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3-Dimensional joint torque calculation of compression sportswear using 3D-CG human model

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Abstract

Recently, there have been many developments in compression sportswear and swimwear. The main purpose of compression sportswear is to keep athletes' muscles warm to prevent muscle strain and fatigue. Now, some compression sportswear has been developed to include a joint protection function. In this study, a design method for joint torque generated by compression sportswear such as competitive swimwear and compression long running tights is proposed. Information on the joint torque generated by sportswear would be useful for compression sportswear design. The proposed method calculates stress-strain relationships of sportswear fabrics using the anisotropic hyperelastic model, and calculates the frictional displacement between the human body and sportswear using a 3D-CG human model. In order to accurately calculate stress, anisotropic material modeling and a stress-softening model were applied to the mechanical characteristics of compression sportswear fabrics. The frictional displacement between the human body and swimwear during swimming was also considered for stress calculations. Typical sportswear fabrics exhibit anisotropic mechanical behavior depending on tensile direction. Also, the stiffness of the fabrics is softened by the maximum strain experienced in each warp and weft fiber. To accurately calculate the joint torques generated by compression sportswear, the anisotropy and stress softening of sportswear fabrics are considered for numerical modeling.

Keywords: Compression sportswear, Anisotropic hyperelasticity, 3D-CG human model

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1. Introduction

Currently, compression sportswear is designed to keep muscles warm in order to prevent muscle strain and damage. Also, recent swimwear has been designed to better adjust to human body shapes in order to reduce water resistance. Now, some types of compression sportswear have been developed to include a joint protection function.

From the perspective of engineering development, plain weave material, rather than knit fabric, is often used for compression sportswear because of its greater stiffness. However, it is known that plain weave material exhibits stress softening under cyclic deformation. To predict the effect of the material of compression sportswear on athletes, three-dimensional stress analyses using a 3D-CG human model were conducted by Matsuda et al. (Nagaoka et al. 2012, Matsuda et al. 2013 and Tanaka et al. 2014).

In this paper, a newly developed short- and long-tights 3D-CG human model are described, and the numerical results of the 3D-CG stress calculations for both running and swimming are presented. To consider stress softening with a plain weave material, an anisotropic hyperelastic model with stress softening was applied(1)(2). The purpose of this study is to develop the stress-calculation-based design method of compression sportswear to visualize the effects of mechanical factors of sportswear fabrics easily.

From the simulation results, the hip-joint torque generated by compression sportswear was calculated numerically. The optimal fiber orientation angle of swimwear fabrics and the initial stretch of competition swimwear were demonstrated for production of the maximum hip joint torque. Moreover stress-distributions of long-tights in jogging and sprint motions were visualized to understand knee joint support of compression long-tights.

2. Model for plain weave material

For the plain-weave sportswear material model, the strain energy function considering stress softening proposed by Matsuda et al. (2013) was applied.

$$\mathrm{W} = \mathrm{W}_{iso}(\mathbf{C}) + S(I_4^{(1)}{}_{\max})\mathrm{W}_{ani}(\mathbf{C},\mathbf{M}^{(1)}) + S(I_4^{(1)}{}_{\max})\mathrm{W}_{ani}(\mathbf{C},\mathbf{M}^{(2)}) \tag{1}$$

Here, $\mathbf{C}$ is the right Cauchy-Green deformation tensor. $\mathbf{M}^{(1)}$ and $\mathbf{M}^{(2)}$ are the structural tensors. $I_4^{(1)}{}_{\max}$ and $I_4^{(2)}{}_{\max}$ are maximum elongations experienced by swimwear fabrics. $\mathrm{W}_{iso}(\mathbf{C})$ is the Mooney-Rivlin model proposed by Rivlin et al. (1951), and the anisotropic part W_{ani} as proposed by Asai et al. (2010). Softening functions $S(I_4^{(1)}{}_{\max})$ and $S(I_4^{(2)}{}_{\max})$ proposed by Matsuda et al. (2013) are defined as follows:

$$S(I_4^{(1)}{}_{\max}) = 1-\alpha_1\left[1-\exp\left\{-\gamma_1\left(I_4^{(1)}{}_{\max}-1\right)\right\}\right] \ , \ S(I_4^{(2)}{}_{\max}) = 1-\alpha_2\left[1-\exp\left\{-\gamma_2\left(I_4^{(2)}{}_{\max}-1\right)\right\}\right] \tag{2}$$

where, $\alpha_1, \alpha_2 \geq 0$, and γ_1 and γ_2 are the softening parameters for fabrics. These softening functions were proposed to predict cyclic loading test results for the plain weave material used for swimwear and compression sportswear.

The second Piola-Kirchhoff stress tensor $\boldsymbol{S}$ is given by the partial differentiation of the strain energy function W with respect to the right Cauchy-Green tensor $\mathbf{C}$ as follows:

$$\mathbf{S} = 2\frac{\partial \mathrm{W}}{\partial \mathbf{C}} \tag{3}$$

To identify the material parameters of the anisotropic hyperelastic model shown in Eqs. (1) and (2), cyclic tensile tests of plain weave material were conducted. The test specimens were made of a woven fiber consisting of 73% nylon and 27% polyurethane. Specimens were 120 mm long, 30 mm wide, and 0.2 mm thick. Fiber orientation angles of test specimens were 0°, 15°, 30°, 45°, 60°, 75° and 90° to evaluate the anisotropy of plain-weave fabrics. The maximum tensile displacements were 168 mm, 180 mm, 192 mm, 204 mm and 216 mm, which correspond to stretches 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.

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

The Cauchy stress was calculated as in the following equation using the second Piola-Kirchhoff stress tensor.

$$\mathbf{T} = \frac{1}{J}\mathbf{F}\cdot\mathbf{S}\cdot\mathbf{F}^{T} \tag{4}$$

Here, $\boldsymbol{F}$ is the deformation gradient tensor and $\boldsymbol{F}^{t}$ is the transpose of the deformation gradient tensor. J is calculated as $J = \det(\boldsymbol{F})$.

Hip torque was calculated using the stress generated by the swimwear as follows:

$$\mathbf{N} = \mathbf{R}\times\mathbf{f} \tag{5}$$

where, $\mathbf{R}$ is the position vectors between each element of the sportswear and hip joint and **f** is load vector.

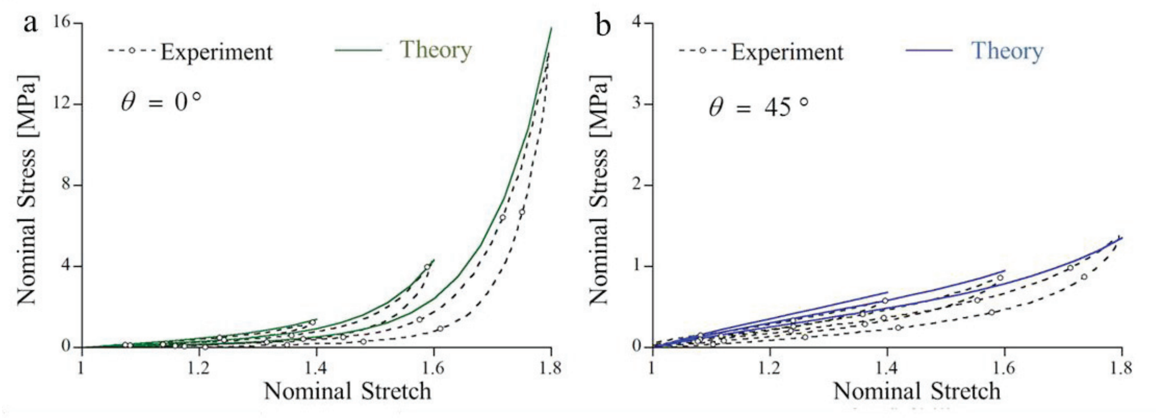

Fig.1 Comparisons of cyclic loading tests and theoretical calculation by nominal stress (a) θ =0° (b) θ =45°

3. 3D-CG stress calculation of compression sportswear

3.1. 3D-CG model for running and swimming

In Fig. 2(a) and (b), the sub-mesh of short-tights (swimwear) and long-tights (running wear) models are shown. These models deform together with the 3D-CG human model. In this research, all nodes of the sub-mesh are fixed to the surface of the 3D-CG human model. Exercise motions were applied to 3D-CG model, and displacement of 3D-CG were input to the sub-mesh model. In Fig. 2(c) and (d), 3D-CG human models with a positive direction of extension and with external rotation torque are shown. Three-dimensional stress calculations of swimwear and compression sportswear were conducted to determine the effect of mechanical characteristics of a plain-weave material on the human body. The 3D-CG human model, which consists of 57,416 nodes, was controlled by the 3D-CG software Autodesk Maya. Surface strain of the 3D-CG human model was calibrated using movements of human volunteers.

Results of stress visualization for jogging and sprinting are shown in Fig. 3. From the simulated results, the stress distribution for running tights and the effect of running form were evaluated. These data would provide important information for the design of joint-support functions in sportswear for beginner to elite athletes.

Stress calculations for the front crawl were also conducted and the simulated results are shown in Fig. 4. One cycle of the motions constituting the front crawl was represented by 45 individual 3D-CG images (two of which are included here).

The hip joint extension and external torques are shown in Fig. 5(a) and (b). The relationships between the average extension torque of one front-crawl motion and the initial width and length of stretch are shown in Fig. 6(a) and (b), respectively. In Fig. 7, the relationships between fiber orientation angle α and average extension torque are shown. Here α is defined as the angle between warp direction and human body length direction. The simulated results suggested that swimwear gives the swimmer better extensional support when the fiber orientation angle α is between 150° and 180°.

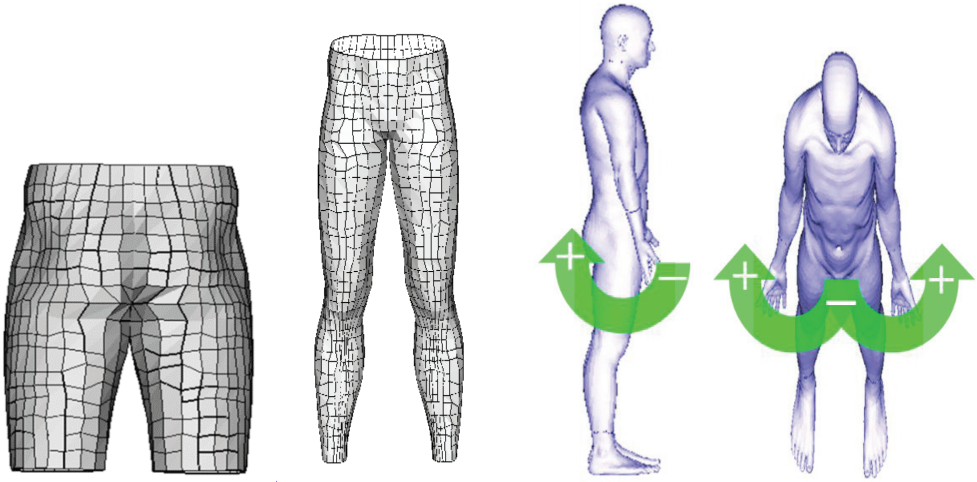

Fig. 2 (a) Sub-mesh for short spats model (swimwear), (b) Long-tights model (running), (c) 3D-CG human model with positive direction of extension torque, and (d) 3D-CG human model with positive direction of external rotation

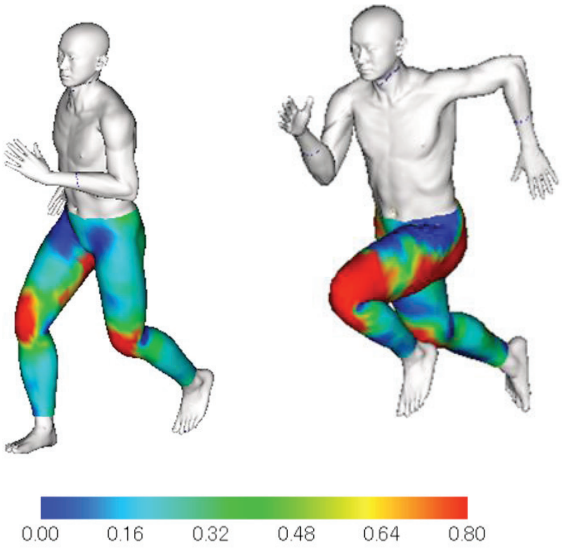

Fig. 3 (a) Stress visualization of compression long tights for jogging, (b) Stress visualization of compression long tights for jogging for sprint

4. Conclusion

Three-dimensional stress calculations of compression sportswear using 3D-CG human models were presented in this paper. Stress softening of swimwear fabrics was considered in stress calculations using an anisotropic hyperelastic model. The stress softening function was formulated to decrease as the recorded maximum elongation increased. Hip joint extension and external torque were calculated and the effect of initial stretch and fiber orientation angle of swimwear on hip-joint torque during the front crawl were investigated.

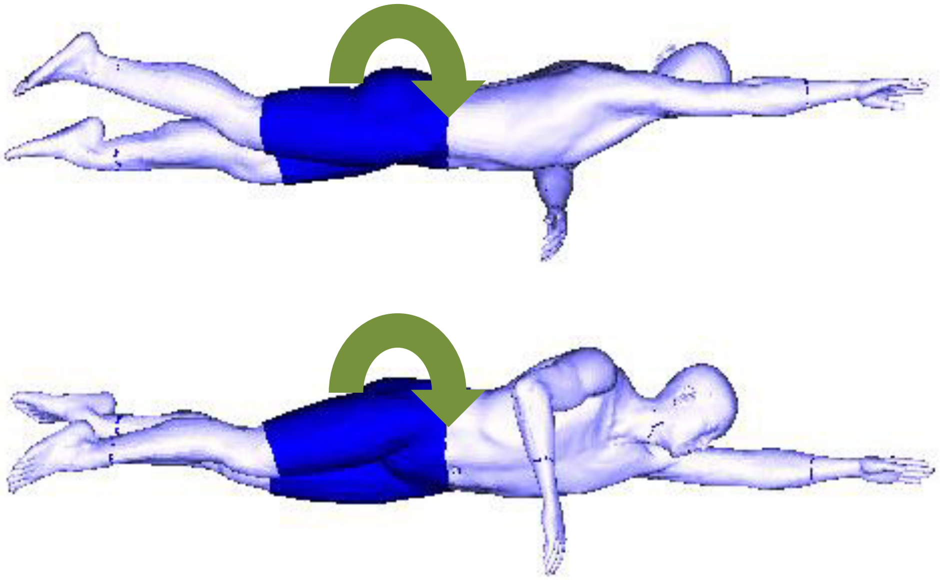

Fig. 4 Swimming motions of 3D-CG human model and swimwear sub-mesh

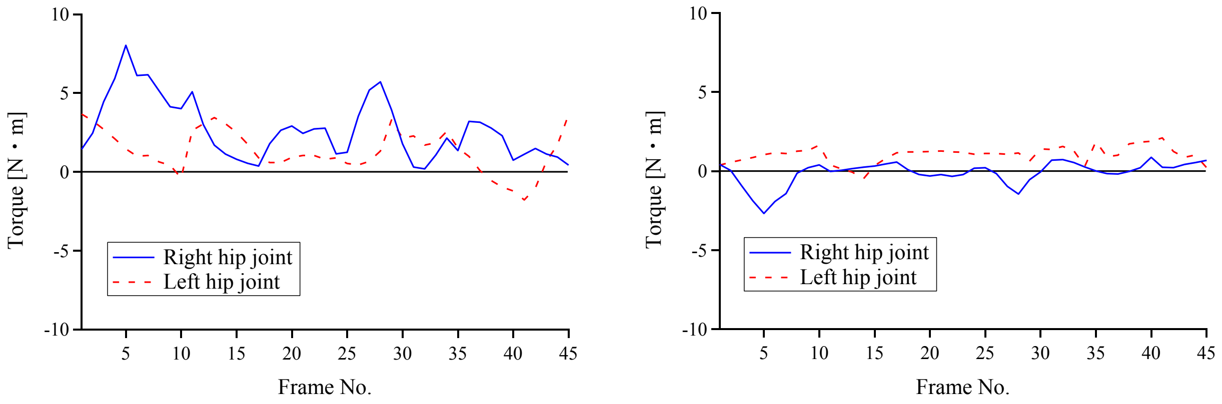

Fig. 5 (a) Extension torque of hip joint calculated with 3D-CG and an anisotropic hyperelastic model (b) External torque of hip joint calculated with 3D-CG and an anisotropic hyperelastic model

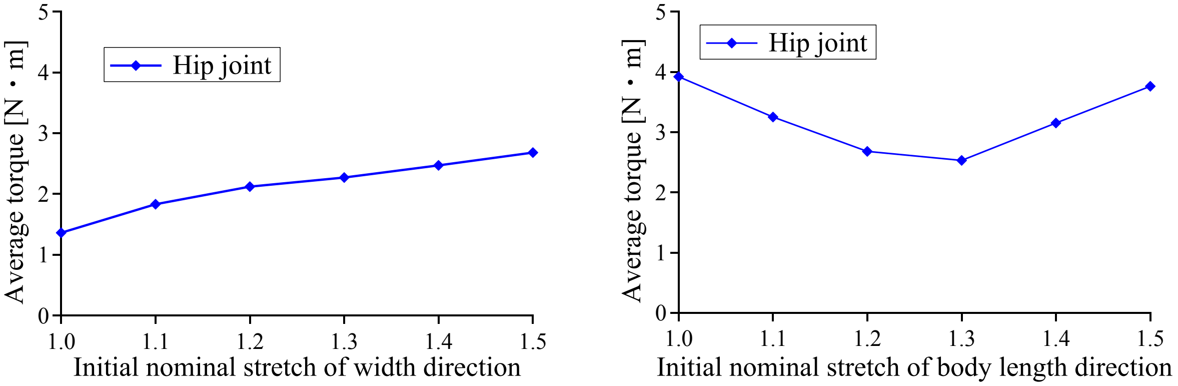

Fig. 6 (a) Relationship between maximum hip joint torque and initial material stretch in width direction (b) Relationship between maximum hip joint torque and initial material stretch in body length direction

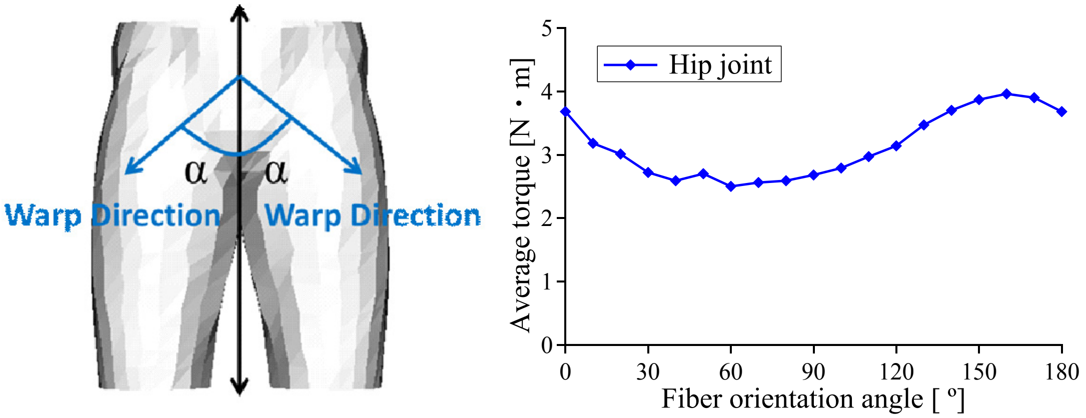

Fig. 7 (a) Relationship between hip extension torque and fiber orientation angle α

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