Development of Widely Useable Simulator for Optimization of Walking Form in Water

Keiko AKIYAMA\textsuperscript{a}, Motomu NAKASHIMA\textsuperscript{b}\textsuperscript{*}

\textsuperscript{a}Graduate School of Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan
\textsuperscript{b}Tokyo Institute of Technology, Tokyo 152-8552, Japan

Received 31 January 2010; revised 7 March 2010; accepted 21 March 2010

Abstract

The objective of this study was to develop the widely useable simulator for optimization of walking form in water. The simulator consists of two calculation parts, one for joint torque and another for muscle force. In the simulation, joint angles are set as design parameters, and joint torque and muscle force are calculated repeatedly until the objective function becomes the maximum value. By using this simulator, the optimal walking form for the training of elderly people was calculated as example. It was found that the large fluid forces act on the shank and foot during the swing phase in the obtained optimal form.

© 2010 Published by Elsevier Ltd.

Keywords: Walking in Water; Optimum Gait; Simulation; Fluid Force; Muscle and Skeleton

1. Introduction

Exercises in water such as swimming and walking are recently becoming popular to various people. In particular, walking in water is easy to perform without any special practices. In walking in water, the body load due to gravity is cancelled by buoyancy, and that due to fluid force exerted on the lower extremities can be effectively controlled by changing walking forms. Therefore, walking in water is suitable for not only daily exercise but also rehabilitation and sports injury.

In order to change the body load, various walking forms in water have been proposed to date\textsuperscript{(1)}. However, their theoretical investigations have not been sufficient. Most of researches about walking in water are from physiological aspects\textsuperscript{(2)}\textsuperscript{(3)}, not from biomechanical ones. Therefore, it is important to develop a biomechanical simulation tool which can analyse the fluid force exerted on the lower extremities and optimize the walking form. The objectives of this study were to develop a widely useable simulator for optimization of walking form in water, and to obtain the optimal walking form for the training of elderly people as an example of its application.
2. Developed simulator

2.1. Calculation flow

The calculation flow of the simulator is schematically shown in Fig. 1. The simulator consists of two calculation parts, for joint torque and muscle force. The joint angles (hip, knee and ankle) are set as the design parameters of the optimization first. Joint angles are divided into ten steps in one cycle. The former six steps correspond to stance phase, and the latter four steps swing phase. The joint angles of four steps in swing phase are set as design parameters in the optimization. Therefore, the number of design parameters is total twelve (four steps for three joints). Next, the joint torques are computed in the calculation part for the joint torque. Then, inputting the joint torque, the muscle forces are computed in the calculation part for the muscle force. The objective function for the optimization is calculated using the joint torques and the muscle forces. The joint torques and the muscle forces are calculated repeatedly until the objective function becomes the maximum value. The Downhill Simplex method is employed for the optimization. The details of the calculation parts for the joint torque and muscle force are explained in the following sections.

![Fig. 1 Structure of form optimizing simulator](image)

2.2. Calculation part for joint torque

This part has been developed based on the swimming human simulation model SWUM. The analytical model is schematically shown in Fig. 2. In the simulation model, the human body is defined as a link of the rigid bodies. The motion of the human model (velocity of the center of mass for the human model and the joint angles) and the ground reaction force (GRF) 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. As the sum of these forces, the joint torque and the joint force are calculated. The fluid force was assumed to be computable using the velocity and the acceleration in the 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 are described in the previous paper (4). The inputting data, the motion of the human model and GRF were measured in the experiment by Miyoshi, et al (7). Note that the joint angles only in the sagittal plane were employed in the calculation, since the walking is mainly performed in the sagittal plane.

2.3. Calculation part for muscle force

The musculoskeletal model by Yamazaki(8), which is schematically shown in Fig. 3, was employed for the calculation of the muscle force. In this model, 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 modelled 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.
3. Optimization of walking form in water for training of elderly people Developed simulator

3.1. Objective function

In order to clarify the ‘optimal form for the training of elderly people’, the effect of the aging was investigated first. The muscle forces of the walking in water in normal form between 20’s and 70’s males were computed using the developed simulation model. The body model of 70’s male was based on the available database of body size (9). The GRF of 70’s man was calculated by normalizing the GRF of 20’s male as below:

\[
GRF_{70} = \frac{M_{70}}{M_{20}} \cdot GRF_{20}
\]

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

The physiological cross-sectional areas (PCSA) of 70’s male are shown in Table 1. These data were determined based on the values by Kuno (10), Tanaka et al. (11), Molse et al. (12), and McNeil et al. (13).

Table 1 Physiological cross-sectional areas of 70’s male normalized by those of 20’s male

|       | GM | HAM | GAS | SOL | ILI | RF | VM | TA |
|-------|----|-----|-----|-----|-----|----|----|----|
| 70’s/20’s | 0.92 | 0.92 | 0.84 | 0.84 | 0.65 | 0.78 | 0.78 | 0.83 |

The computed muscle forces of ILI and TA of 20’s and 70’s males in one cycle are shown in Fig. 4. In Fig. 4, \( t = 0 \) to 0.6 correspond to stance phase, and \( t = 0.6 \) to 1 swing phase. The muscle forces of 70’s male are considerably lower than 20’s male due to the decline of PCSA. This agrees with the result, by Kuno (10) and McNeil et al. (13), that the decline of these two muscles may be the reason of falling down. Therefore, the optimal form was defined as the form in which these two muscles are actively employed. Based on this definition, the objective function was formulated as below:

\[
Obj = \sum_{i=1}^{4} \left[ \frac{MF_i}{PCSA_i} \right]^2 + \sum_{i=1}^{4} \left[ \frac{MF_i}{PCSA_i} \right]^2
\]

( \( MF \) : Muscle force, \( I \) : ILI, \( T \) : TA)

In the objective function, these two muscle forces were evaluated as muscle stresses by being divided by PCSA. In addition to this, the penalty function was employed so that the joint angles and joint torques do not exceed their determined maximum values. If the joint angle or torque exceed their maximum values, the excess amount is...
subtracted from the objective function. The joint range of motion and the maximum voluntary contraction of 20’s and 70’s male referred from human characteristics database (14).

3.2. Results of optimization

About 600 times iterations were required in order to obtain the solution of the optimization. The calculation time was about six hours by a 1.2GHz PC. The forms before and after optimization are shown in Fig. 5. The dark lines emitting from each part of the body represent the point of applications, directions and magnitudes of the fluid forces. It is found that the large fluid forces act on the shank and foot at \( t = 0.9 \) after optimization since the thighs are moved quickly at these moment.

The muscle forces of ILI and TA for the right leg after the optimization in one cycle are shown in Fig. 6. They become much larger than those in Fig. 4 at \( t = 0.9 \). It indicates that they are greatly recruited in the optimal form.

Fig. 5 Animation images of forms before and after communication
4. Conclusion

The widely usable simulator for optimization of walking form in water was developed. As an example of its application, the optimal form for the training of elderly people to prevent from falling down was obtained by the simulator. By the optimal form, ILI and the TA muscles can be selectively trained. In the future, various walking forms for various objectives will be clarified by this simulator.

References

(1) Konishi, K., Walking in Water, Liber Press (in Japanese), (1999), p. 28-83.
(2) Nakayama, S., New method for hydrotherapy and effects of flowwater training system, The Journal of Japanese Physical Therapy Association, Vol. 17, No. 3 (1990), pp. 211-215.
(3) Migita, T., Hotta, N., Ogaki, T., Kanaya, S., Fujishima, K. and Masuda, T., Comparison of the physiological responses to treadmill prolonged walking in water and on land, Japan Journal of Physical Education, Health and Sport Sciences, Vol. 40, No. 5 (1996), pp. 316-323.
(4) Nakashima, M., Sato, K. and Miura, Y., Development of Swimming Human Simulation Model Considering Rigid Body Dynamics and Unsteady Fluid Force for Whole Body, Journal of Fluid Science and Technology, Vol. 2, No. 1 (2007), pp. 56-67.
(5) Nakashima, M., Mechanical Study of Standard Six Beat Front Crawl Swimming by Using Swimming Human Simulation Model, Journal of Fluid Science and Technology, Vol. 2, No.1 (2007), pp.290-301.
(6) SWUM Developer Team, "Swimming Human Simulation Model SWUM". SWUM Website. (online). available from <http://www.swum.org/>, (accessed 2009-10-21).
(7) Miyoshi, T., Shirotta, T., Yamamoto, S., Nakazawa, K. and Akai, M., Lower Limb Joint Moment during Walking in Water, Disability and Rehabilitation, Vol. 25, No.21 (2003), pp. 1219-1223.
(8) Yamazaki, N., Analytical Model and Simulation of walking, Biomechanism (in Japanese), Vol. 3 (1975), pp. 261-269.
(9) AIST Digital Human Research Center, “AIST database of human size and shape”. AIST Website. (Online). available from <http://riodb.idase.aist.go.jp/hbobydb/index.php.ja>, (accessed 2010.01.20).
(10) Kuno, S., Relation between cross-sectional area of popas major muscle and running/walking ability (in Japanese), Journal of the Society of Biomechanisms, Vol. 24, No. 3, (2000), pp. 148-152.
(11) Tanaka, M., Yamada, M., Yamaguchi, Y. and Majima, T., Change in Cross-Sectional Areas of Thigh Muscles of Healthy Subjects with Aging, The Journal of Japanese Physical Therapy Association, Vol. 11, No. 2, (1990), 75-79.
(12) Christopher I. Morse, Jeanette M. Thom, Neil D. Reeves, Karen M. Birch, Marco V. Narici, In Vivo Physiological Cross-sectional Area and Specific Force are Reduced in the Gastrocnemius of elderly men, Journal of Applied Physiology, Vol. 99 (2005), pp. 1050-1055.
(13) Chris J. McNeil, Anthony A. Vandervoort, Charles L. Rice, Peripheral Impairments Cause a Progressive Age-related Loss of Strength and Velocity-dependent Power in Dorsiflexors, Journal of Applied Physiology, Vol. 102 (2007), pp. 1962-1968.
(14) National Institute of Technology and Evaluation, “Human Characteristics Database”. National Institute of Technology and Evaluation Website. (Online). available from <http://www.tech.nite.go.jp/human/indexeng.html>, (accessed 2010-01-20).