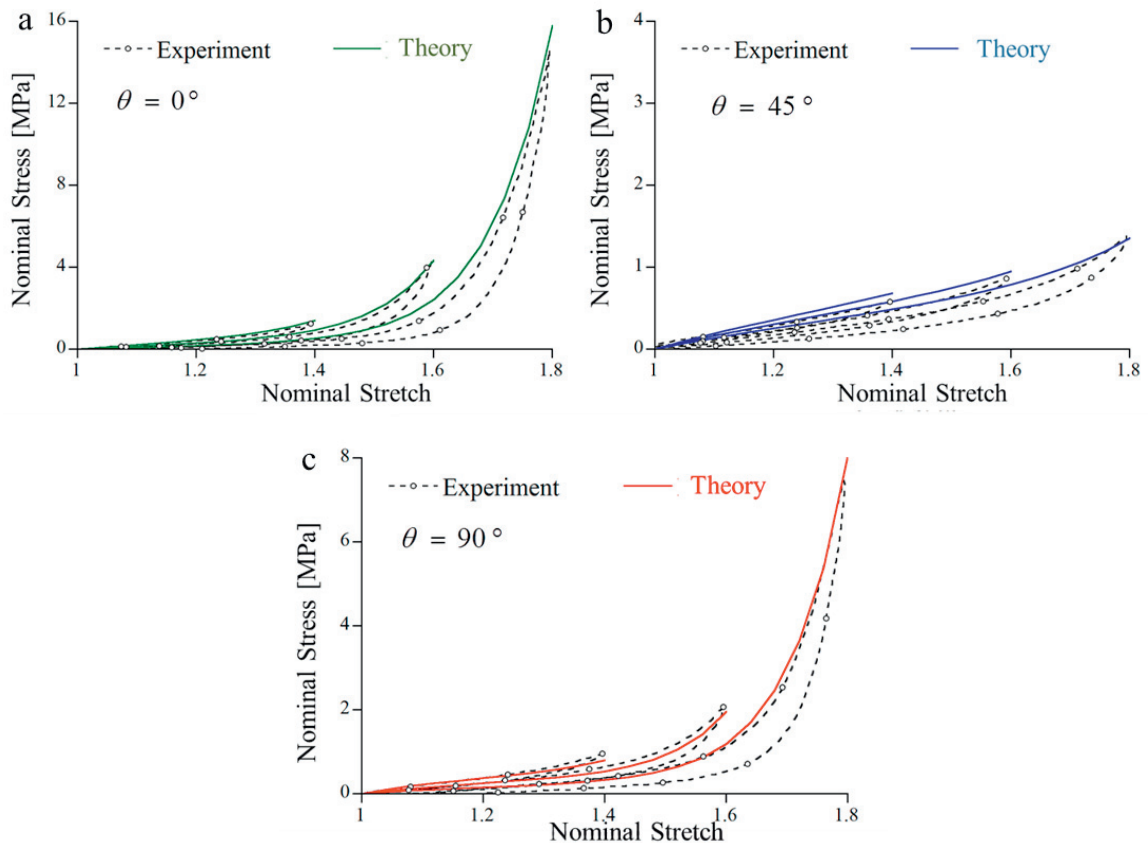


Fig.1 Comparisons of cyclic loading tests and theoretical calculation by nominal stress (a) $\theta = 0^\circ$ (b) $\theta = 45^\circ$ (c) $\theta = 90^\circ$

2.3. Pressure measurement tests

The pressure measurement tests were conducted to measure the pressure of swimwear tightening using acrylic cylinder. The diameter of the acrylic cylinder was 150mm which was similar to circumference of the thigh. The materials of the test specimens were the same of the cyclic loading tests. The width of the test specimen was 150 mm and the thickness was 0.2mm. The diameters of the test specimens were 125.0mm, 107.1mm and 93.8mm

which were corresponded to stretch of 120%, 140% and 160% along the circumference when placed to the cylinder of 150mm in diameter. The fiber orientation angle θ was assumed as the angle of directions between the warp and longer direction of cylinder. The angle θ of the specimen was 90° . The pressure was measured by six sensors of air-pack. The pressure test equipment is shown in Fig.2 (a) and Fig.2 (b). Fig.2 (c) shows the comparison of pressure in the test results and theoretical calculation. The pressure of theoretical calculation was calculated using Eq. 1, Eq. 2 and Eq. 3 as follow:

$$P = \frac{f}{\rho} \quad (4)$$

where, f is load per unit width generated in the tangential direction when the test specimen is placed to the cylinder and ρ is radius of curvature. In this paper, ρ is corresponded to radius of the cylinder. The theoretical pressure calculated by the proposed model showed similar trend of pressure measurement tests in Fig.2 (c).

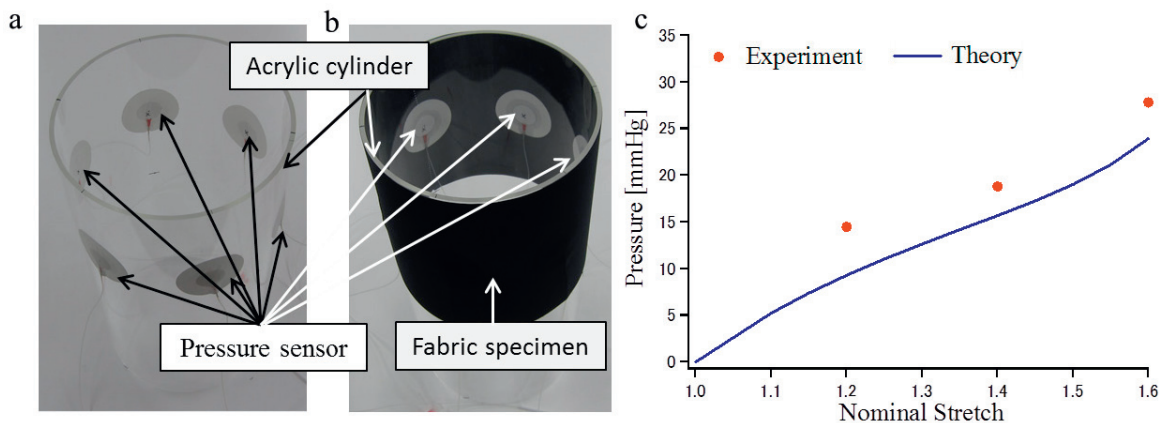


Fig.2 (a) Pressure test equipment (b) Pressure test equipment with fabric specimen
(c) Comparison of pressure in the pressure test results and theoretical calculation.

2.4. 3-dimensional stress calculation of swimwear

3-dimensional stress calculation of swimwear was conducted to calculate the effect of mechanical characteristics of swimwear on the human body. In this paper, deformations of swimwear were calculated from swimming motion of 3D-CG human model introducing the polygonal model of swimwear proposed by Matsuda et al. (2013). The 3D-CG model simulates the human body using 57416 nodes. One cycle of the swimming motions of crawl, backstroke, butterfly and breaststroke were represented by 45, 40, 34 and 29 of 3D-CG images, respectively. Fig.3 (a) showed the mesh of the swimwear used in the stress calculations. Fig.3 (b) shows the snapshot of 3D-CG human model during swimming butterfly. Fig.4 (a) shows Cauchy stress distribution of the swimwear generated during crawl. The Cauchy stress was calculated as following equation using the second Piola-Kirchhoff stress tensor.

$$\mathbf{T} = \frac{1}{J} \mathbf{F} \cdot \mathbf{S} \cdot \mathbf{F}^T \quad (5)$$

Here, \mathbf{F} is the deformation gradient tensor and \mathbf{F}^T is the transpose of the deformation gradient tensor. J is calculated as $J = \det(\mathbf{F})$. In Fig.4 (a), smooth stress distribution of swimwear was confirmed. Here, the strain energy function of the previous study was defined as follow:

$$W = W_{iso}(\mathbf{C}) + W_{ani}(\mathbf{C}, \mathbf{M}^{(1)}) + W_{ani}(\mathbf{C}, \mathbf{M}^{(2)}) \quad (6)$$

Material constants of Eq. 6 were identified to approximate to the monotonic loading test results (0°, 45° and 90°). Fig.4 (b) shows the comparison of the stress calculation of crawl using Eq. 1 and Eq. 6. In Fig. 4 (b), stress calculated using the proposed stress softening model in this study is shown. The stress of swimwear fabrics during swimming is similar to the cyclic tensile loading. Therefore, the proposed stress softening model in this study enabled accurate stress calculation of the swimwear. Fig.5 (a) and (b) show the relationships between the torques generated in each hip joints. This torque was calculated using the stress generated by the swimwear as follows:

$$\mathbf{N} = \mathbf{R} \times \mathbf{F} \quad (7)$$

where, \mathbf{R} is the position vectors between each elements of the swimwear and hip joint and \mathbf{F} is load vector. The torques of Fig.5 (a) and (b) are the value in kicking direction of crawl and butterfly. For symmetry movements of butterfly, Fig.5 (b) showed the torques of hip joints were high at a similar time. The proposed stress calculation method would enable the design of high performance competitive swimwear because the characteristics of each swimming motions are different.

3. Conclusion

3-dimensional stress calculation of competitive swimwear using 3D-CG of human model was investigated in this paper. Anisotropic hyperelastic model considering stress softening was introduced to reproduce the characteristics of the swimwear fabrics on the analysis. The stress softening function was formulated to decrease as the recorded maximum elongation increased. The material parameters of the anisotropic hyperelastic model were approximated to the cyclic tensile loading test results. In addition, the pressure measurement tests were conducted to measure the swimwear tightening pressure using acrylic cylinder. Finally, the swimming motions of 3D-CG model which represent human body motions were applied to stress calculation of polygonal model of swimwear by using the anisotropic hyperelastic model. The stress calculations enabled the visualizations of stress distributions of swimwear in 4 strokes (crawl, backstroke, butterfly and breaststroke). In addition, the torque generated in hip joint was calculated using proposed stress softening model. Therefore, 3-dimensional stress calculation investigated in this paper enabled the new design of competitive swimwear considering the torque generated in each hip joints.

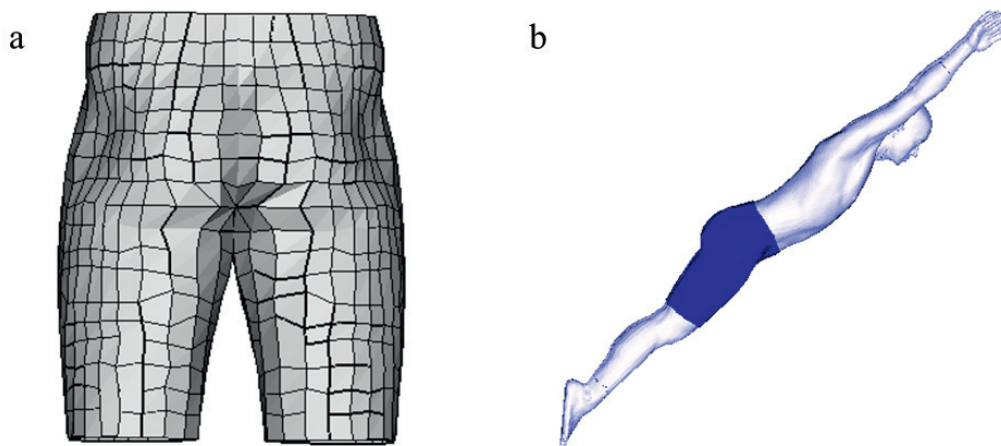


Fig.3 (a) The mesh of the swimwear (b) 3D-CG human model

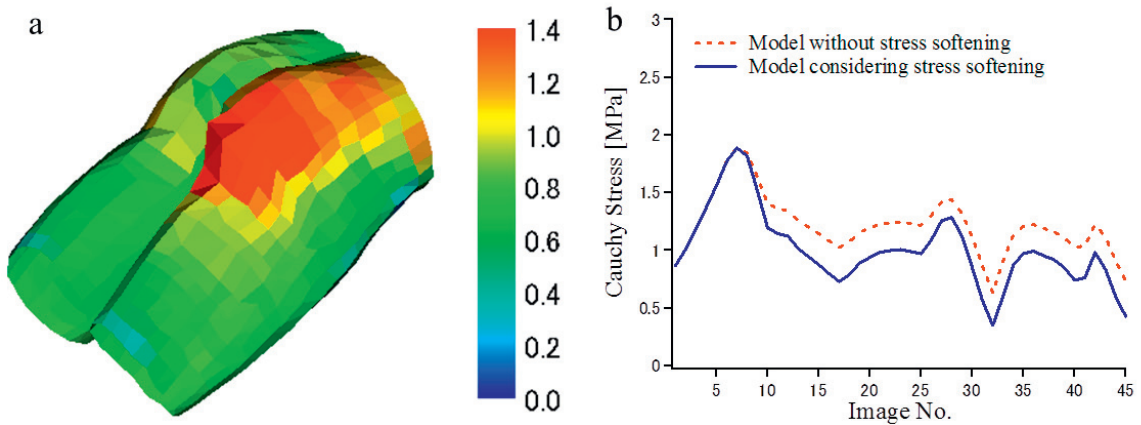


Fig.4 (a) Cauchy stress distribution of the swimwear
(b) The comparison of stress calculation between this study and previous study

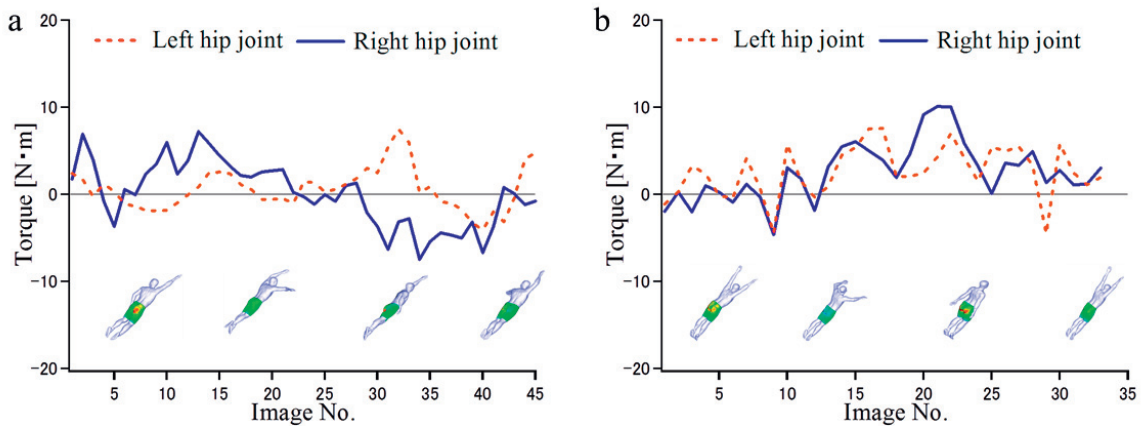


Fig.5 The torque generated in each hip joint (Direction of kicking) (a) Crawl (b) Butterfly

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