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A new method for designing sportswear by using three dimensional computer graphic based anisotropic hyperelastic models and musculoskeletal simulations

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Abstract

The purpose of this study is to develop a new method for designing compression sportswear from the viewpoint of force by simulation. Applied simulation techniques are 1) skin strain simulation, 2) fabric strain simulation using the anisotropic hyperelastic model, and 3) musculoskeletal simulation. For skin strain simulations, a three dimensional computer graphic (3D-CG) polygon strain was calculated as a skin strain using a 3D-CG model that simulates the human body (CG-Human-Model). The initial strain and the strain caused by physical exercise were given to the polygon model representing the shape of the sportswear (CG-Sportswear-Model). For compression sportswear, the strain of the fabric is approximately the same as skin strain, thus the strain of the CG-Human-Model was given to the CG-Sportswear-Model. In-plane and out-of-plane forces resulting from the CG-Sportswear-Model are calculated using anisotropic hyperelastic models. These forces were given to the musculoskeletal simulation as the external forces, and muscle activity required for any given physical exercise (e.g. swimming motion) was calculated. Information of forces and muscle activity are very useful in designing compression sportswear. It is believed that this new method for designing compression sportswear based on simulation is a sophisticated technique because this method takes into account not only forces resulting from sportswear but also the effect of these forces on physical exercise.

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Keywords: Compression sportswear; 3-dimensional computer graphics; anisotropic hyperelastic model; musculoskeletal simulation

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1. Introduction

Recently, many types of compression sportswear have been developed. Previous studies have reported that compression sportswear enhances exercise performance [1, 2] or recovery from fatigue after exercise [3, 4]. These studies also suggest that the major advantage is caused from the cardiovascular effect resulting from clothing pressure. Clothing pressure is the normal force applied on the body when wearing clothes. Therefore, in order to design compression wear from the viewpoint of clothing force, a method for predicting clothing pressure by using finite element analysis has been reported [5, 6].

Also, like normal forces produced by clothing pressure (out-of-plane force), tangential force by tension of clothing (in-plane force) affects physical exercise. However, the relationship between the effect and the mechanical properties, such as in-plane or out-of-plane force, of the compression sportswear is not clear. In other words, designing compression sportswear reflecting the forces from sportswear both out-of-plane and in-plane force enables development of the highly-functional compression sportswear.

Therefore, the aim of this study is to develop a new method for designing compression sportswear that takes into account in-plane and out-of-plane forces generated by the compression sportswear and the effect of these forces on the physical exercise. To be more specific, the effect of compression sportswear is obtained in the procedure as shown in Fig. 1.

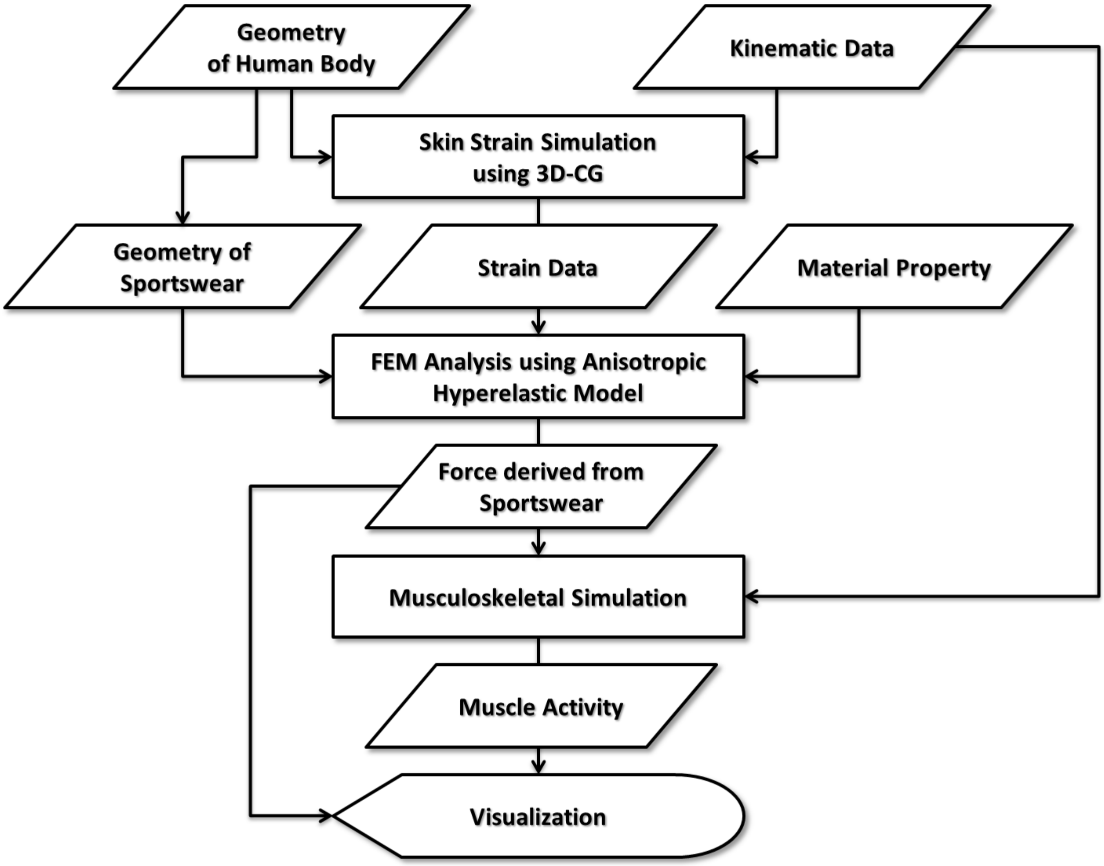

Fig. 1. Flowchart of a new method for developing compression sportswear.

2. Skin strain simulation

Due to the tightness, the strain of the compression wear material during exercise is affected by the skin strain. The strain direction and amount of the compression wear material are assumed to be the same as that of the skin. Based on this assumption, estimation of the garment forces can be conducted by measuring skin strains. In this study, instead of the measurement of the skin strain during exercise which might be unrealistic, we apply 3D-CG based skin strain simulation reported by Shimana et al [7].

2.1. 3D-CG model of the human body

A 3D-CG model of the human body (CG-Human-Model; Fig. 2(a)) used in this study was created by commercial 3D-CG software Autodesk™ MAYA. The CG-Human-Model has 57,416 vertices and 63,376 polygons, as well as a virtual skeleton inside. This model can also simulate scapulohumeral rhythm, swelling of muscle and skin strains associated with joint motion.

The kinematic data applied to the CG-Human-Model were obtained from motion capture system. The obtained 3-dimensional coordinates of the markers on the human body were converted to kinematic data of segments of the human body using Autodesk™ MotionBuilder, and then 3D-CG animation was created. In addition, as an advantage of the characteristics of using 3D-CG in this system, it is also possible to manually create animation from motion video in cases where motion capturing could be difficult (e.g. very high-speed motion or underwater exercise). Fig. 2(a) shows one frame in front crawl swimming animation that was created using the CG-Human-Model.

2.2. Skin (polygon) strain calculation

Usually, the polygon in the 3D-CG is composed of three or four vertices on the 3D coordinates. Using these vertices on 3D coordinates, the strain of each polygon is calculated as follows.

At first, the coordinate system of a pre-deformation polygon and post-deformation one were aligned. Then the transformation matrix that converts each vertex in the polygon from the pre-deformation polygon to the post-deformation one was calculated by the least square method.

$$\tilde{\mathbf{P}}i = [\mathbf{D}]\mathbf{P}i + \varepsilon i \qquad (1)$$

where:

$\tilde{\mathbf{P}}i$ Coordinates of each vertex in the post-deformation polygon

$[\mathbf{D}]$ Transformation matrix

$\mathbf{P}i$ Coordinates of each vertex in the pre-deformation polygon

εi Error of coordinates in each vertex

In accordance with the concept of small elastic strain, this transformation matrix can be separated into rotational and strain components.

$$[\mathbf{D}] = [\mathbf{S}] + [\mathbf{H}] \qquad (2)$$

where:

$[\mathbf{S}]$ Strain component included in $[\mathbf{D}]$

$[\mathbf{H}]$ Rotational component included in $[\mathbf{D}]$

On the other hand, it is possible to calculate strain direction by using a rotation matrix that is calculated when the coordinate systems are aligned.

Strain during any motion can be determined by applying the above-mentioned calculation to all polygons in all frames of animation. Fig. 2(b) shows an example of the visualized skin strain of the CG-Human-Model during front crawl swimming. The red and blue areas represent the stretch and shrinkage area, respectively.

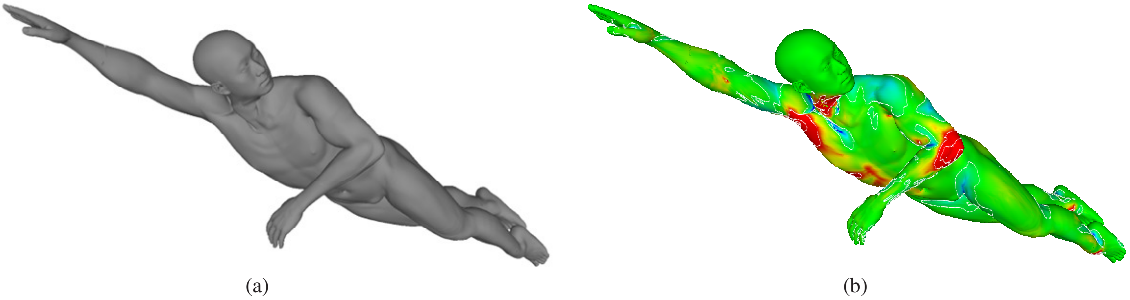
(a) (b)

Fig. 2. (a) CG-Human-Model used in this study; (b) Example of visualized skin strain

3. Anisotropic hyperelastic simulation

In this section, a method for estimating in-plane and out-of-plane forces resulting from compression sportswear such as swimwear by using the anisotropic hyperelastic model is described.

It is difficult to calculate forces by using the CG-Human-Model directly, because there is no regularity in the sequence of vertices and polygons. Thus, in order to solve this difficulty, an anisotropic hyperelastic simulation is applied to a mesh model representing the shape of the sportswear (CG-Sportswear-Model). Fig. 3(a) shows an example of the CG-Sportswear-Model representing a swimwear. The sequence of nodes (correspond to vertices in the 3D-CG) and elements (correspond to polygons in the 3D-CG) is aligned regularly in this model. This model has 760 nodes and 721 elements, while the area of the CG-Human-Model covered by this swimwear model includes 10,030 vertices and 9,857 polygons. These smaller numbers of nodes and elements of the CG-Sportswear-Model enabled to reduce computational costs.

Since compression sportswear has the initial strain once it is actually worn by humans, and because it is a smaller dimension than the human body, that initial strain was given to the CG-Sportswear-Model. Also based on the assumption described in the beginning of paragraph 2 that the strain direction and amount of compression wear material are assumed to be the same as that of the skin, the strain of the CG-Human-Model was given to the CG-Sportswear-Model.

In-plane and out-of-plane forces were derived from the strain of the CG-Sportswear-Model by using the anisotropic hyperelastic model that was proposed by Nagaoka et al. [8]. The applicability of the compression sportswear (swimwear) of this model has been shown by Tanabe et al. [9]. Fig. 3(b) shows the distribution of von Mises stress calculated from the swimwear model during front crawl swimming.

This simulation can easily be applied to the various types of sportswear by changing the fabrics property, in case of a single or combination of several types of fabrics. By comparing the simulation results under various boundary conditions, prior confirmation of the design may be completed and designs of the compression sportswear will become more efficient and effective.

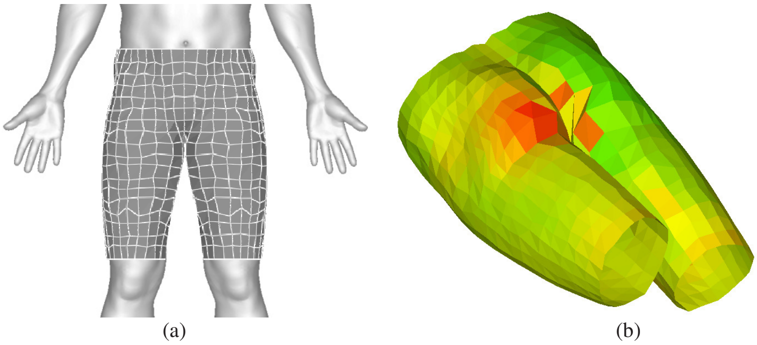

Fig. 3. (a) Example of the CG-Sportswear-Model representing a man's swimwear; (b) Distribution of von Mises stress during front crawl swimming.

4. Musculoskeletal simulation

The musculoskeletal simulation was used to estimate the effect of in-plane and out-of-plane forces derived from the anisotropic hyperelastic model during physical exercise.

Musculoskeletal simulation software can estimate muscular output by optimizing calculations from joint torque that were derived using inverse kinetics calculations. Any types of musculoskeletal simulation software, such as SIMM™ (MusculoGraphics, Inc.), AnyBody Modelling System™ (AnyBody Technology, Inc.) or OpenSIM (NCSSR) can be utilized for this study.

Typically, data that is put in to the musculoskeletal simulation are kinematic data obtained from motion capture systems and external forces applied to the body such as ground reaction force. In addition, in-plane and out-of-plane forces that resulted from compression sportswear were also used as an external force in this study. External forces as a load to each vertex on the CG-Sportswear-Model were expressed as the torque by multiplying the length between each vertex and the joint center. The method of converting load to torque increases the versatility.

An example of a simulation result by using the AnyBody Modelling System™ is shown in Fig. 4. The bar graph represents the averaged muscle forces around the hip joint. In this simulation, the forces caused by swimwear while crawling were taken into account. The final result achieved from this simulation (muscle force and power), as shown in Fig. 4, can be used as the evaluation parameter of the design, and this leads to a more efficient and effective design of compression sportswear.

5. Conclusion

In this study, a new method for designing compression sportswear was proposed by using 3D-CG based skin strain simulations, anisotropic hyperelastic models, and musculoskeletal simulations. Traditionally, the design of compression sportswear is dependent on the qualitative past experience, and repeat trials are needed to complete product development. For this method, a mechanical and quantitative approach enabled the optimal design of compression sportswear.

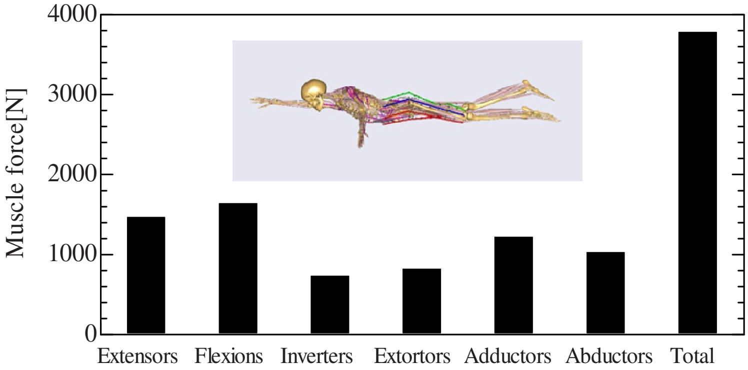

Fig. 4. Example of analysis: average muscle force of hip joint muscles in front crawl swimming

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