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# Musculoskeletal simulation of sports motion considering tension distribution in a whole body compression garment

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## Abstract

Compression garments are widely used in various sports activities. Since the cloths in a compression garment are sufficiently attached to the human body, it is possible for a compression garment to have particular mechanical functions by appropriately arranging the tension distribution in the garment. However, the effects of such garment on muscle activity have not been sufficiently investigated yet. Therefore, a method of musculoskeletal simulation for such problems were developed in the present study. In the developed musculoskeletal model, particular belt-like parts of cloths which had larger tension against stretch were modelled as virtual ligaments. In order to distribute the virtual ligaments, 403 reference points for upper half of the body were defined on the whole body in the musculoskeletal model. These points could be used as start, end and via points for the virtual ligaments. As an example of analysis, a running motion was analyzed in the present study. The running motion was acquired from the experiment using motion capture system, and put into the simulation model. One simple pattern of tension distribution was examined by the simulation. From the simulation, it was confirmed that the muscle activity changed according to the tension of the belt-like cloths. Therefore the developed simulation method will be useful for the design (the arrangement of the belt-like cloths) of the whole body compression garments.

*Keywords:* musculoskeletal simulation; compression garments; belt-like cloth; tension property

## 1. Introduction

Compression garments are widely used in various sports activities. Since the cloths in a compression garment are sufficiently attached to the human body, it is possible for a compression garment to have particular mechanical functions, such as reducing the muscle force of particular muscles, by appropriately arranging the tension distribution in the garment. However, the effects of such garment on muscle activity have not been sufficiently investigated yet, although the effects of compression garment on aerobic energy cost were studied [1]. Therefore, a method of musculoskeletal simulation for such problems was developed in the present study. In the developed musculoskeletal model, particular belt-like parts of cloths shown in Fig. 1, which had larger tension against stretch than the other parts, were modelled. A similar method has been already developed by Nakashima et al. [2] for a swimwear. That method was extended to general compression garments in the present study.

As the target sport of such compression garment, running was focused in the present study. Running is not only a basic motion of human, but also a sport which is popular worldwide for various purposes, such as competition, recreation and exercise for fitness. Many studies have been conducted for running from various aspects, such as muscle activity [3], motion analysis [4,5], and ground reaction force [6]. However, the effects of belt-like cloths on the muscle activity have not been investigated yet. In this paper, the simulation method is described and an example of analysis for running is shown.

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Fig. 1. Belt-like cloths in a compression garment.

## 2. Model of musculoskeletal simulation

The model of musculoskeletal simulation in the present study was constructed using a commercially available musculoskeletal simulation software AnyBody Modeling System [7] which was developed by AnyBody Technology Inc. In AnyBody Modeling System, a human body is represented by a series of rigid body links with muscles modeled as 581 wires for the whole body. The following body segments are modeled; head, neck, chest, waist, pelvis, scapulae, upper arms, forearms, hands, thighs, shanks, and feet. By putting joint angles as relative body motion, absolute body movement, and external forces acting on the human body into this model, the muscle activity is calculated from the inverse dynamics calculation and the optimizing calculations. In the calculation of muscle forces, the equilibrium equation is written by

$$\boldsymbol{Cf} = \boldsymbol{d} \qquad (1)$$

In Eq. (1), $\boldsymbol{C}$, $\boldsymbol{d}$ and $\boldsymbol{f}$ are coefficient matrices depending on position, external forces, and unknown internal forces, respectively. In addition, equation $\boldsymbol{f} = [\boldsymbol{f}^{MT}\boldsymbol{f}^{RT}]^T$ holds in which $\boldsymbol{f}^M$ and $\boldsymbol{f}^R$ are muscle forces and joint reaction forces, respectively. If $\boldsymbol{f}$ has elements more than the equations, the solutions present countlessly. Therefore, the muscle forces are estimated by solving an optimization problem in which the following objective function and constraints are used. Note that $N_i$ in the following equation represents the pre-determined maximum muscle force for each muscle.

Minimize

$$G\left(\boldsymbol{f}^M\right) = \sum_i \left(\frac{f_i^M}{N_i}\right)^3 \qquad (2)$$

Subject to

$$\boldsymbol{C}\,\boldsymbol{f} = \boldsymbol{d} \qquad (3)$$

and

$$f_i^M \geq 0, \quad i \in \{1, 2, \ldots, n^M\} \qquad (4)$$

## 3. Modeling method for tension property of a compression garment

The belt-like cloths in the compression garment were modeled as ligaments of the human body in the AnyBody Modeling System. This model is called “virtual ligament model”. The virtual ligament as a belt-like cloth was defined to connect the reference points on the human model with each other, and to exhibit tension force only when stretching. The schematic figure of the virtual ligament model is shown in Fig. 2. By adjusting several parameters in the virtual ligament model, it was possible to reproduce a relatively simple tension curve. For example, tension curves for a two cloths, which were acquired by uniaxial tensile test and reproduced by the virtual ligament model, are shown in Fig. 3.

In order to model the arrangement of the belt-like cloths on the human model using the virtual ligament model, it was necessary to define which point on the human model was connected to the other point. Although the compression garments both for the upper and lower half of the body exist, the compression garment for the lower half of the body was targeted in the present study. To analyze this, 403 reference points were defined on the human model, as shown in Fig. 4. The virtual ligaments were defined so that a point was connected to another point among the 403 points. An example of actually defined virtual ligaments is shown in Fig. 5. Since it was possible to specify not only the start and end points, but also “via points”, it was possible to define a