Simulation Analysis of Optimal Form and Orthosis during Walking in Water for Elderly People*

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Abstract
The objective of this study was to obtain optimal walking form and orthosis during the exercise of walking in water for elderly people in order to prevent falling down. Since it is effective to increase the muscle strength of iliopsoas and tibialis anterior to prevent falling down, the walking form and orthosis, by which these muscles can be trained, was optimally designed by a simulator which can compute body load considering fluid force. The walking form obtained by the simulation was the one in which the shank is quickly and widely moved in the end of the swing phase. Since a large fluid force acted on the lower limbs by this motion, the target muscles were greatly exerted to resist the fluid force. On the other hand, the orthosis obtained by the simulation was one whose width and depth were small, and the density of the foot part was large. Since the large gravity and inertial force acted by the large density of the foot part, the target muscles were greatly exerted to resist these forces. Therefore, both the walking form and orthosis can be effective for the rehabilitation of elderly people.

Key words: Biomechanics, Bio-Motion, Rehabilitation, Musculoskeletal System, Walking in Water

1. Introduction
The elderly people have been increasing in Japan recently. In particular, the population aged 65 or older is about 26 million and it is 20.2% of total population (1). A country in which this percentage is over 14% is generally defined as an aged society, and the elderly people are predicted to increase in the future (2). In addition to this, the elderly people who need care are also increasing. In fact, though the population of elderly people who need care was 2.18 million in 2000, it became 3.35 million in 2002 (2). The main factors for the care are stroke, debilitation, and fractures due to falling down (1). Therefore, as falling down of elderly people is the main reason for fractures, it makes the elderly people need care.

Several plans to prevent the elderly people from needing care have been promoted by the Ministry of Health, Labor and Welfare in Japan since 2003 (2). For example, the lecture class of preventing falling down was proposed, and the classes are conducted in 47.3% municipalities in Japan. In these classes, rehabilitation with the training of the muscles is conducted for the elderly people (3)(4)(5). The methods for the rehabilitation are walking, jogging, swimming, exercise in water, tennis and volleyball. However, since the excessive compressing stress on the joints may be loaded during the exercise on the land, such as
walking and jogging, this might be at a risk for the damage on the articular cartilage and for falling down. On the other hand, since the swimming and exercise in water are conducted in water, the compressing stress on the joints is decreased by buoyancy and the risk for falling down becomes low. Therefore, swimming and exercise in water can be effective for rehabilitation. In particular, since walking in water, which is the most popular aquatic exercise in water, does not need special training, it is partly applied for rehabilitation. However, since the load on the joints is decreased during exercise in water, there is the possibility that the muscles might not be trained sufficiently.

On the other hand, fluid forces such as the drag and the inertial force due to the added mass of fluid also act on the whole body in water. Since the fluid force is the resistive force during moving the body, it is possible to exert muscle forces actively by the effective use of the fluid force. The fluid force is varied by changing the velocity, acceleration, density and shape of the body. The velocity and acceleration can be controlled by changing the form during walking in water. The density and shape can be controlled by attaching the orthosis. Therefore, by the appropriate walking form or orthosis which can exert the fluid force effectively, the muscles can be trained during walking in water. The walking form can be changed without any tool, while the orthosis does not need to master the walking form. Therefore, the walking form and orthosis have each merit. If the muscles can be trained without loading on the joints by the walking form and orthosis, walking in water can be widely applied for the rehabilitation of elderly people.

As the walking form in water, 27 forms have already been proposed \(^7\). However, these forms are proposed for general purpose and not for a particular target. Therefore, the effectiveness of the forms has not been sufficiently clarified. On the other hand, as for the orthosis, the mitt-type orthosis which is attached on the hand has been proposed for training the muscles of the upper half of the body by exerting drag \(^8\). A wristband orthosis which is attached on the wrist or ankle has also been proposed for training the muscles of the upper and lower half of the body by exerting drag and inertial force \(^9\). However, these orthoses have not been developed for a particular target such as elderly people.

Therefore, the objective of this paper was to develop the optimal walking form and orthosis for the rehabilitation to prevent elderly people from falling down. For this purpose, our developed optimizing simulator for walking in water \(^10\) was utilized. This simulator enables the solving of the optimal walking form and orthosis for a particular target computationally \(^11\)(\(^12\)). In particular, the orthosis for ACL injuries was not only solved by the simulator, but also the effect for the training was confirmed by an experiment using subjects. In this paper, the simulation method is described first. Then, the optimal walking form and orthosis developed by the simulator are explained. Finally, the effectiveness of the walking form and orthosis is discussed.

### 2. Simulation Method

#### 2.1 Calculation flow

For the simulation of the present study, the simulator for the optimization of the walking form in water, which has been developed by the authors \(^10\), was utilized. The calculation flow of the simulator is schematically shown in Fig. 1. The simulator consists of three calculation parts: for joint torque and muscle force. The initial values of the design parameters of the optimization are first set. Next, the joint torques are computed in the calculation part for the joint torque. Then, by inputting the joint torque, the muscle forces are computed in the calculation part for the muscle force. The objective function for the optimization is then calculated using the joint torques and muscle forces. This calculation is repeated until the objective function converges to the maximum value. The Downhill Simplex Method is employed for the optimization. The details of the calculation parts for the joint torque and the muscle force are explained in the following subsections.
2.2 The calculation part for the joint torques

This part was developed based on the swimming human simulation model SWUM\(^{(13)(14)(15)}\). The analytical model is schematically shown in Fig. 2. The human body is defined as a link of rigid body segments in the simulation model. The motion of the human model (velocity of the center of the mass for the human model and the joint angles), the ground reaction force (GRF) and its center of pressure (COP) are input. Then, the inertia force and the gravity exerted on the human model are computed by solving the inverse dynamics problem. In addition to these forces, the fluid force exerted on the human model is computed using the fluid force model. The components of the fluid force are the inertial force due to the added mass of the fluid, the drag and buoyancy. As the sum of these forces, the joint torques and the joint forces are calculated. The fluid force was assumed to be
computable using the velocity and the acceleration in each part of the body, and it was formulated using the parameters of the fluid force, which were determined by the experiment. The details of the fluid force model were described in the previous paper (15). The inputted data, GRF, was measured in an experiment of the previous studies (16)(17). Note that the joint angles only on the sagittal plane were employed in the calculation, since walking is mainly performed in the sagittal plane.

2.3 The calculation part for the muscle forces

The musculoskeletal model by Yamazaki (18), which is schematically shown in Fig. 3, was utilized for the calculation of the muscle forces. In this model, the main eight muscles (GM: gluteus maximus, ILI: iliopsoas, HAM: hamstrings, RF: rectus femoris, VM: vastus medialis, SOL: soleus, GAS: gastrocnemius and TA: tibialis anterior) were modeled as wires. The muscle forces are obtained by solving the optimization problem in which the sum of squares of the muscle stresses ($\sum \sigma^2$ in Fig. 1) is minimized. The muscle stresses are calculated by dividing the muscle forces by the physiological cross sectional areas.

3. Optimal Design of Walking Form and Orthosis

3.1 Design parameters

3.1.1 Walking form

The joint angles (hip, knee and ankle) are set as the design parameters of the optimization. The scheme of the design parameters are shown in Fig. 4. Each joint angle in one cycle is represented by ten control points at constant intervals and a curve interpolating the control points. The former six control points correspond to the stance phase, and the latter four correspond to the swing phase. The joint angles of the four points in the swing phase are set as design parameters in the optimization. Therefore, the number of design
parameters is twelve in total (four points for three joints). The initial values of design parameters were set as the joint angles of the normal walking form taken from the previous studies.\(^{16,17}\)

![Fig. 4 Scheme of the design parameters of the walking form](image)

### 3.1.2 Orthosis

To begin with, the basic structure of the orthosis was decided. In order to train the muscle, it is effective to exert the fluid force on the lower extremities. The fluid force is affected by the shape and density of the orthosis. In particular, the drag force is mainly affected by the width (right/left direction) of the orthosis while the buoyancy is affected by the volume and density. Therefore, the fluid force can be basically controlled by changing the width, depth (forward/backward direction) and density. From this discussion, the orthosis to be designed was determined as the one which had a particular width, depth and density for each part of the lower extremities (thigh, shank and foot).

Therefore, the width, depth, and density were directly defined as the design parameters. In the simulation model, each part of the body is defined as an elliptic cylinder. The size of each elliptic cylinder is defined as the width and depth of the top and the bottom surfaces and the height of each elliptic cylinder. The width and depth of the orthosis can be expressed by adding the width and depth of the orthosis to those of the human model. This is schematically shown in Fig. 5. The density of the orthosis is also expressed as the density of the added part (gray part in Fig. 5) to the elliptic cylinder. The design parameters were finally the depth (\(T_{T1}, T_{B1}\)), width (\(T_{T2}, T_{B2}\)) and density (\(\rho\)) of each part. The number of the design parameters was 15 (Five parameters for three parts of the lower extremities). The initial values of the design parameters were set to zero for the width and depth, and 1042kg/m\(^3\) for the density which is the same as the human body.

![Fig. 5 Schematic figure of design parameters with respect to size of the orthosis](image)
3.2 Objective function

The muscle training is effective for preventing falling down as described in § 1. In particular, the decline of the iliopsoas (ILI) and tibialis anterior (TA) are the main reason of falling down \(^{(19,20)}\). Therefore, the optimal form and orthosis were defined as the form or orthosis which maximizes the muscle forces of the ILI and TA. Based on this definition, the objective function was formulated as below:

\[
Obj = \sum_{n} \left( \frac{MF_{n, ILI}}{PCSA_{n, ILI}} \right)^2 + \left( \frac{MF_{n, TA}}{PCSA_{n, TA}} \right)^2
\]

(1)

*\(MF_{n, ILI}\) : Muscle force of the ILI

*\(F_{n, TA}\) : Muscle force of the TA

*\(PCSA\) : Physiological cross sectional area of the muscle

The first term is the time integral for muscle stress of the ILI for one cycle and the second term is the integral for the muscle stress of the TA for one cycle. The objective function was defined as the sum of these two terms.

3.3 Constraint conditions

The penalty function was utilized so that the joint torques do not exceed their determined maximum values. If the joint torques exceed their maximum values, the excess amount is subtracted from the objective function. The maximum values of the joint torques were determined based on the maximum voluntary joint torque of a 70's male obtained from the human characteristics database \(^{(21)}\). In the analysis of the walking form, the penalty function was also utilized so that the joint angles do not exceed their determined range of motion. If the joint angles exceed their determined values, the excess amount is subtracted from the objective function. The range of motion of a 70's male was obtained from the human characteristics database \(^{(21)}\). In the analysis of the orthosis, the penalty function was utilized so that the width, depth and density of the orthosis do not become negative. If the width, depth or density becomes negative, the absolute value of the parameter is subtracted from the objective function.

3.4 Other conditions

The body geometry of the human model was determined based on the size of a 70-79 year-old Japanese male obtained from the AIST database of human size and shape \(^{(22)}\). The ground reaction force (GRF) was obtained by scaling the GRF of a 20's male which was measured in the previous paper \(^{(16,17)}\) as follows:

\[
GRF_{70s} = M_{70s} \times \frac{GRF_{20s}}{M_{20s}}
\]

(2)

GF : Ground reaction force, \(M\) : Mass of the body model

4. Results and Discussion

4.1 Results of design parameters

4.1.1 Walking form

Iterations of about 600 times were required in order to obtain the solution for optimization. The calculation time was 6 hours on a 1.2GHz PC. The walking forms before and after optimization are shown in Fig. 6. The water surface is divided into different colored areas in which each width of the area corresponds to the moving distance in a half cycle. Therefore, the sum of the widths of one dark and one pale colored area becomes the moving distance in one cycle. The red lines emitting from each part of the body represent the points of applications, directions and magnitudes of the fluid forces acting on the body.
The joint angles are shown in Fig. 7. From Fig. 6 and 7, it can be seen that the knee joint was widely flexed in $t = 0.6–0.7$ and then the knee joint was widely and quickly extended in $t = 0.7–0.9$ in the optimal walking form. Also a large fluid force was exerted when the knee joint was extended in $t = 0.7–0.9$ in the optimal walking form.

4.1.2 Orthosis

Iterations of about 800 times were required in order to obtain the solution for optimization. The calculation time was 15 hours on a 1.2GHz PC. The optimized values of the design parameters are shown in Table 1 and 2. The images of with and without orthosis are shown in Fig. 8. The walking apparatus with the orthosis is shown in Fig. 9. From Table 1 and Fig. 8, it can be seen that the width and depth are not so large (below 33 mm). Compared Fig. 9 with Fig. 6 (b), the fluid force acting on the lower extremities is smaller in the orthosis than in the form. This is because the width and depth of the orthosis which influence the fluid force were small. On the other hand, it can be seen that the density of the thigh and foot parts of the orthosis are larger, and the shank part of the orthosis is smaller than the human density ($1042 \text{kg/m}^3$) from Table 2. The density of the foot part is especially large.
Fig. 7 Time history of joint angle for the right leg before and after optimization

Table 1 Optimized design parameters (Thickness of width and depth)

<table>
<thead>
<tr>
<th></th>
<th>(T_{T1}) [mm]</th>
<th>(T_{T2}) [mm]</th>
<th>(T_{B1}) [mm]</th>
<th>(T_{B2}) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh</td>
<td>29</td>
<td>33</td>
<td>32</td>
<td>2.4</td>
</tr>
<tr>
<td>Shank</td>
<td>17</td>
<td>21</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Foot</td>
<td>19</td>
<td>5</td>
<td>15</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 2 Optimized design parameters (Density)

<table>
<thead>
<tr>
<th></th>
<th>Orthosis only [kg/m(^3)]</th>
<th>Orthosis + Each segment [kg/m(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh</td>
<td>4320</td>
<td>2543</td>
</tr>
<tr>
<td>Shank</td>
<td>560</td>
<td>820</td>
</tr>
<tr>
<td>Foot</td>
<td>8110</td>
<td>4214</td>
</tr>
</tbody>
</table>

Fig. 8 The Apparatus of optimized orthosis
4.2 Results of muscle forces

The muscle forces of the optimized form and orthosis for the right leg are shown in Fig. 10. The time, $t$, is normalized by the walking cycle. The moment $t = 0$ (and $t = 1$) was the heel contact. The period $t = 0–0.6$ was the stance phase, and $t = 0.6–1$ was the swing phase. As shown in Fig. 10(e)(h), the ILI and TA muscle forces were greatly exerted both in the optimized form and orthosis. In the optimized form, the peak values of these muscle forces were about 6 times larger in $t = 0.9$ than those of before optimization. In the optimized orthosis, the peak value of the ILI muscle force was about 6 times larger in $t = 0.8$ and the peak value of the TA muscle force was about 5 times larger in $t = 0.9$ than those of before optimization. For the orthosis, this was because the large fluid force acted on the shank and foot in the quick knee extension at $t = 0.9$, as shown in Fig. 6(b)(v). For the orthosis, the TA muscle was acted in order to exert the large ankle dorsiflexion joint torque opposing large gravity and inertial force due to heavy foot. For the ILI in the orthosis, it was acted in order to exert the hip flexion joint torque. One possible reason for the large ILI muscle force is the small RF muscle force in the orthosis (Fig. 10 (f)). Since the RF is the knee extensor as well as the hip flexor, the RF muscle force becomes small when the knee extension torque is small. The small knee extension torque is considered to be caused by the heavy foot since it contributes to the extension of the bending knee during the swing phase. For the span of the muscle forces exerted, the orthosis exerted muscle forces longer than the form (orthosis: $t = 0.6–0.9$, form: $t = 0.8–0.9$). For the other muscles, though the posterior muscle forces were about the same as the before optimization in the form, as shown in Fig. 10 (a)(b)(c)(d), the HAM muscle force was larger than before optimization in the orthosis (Fig. 10 (b)).

5. Conclusions

In this paper, the optimal walking form and orthosis during walking in water in order to prevent falling down for the elderly people were solved by simulation. Since it is effective to increase the muscle strength of TA and ILI in order to prevent falling down, the form and orthosis by which these muscles can be trained were analyzed. The findings obtained in this paper are summarized as follows:

1. The optimized walking form was the one in which the shank was widely and quickly moved in the end of the swing phase. Since a large fluid force acted on the lower limbs at this moment, the ILI and TA was greatly exerted in order to resist these fluid forces.

2. The optimized orthosis was the one whose width and depth were small and the density of the foot part was large. Since the large density of the foot part exerted the large inertial force and gravity, the ILI and TA was greatly exerted in order to resist these forces.

3. Both walking form and orthosis can be effective for the rehabilitation of the elderly people.

In the future, it is important to confirm the effectiveness of this walking form and
orthosis by experiment.

Fig. 10 Time history of the muscle forces for the right leg before and after optimization
References
