

Evaluation of 3-Axial Knee Joint Torques Produced by Compression Sports Tights in Running Motion [†]

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Abstract: In this paper, 3-axial knee joint torques given by compression sports tights were performed by numerical simulations using 3-dimensional computer graphics of a human model. Running motions of the human model were represented as the 3-dimensional computer graphics, and the running motions were determined by the motion capturing system of human subjects. Strain distribution on the surface of the 3-dimensional computer graphics of the human model was applied to the boundary conditions of the numerical simulations. An anisotropic hyperelastic model considering stress softening of fabric materials was implemented to reproduce the mechanical characteristics of the compression sports tights. Based on the strain-time relationships, knee joint torques in 3-dimensional coordinates given by the compression sports tights were calculated. As a result, the three types of knee joint torque generated by the compression sports tights in running motions were calculated. From the calculated results, the maximum value of flexion/extension, varus/valgus, and internal/external knee joint torques were given as 2.52, 0.59, and 0.31 Nm, respectively. The effect of compression sports tights on the knee joint was investigated.

Keywords: sportswear; anisotropic hyperelastic model; torque; knee; running motion

1. Introduction

In this paper, numerical simulation of the functional support effect of compression sports tights was investigated. For numerical simulation, the stress calculation part of the finite element method was applied. The 3D-CG human model reproducing displacements of human skin in running motion was applied to the displacement of stress calculation. An anisotropic hyperelastic model was introduced as the material model of fiber material used in compression sports tights. The knee joint torques generated by the compression sports tights were calculated. Prevention of cyclic force acting on the lower limb in running is an important issue for developing compression sports tights. General compression sports tights were designed not to disturb the flexibility of the knee joint. The flexion/extension joint torques generated in the knee joint were possible to investigate [1]. The knee joint will receive the other joint torques, the varus/valgus, and the internal/external torques in running by the compression sports tights. Some research showed that the knee-kinematics and the knee loading were changed in prolonged running. Moreover, the varus/valgus and the internal/external torques might increase the possibility of knee injuries [2]. From the engineering view, the numerical design method of varus/valgus and internal/external torques given by the compression sports tights in arbitrary movement like running, walking, climbing and jumping,

would be useful. In this paper, 3-axial torques given by compression sports tights acting on the knee joint are performed to investigate the effective protection of knee joint in running motions.

2. Materials and Methods

In this study, the anisotropic hyperelastic model considering stress softening was introduced to reproduce the mechanical characteristics of the compression sports tights. The strain energy function considering stress softening proposed by Matsuda et al. [3].

The 2nd Piola–Kirchhoff stress \mathbf{S} tensor is given by the partial derivative of the strain energy function $W(\mathbf{C})$ with respect to the right Cauchy–Green tensor \mathbf{C} as follows:

$$\mathbf{S} = 2 \frac{\partial W(\mathbf{C})}{\partial \mathbf{C}} \quad (1)$$

The strain energy function $W(\mathbf{C})$ is defined as the sum of isotropic part W_{iso} and anisotropic parts $W_{ani}^{(1)}$ and $W_{ani}^{(2)}$.

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

W_{iso} is the Mooney–Rivlin model proposed by Rivlin et al. [4]. The modified Itskov model proposed by Asai et al. [5] was used for the anisotropic parts. Tensile and shear stiffness of fiber separately can be defined by the Itskov model. $S(I_{1,max})$ is softening function reproducing the softening properties of the material. $I_{1,max}$ is maximum stretch experienced previously. Displacement of compression sports tights was acquired with the strain of human skin calculation.

The Cauchy stress tensor \mathbf{T} is defined as the following equation using the deformation gradient tensor \mathbf{F} and the second Piola–Kirchhoff stress tensor \mathbf{S} .

$$\mathbf{T} = \frac{1}{J} \mathbf{F} \cdot \mathbf{S} \cdot \mathbf{F}^T \quad (3)$$

where J is calculated as $J = \det(\mathbf{F})$. Knee joint torque vector \mathbf{M} in the Cartesian coordinate system was calculated using the stress generated by the compression sports tights in running motion as follows:

$$\mathbf{M} = \sum (\mathbf{r}_i \times \mathbf{f}_i) \quad (4)$$

where, \mathbf{r}_i is the position vectors between the knee joint and i -th node of the sub-mesh of compression sports tights. \mathbf{f}_i is load vector at each node of i -th node of the sub-mesh. Now we separate the knee joint torque vector \mathbf{M} to \mathbf{M}_{up} and \mathbf{M}_{low} . \mathbf{M}_{up} and \mathbf{M}_{low} are knee joint torques generated by the upper part and lower part of the compression sports tights.

$$\mathbf{M}_{up} = \sum_{i=1}^{N_{up}} (\mathbf{r}_i^{up} \times \mathbf{f}_i^{up}) \quad (5)$$

$$\mathbf{M}_{low} = \sum_{i=1}^{N_{low}} (\mathbf{r}_i^{low} \times \mathbf{f}_i^{low}) \quad (6)$$

where \mathbf{r}_i^{up} and \mathbf{r}_i^{low} are the position vectors from the knee joint to i -th node of the upper and lower parts of the compression sports tights, respectively. \mathbf{f}_i^{up} and \mathbf{f}_i^{low} are the force vectors at each node of the upper and lower parts of the compression sports tights, respectively. Here we define two-unit vector \mathbf{u} and \mathbf{v} . \mathbf{u} is the unit vector from the knee joint to the hip joint. \mathbf{v} is the unit vector from the knee joint to the ankle joint. The unit vector \mathbf{w} is calculated as an exterior product of \mathbf{u} and \mathbf{v} . $M_{extension}$ was calculated as scalar product \mathbf{M}_{up} and \mathbf{w} and scalar product \mathbf{M}_{low} and \mathbf{w} as follows:

$$M_{extension} = (\mathbf{M}_{low} - \mathbf{M}_{up}) \cdot \mathbf{w} \quad (7)$$

$M_{rotation}$ is the scalar to rotate the knee joint. $M_{rotation}$ is defined as the sum of the scalar product \mathbf{M}_{up} and \mathbf{u} and the scalar product \mathbf{M}_{low} and \mathbf{v} .

$$M_{rotation} = M_{up} \cdot u + M_{low} \cdot v \tag{8}$$

To calculate valgus torque given by the compression sports tights, other two-unit vectors w^{up} and w^{low} were defined as follows:

$$w_{up} = u \times w \tag{9}$$

$$w_{low} = v \times w \tag{10}$$

The scalar M_{valgus} is correspond to the torque to extend the knee joint in the frontal plane. M_{valgus} was calculated as the sum of the scalar product M_{up} and w_{up} and the scalar product M_{low} and w_{low} .

$$M_{valgus} = M_{up} \cdot w_{up} + M_{low} \cdot w_{low} \tag{11}$$

3. Results

A sub-mesh of compression sports tights was introduced to the 3-dimensional computer graphic model (3D-CG model) of the human body. This model was developed by Shimana et al. [6]. The details of sub-mesh of compression sports tights in this research are shown in Figure 1. The number of nodes and 8-node elements of the sub-mesh is 2873 and 2826, respectively. In this simulation, the compression sports tights were assumed to be fixed on the human body. The right Cauchy-Green tensor C of the compression sports tights in running motions was calculated using the displacement field of the 3D-CG model. Based on the right Cauchy–Green tensor C , the nonlinear stress-strain relationships of the compression sports tights were obtained. For numerical calculation, initial elongation of 1.33 in the horizontal direction and 1.05 in the vertical direction were given to the sub-mesh of tights. Material No. 1 and material No. 2 were selected as the fiber material of the compression sports tights. The stiffness of material No. 1 was higher than No. 2. The material distribution of compression sports tights A is shown in Figure 2. The running motions of 3D-CG are shown in Figure 3. The running motion consists of 76 frames of 3-dementional elements, which is one-cycle of the running motion. The running motion started from the moment that the right foot of 3D-CG touched the ground and finished at the moment that the right foot touched the ground again. The swing phase of running is shown from 40% in running motion to 80% in running motion in Figure 3. The knee joint angle was defined as θ .

The relationship between knee joint angle and running cycle is shown in Figure 4. The calculated results of the 3-axial right knee joint torque generated by compression sports tights in running motion are shown in Figure 5. Flexion, valgus and external torques were defined as a positive value. From the calculated result, the internal/external and varus/valgus torques were observed in running motion. The maximum values of the flexion/extension, the varus/valgus, and the internal/external joint torques were recorded as 2.52, 0.59, and 0.31 Nm, respectively. From Figure 5, external torque in the swing phase, and internal torque in the grounding phase are observed. The torsional effect of compression sports tights to the knee joint in running motion was able to be calculated.

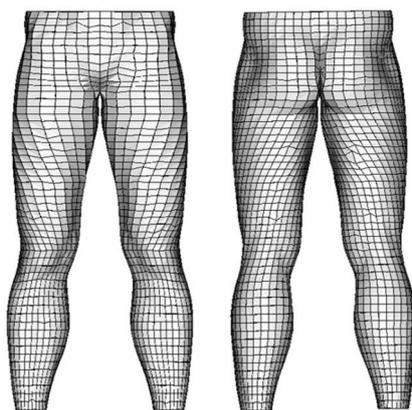


Figure 1. 3D-CG sub-mesh of compression sports tights.

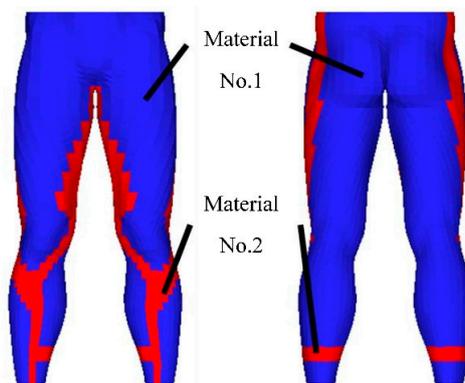


Figure 2. The placement of the materials on the sub-mesh of compression sports tights A.

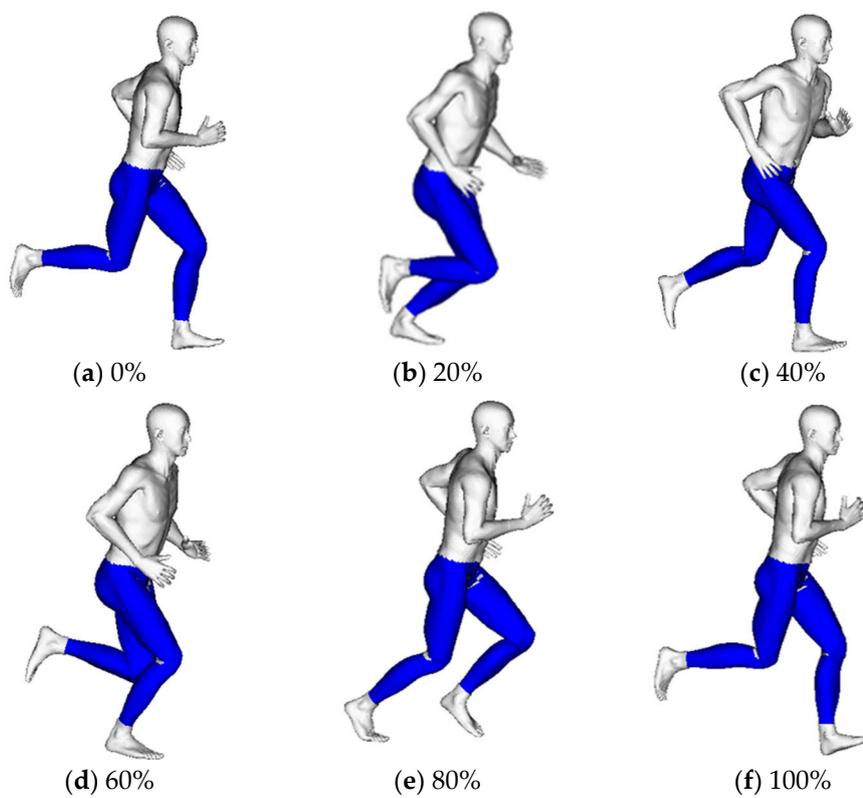


Figure 3. 3D-CG model in running cycle.

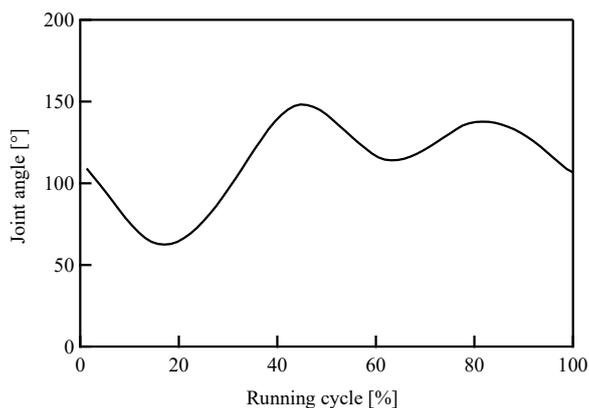


Figure 4. Relationship between knee angle and running cycle.

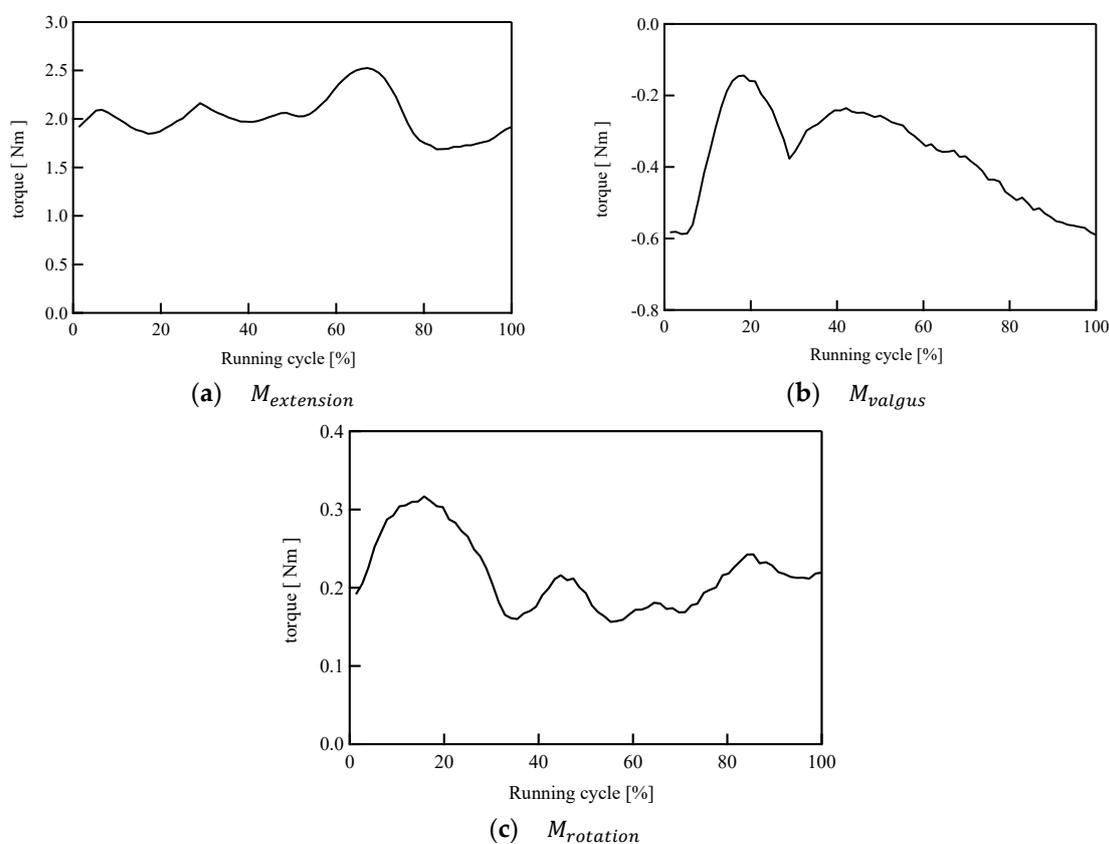


Figure 5. Relationship between 3-axial right knee joint torque and running cycle.

4. Discussion

The numerical method to evaluate 3-axial knee joint torques given by the compression sports tights in running motion was investigated. The results in this paper indicate that the compression sports tights give the knee joint support effects in varus/valgus and internal/external directions to the knee joint. Moreover, compression sports tights with specific features could be designed easily because materials of compression sports tights with different stiffness were easily combined in this numerical design method. Some research showed that the human produced approximately 100 Nm of the knee joint flexion/extension torques in running motion [7]. It is quite larger than the torque calculated in this research. However, the varus/valgus and the internal/external joint torques given by the compression sports tights can be expected as effective protection in long and repeated running/walking exercises such as a marathon, ultra-marathon, trail running/walking, etc. For future

work, experimental evaluations of 3-axial knee joint torque generated by the compression sports tights should be conducted to evaluate the applicability of our proposed method.

5. Conclusions

Numerical calculation of 3-axial knee joint torques generated by the compression sports tights was investigated in this paper. The 3-dimensional stress generated by compression sports tights in running was calculated. The anisotropic hyperelastic model reproducing the mechanical characteristics of the compression sports tights was introduced to the 3-dimensional stress calculation. The 3-axial knee joint torques generated by compression sports tights were shown. Moreover, the possibility of effective protection given by compression sports tights acting on the knee joint in running motions was investigated in this paper. From the calculated results, the design method of compression sports tights considering the 3-axis torques applied to the human body by tights in running was suggested.

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