Disability and Rehabilitation, 2008; 30(2): 81–87

informa
healthcare

RESEARCH PAPER

Robotic gait trainer in water: Development of an underwater gait-training orthosis

TASUKU MIYOSHI[1,2], KAZUAKI HIRAMATSU[3], SHIN-ICHIRO YAMAMOTO[1], KIMITAKA NAKAZAWA[4] & MASAMI AKAI[4]

[1]*Shibaura Institute of Technology, Saitama,* [2]*Japan Foundation for Aging and Health, Aichi,* [3]*Hitachi Medical Corporation, Chiba, and* [4]*Research Institute of National Rehabilitation Center for Persons with Disabilities, Saitama, Japan*

Accepted December 2006

Abstract

Purpose. To develop a robotic gait trainer that can be used in water (RGTW) and achieve repetitive physiological gait patterns to improve the movement dysfunctions.

Method. The RGTW is a hip-knee-ankle-foot orthosis with pneumatic actuators; the control software was developed on the basis of the angular motions of the hip and knee joint of a healthy subject as he walked in water. Three-dimensional motions and electromyographic (EMG) activities were recorded in nine healthy subjects to evaluate the efficacy of using the RGTW while walking on a treadmill in water.

Results. The device could preserve the angular displacement patterns of the hip and knee and foot trajectories under all experimental conditions. The tibialis anterior EMG activities in the late swing phase and the biceps femoris throughout the stance phase were reduced whose joint torques were assisted by the RGTW while walking on a treadmill in water.

Conclusion. Using the RGTW could expect not only the effect of the hydrotherapy but also the standard treadmill gait training, in particular, and may be particularly effective for treating individuals with hip joint movement dysfunction.

Keywords: *Gait training, hydrotherapy, pneumatic actuator, powered exoskeleton orthosis*

Introduction

It is now well recognized that the hydrotherapy was useful exercise for patients with arthritis, lower back pain, and various orthopedic disorders [1], since the impact force on the lower limb joints can be easily controlled by varying the depth of immersion. However, the hip joint extension moment and hip extension EMG activities would increase against the water resistance while walking in water [2]. Therefore, the walking speed and immersion level must be monitored during hydrotherapy, especially in individuals with hip joint movement dysfunctions. To our knowledge, there is no evidence that hydrotherapy is useful for individuals who cannot walk independently. One explanation for hydrotherapy not being used is that it is difficult for therapists to monitor the legs of patient who are walking on a submerged treadmill. However, a more definitive reason is the lack of gait training devices that can be used under water.

A combination of underwater exercise and orthotic gait training could be a very effective synthetic training method. Therefore, a new gait trainer for use in water that combines the benefits of traditional treadmill gait training and hydrotherapy could be very effective for individuals who cannot walk independently. The purpose of this study was to develop a robotic gait trainer that can be used in water (RGTW) and to evaluate its efficacy by measuring the lower limb joint angular displacements, foot trajectories, and electromyographic (EMG) activities in healthy volunteers.

Correspondence: Tasuku Miyoshi, PhD, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama-city, Saitama 3378570, Japan. Tel: 81 48 6889405. Fax: 81 48 6875197. E-mail: miyoshi@bpe.se.shibaura-it.ac.jp

ISSN 0963-8288 print/ISSN 1464-5165 online
DOI: 10.1080/09638280701191826

Methods

Concept and structure of the RGTW

The concept of the RGTW is based on physiology: The load-related somatosensory stimulus [3], flexion/extension information of the hip joint from the hip mechano-receptors (for a review; see [4]), and the reciprocal relationship between the right and left leg [5] have an important role in the activation of the spinal locomotor circuits. Based on these findings, the RGTW should control hip joint flexion/extension as well as the timing of each. In addition, robotic devices offer several advantages, such as increased safety, repetition of physiological gait patterns, hand-free operation by an individual therapist, and reduction of the therapist's workload.

Pneumatic actuators (rubber-tube actuators, Hitachi Medical Corporation) were used (Figure 1A) to prevent accidents from short circuits during underwater use. Five actuators were used for each joint movement of one leg: two were used for hip flexion (length 475 mm; MS-0475-040), one for hip extension (320 mm; MS-0320-040), one for knee flexion (390 mm; MS-0390-040), and one for knee extension (245 mm; MS-0245-040) in each leg; a total of ten actuators were attached to both legs. Each actuator was attached to the hip-knee-ankle-foot orthosis with a pair of attachments (Figure 1B). These attachments can easily control the range of motions and/or the assisting torques by changing the combination of attachment points.

Handling and evaluation of the RGTW in healthy subjects

Nine healthy young subjects (22 – 24 years, 170+/−2.2 cm height) participated in this study. They had no history of orthopedic or neurological ailments or recent injury or surgery that affected walking and/or standing upright. Each subject provided informed consent acknowledging the experimental procedures that were approved by the ethics committee of the National Rehabilitation Center for Persons with Disabilities.

First, subjects were asked to walk on a treadmill at 1.2 km/h for 6 min (control) to achieve hip, knee, and ankle joint angular displacement while walking on a treadmill (Aquagator model 1104, Ferno Japan Inc.) in water. We used the joint angular displacement patterns to control the RGTW as a physiological gait pattern. To determine whether the RGTW could be used to establish a healthy gait pattern, the same subjects participated in the experiment in water. The water temperature was set to 34°C, and the water depth was set at 1.4 m (at the level of the axillae). Subjects were then asked again to walk on the treadmill at 1.2 km/h for 6 min using the RGTW without the assist torques. To examine the effect of the assist torque, they walked 100 cycles (10 gait

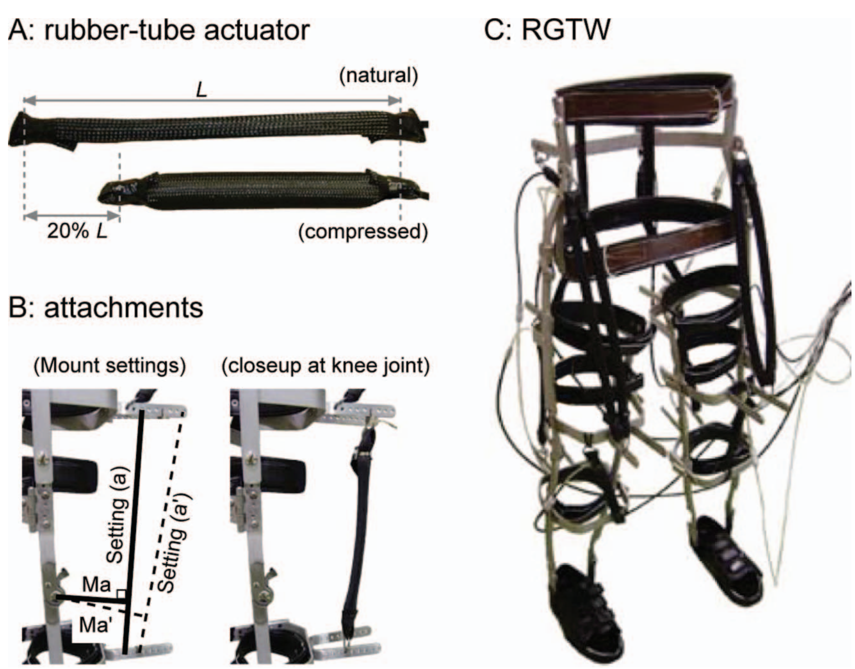

Figure 1. (A) The pneumatic actuators (rubber-tube actuators) used in this study. These were linear motion-type actuators and had a 20% modulus of contraction from natural length. (B) Left: attachment parts that could change the setup of the attachment position and could easily control the assist torque by changing the moment arm (Ma to Ma'). Right: a close-up photograph at the knee joint attached in orthosis. (C) The robotic gait trainer developed for this study that can be used underwater (RGTW).

cycles for each set; a total of 10 sets) with an assist torque using the RGTW. A three-dimensional four-body segment model, consisting of the trunk (trunk + pelvis), thigh, shank, and foot, was defined using five markers with a 3 cm square seal (0.1 mm thickness) at the following landmarks: The illiac crest, greater trochanter, lateral femoral condyle, lateral malleolus, and fifth metatarsal head (MP). All markers were waterproof and placed on the right side of the leg and trunk. The marker data were recorded with a two-camera video-based system (30 Hz). The two cameras were placed on the right side of the subject at an average distance of 2.0 m and along an arc of about 90° to cover one stride. Motion analysis system software (Dipp-Motion XD, DITECT Co., Ltd.) was used to reconstruct the marker positions into three-dimensional coordinates. The joint center of rotation was estimated at the geometric center of the joint. A fourth-order zero-lag Butterworth filter was applied to reduce the noise in the video data (cut-off frequency: 3 Hz).

To determine the heel contact in each step, a foot switch was placed on the surface of the heel of the right foot. Surface electromyographic (EMG) activities were recorded from the muscle bellies of the soleus (SOL), the medial gastrocnemius (MG), the tibialis anterior (TA), the rectus femoris (RF), and the long head of the biceps femoris (BF) muscles of the right leg using pairs of bipolar electrodes (Ag-AgCl, 8 mm diameter) with an inter-electrode distance of 3.0 cm. These electrodes were waterproofed by using a microfilm. All EMG signals were amplified and band-pass-filtered (30 Hz to 5 kHz) with a bioelectric amplifier (MEG-6108, Nihon Koden Co., Ltd.). The foot switch and EMG signals were digitized with a sampling frequency of 1 kHz and stored on a personal computer via an AD converter (WE7251, Yokogawa Electronic Co., Ltd.) for off-line analysis.

Data analysis and statistics

Angular displacements were defined as positive when the hip and knee moved in the flexion direction. The EMG signals were full-wave-rectified after subtracting the DC component. The angular displacements and EMG data were then expressed in relation to the 100% cycle under each walking condition. The mean EMG amplitude of each muscle during the stance and swing phases was also calculated and expressed as a ratio of the stance phase of the control condition. A one-way repeated analysis of variance (ANOVA) was used to determine the significant differences under three experimental conditions. The levels were considered statistically significant at $p < 0.05$.

Results

Figure 2A shows typical gait patterns with the RGTW and clearly demonstrates that they could be accurately recorded under each experimental condition. Figure 2B shows the foot trajectories that were defined as MP markers relative to the instantaneous IL marker while walking on the treadmill in water under each condition. Figure 2C shows ensemble-averaged patterns of hip and knee joint angular displacement in the right leg through a one-step cycle in one subject. These Figures show that each actuator was well controlled by its movement pattern, since both the foot trajectories and the joint angular displacement patterns in the hip and knee joint were preserved throughout a one-step cycle.

Figure 3 shows the ensemble-averaged EMG activities of the SOL (top panels), the MG (middle upper), the TA (middle), the BF (middle lower), and the RF (bottom) through a one-step cycle in the same subject (shown in Figure 2). As for the SOL, the MG, and the RF EMG activities, there were no remarkable changes throughout the one-step cycle. When the RGTW worked, the TA EMG activities at the late swing phase (about 80 – 100% cycle) and the BF EMG activities throughout the stance phase decreased more significantly than those under the other conditions. These situations are shown clearly in Figure 4. When the subjects used the RGTW while walking on the treadmill in water, their TA and BF EMG activities decreased more than they did under the control conditions and without an assist torque.

Discussion

The main objectives of this study were to develop a new gait orthosis that can be used in water (RGTW) and to investigate the lower limb joint angular displacements, foot trajectories, and EMG activities while walking on a treadmill in water with the RGTW. The results are as follows: (i) We developed a safer robotic gait trainer that can be used in water (RGTW); (ii) both the foot trajectories and the joint angular displacement patterns of the hip and knee joint were preserved with the use of the RGTW; and (iii) the assist torques reduced the enhanced BF and TA EMG activities. It is noteworthy that this new device (RGTW) can be used under severe experimental conditions, even while submerged, without disturbing the gait patterns, and both the lower limb joint angular displacements and foot trajectories were unaffected when the RGTW was in use. However, the extent to which the findings from this study can be applied to patients with movement dysfunctions is unclear because the data is based on experiments limited to healthy subjects.

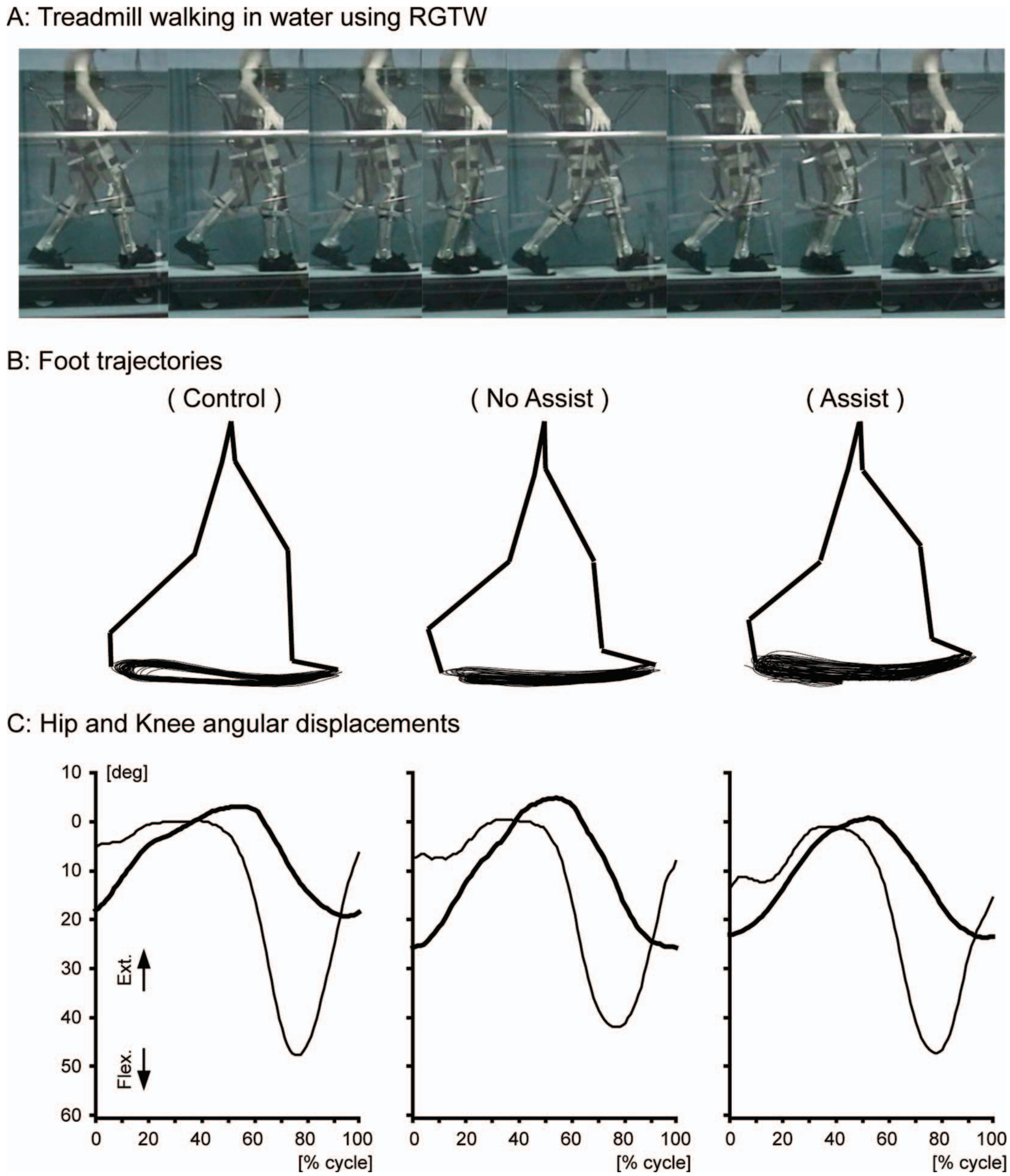

Figure 2. (A) A typical gait pattern throughout a one-step cycle with the RGTW while walking on a treadmill in water. (B) Endpoint path relative to the instantaneous IL position while walking on a treadmill in water (left column), using the RGTW without an assist torque (middle column), and using the RGTW with an assist torque (right column). The spatial coordinates of the MP were superimposed over 100 consecutive step cycles performed by one subject. (C) Ensemble-averaged profiles of hip (thick lines) and knee (thin lines) angular displacements throughout the one-step cycle in the sagittal plane while walking on a treadmill in water (left column), using the RGTW without an assist torque (middle column), and using the RGTW with an assist torque (right column) in the same subject. All Figures show the angular deviation from an upright standing position.

Ivanenko et al. [6] demonstrated that the foot trajectories of various bodyweight support treadmill walking were preserved, whereas the patterns changed significantly only when the load information from the foot was unavailable. In this respect, the results showing preserved foot trajectories and joint angular displacement patterns when using the RGTW while walking on a treadmill in water could explain the same mechanisms, namely, the functional roles of the load information from the foot while walking on a treadmill, since the water immersion level was maintained throughout the experimental conditions. Therefore, repetitive physiological gait patterns were achieved in the control with assist torques and the RGTW for the hip and knee joint angular displacement patterns in healthy subjects walking on a treadmill in water. Water walking therapy with an RGTW might be effective

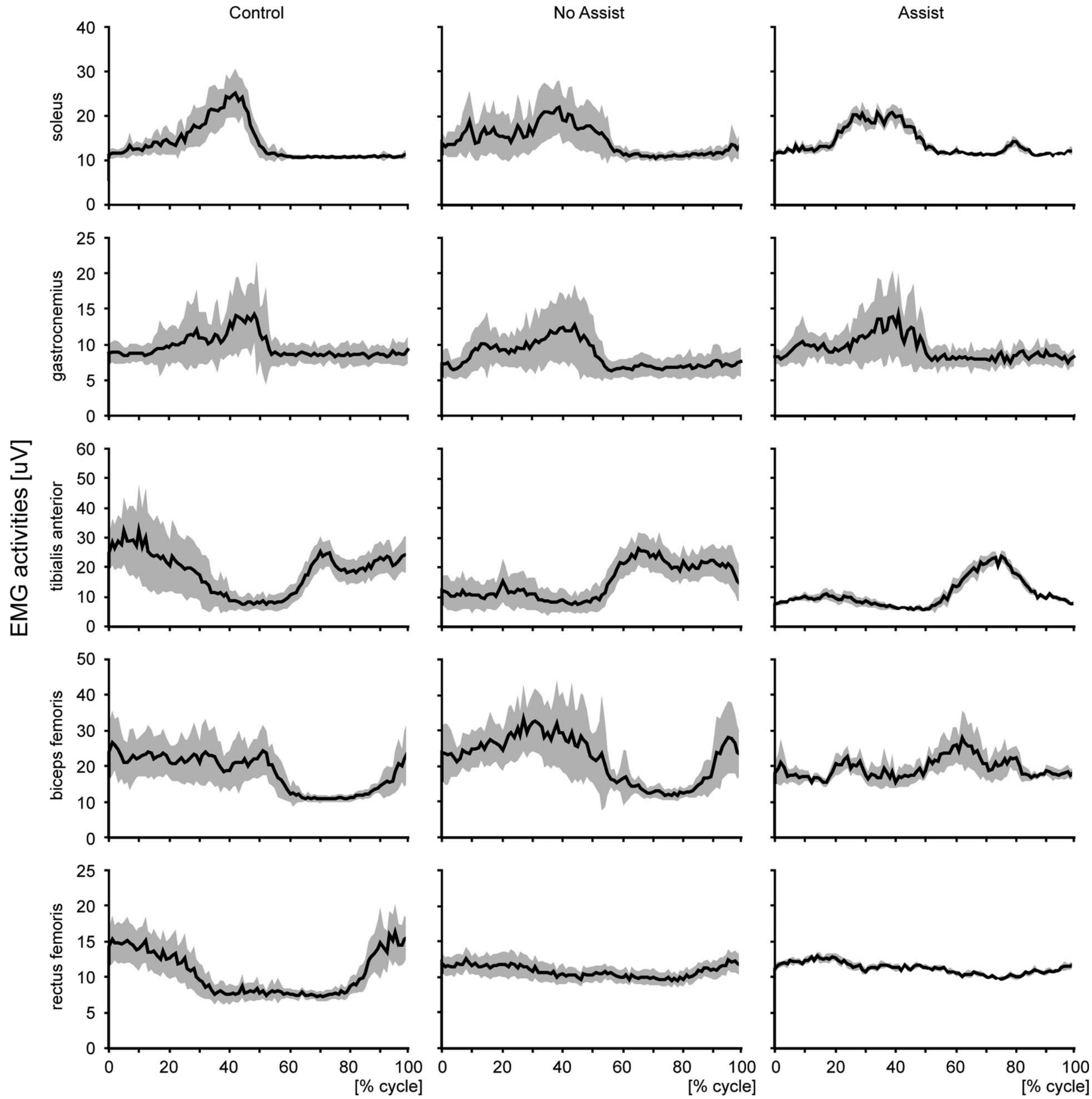

Figure 3. Ensemble-averaged profiles of EMG activities throughout a one-step cycle: soleus (top), medial gastrocnemius (middle upper), tibialis anterior (middle), biceps femoris (middle lower), and rectus femoris (bottom) in the same subject, as shown in Figure 2. The most interesting findings in the EMG activities were the BF and the TA; the BF EMG activities throughout the stance phase were drastically decreased by the hip extension assist torque using the RGTW, and the TA EMG activities at the late swing phase were also reduced by the knee flexion assist torque. The gray area denotes the standard deviations through the one-step cycle.

for rehabilitation as well as for general exercise leading to gait-training motivation for patients with movement dysfunctions.

With regard to the functional roles of the SOL and MG EMG activities while walking on land, Gottschall and Kram recently reported that the MG plays an important role in forward propulsion, whereas the SOL does not [7]. Miyoshi et al. [8] demonstrated that dissociative activation patterns occurred in the triceps surae muscle of subjects walking in water; the SOL EMG activities increased with an increase in the load, whereas the MG EMG activities were enhanced with an increase in the walking speed. The SOL and MG EMG activities while using the RGTW did not change significantly because the water depth and treadmill speed were unchanged during the experiment. The amplitudes of the TA EMG activities at the swing phase increased under all conditions, which was unanticipated. In water, the load is reduced by buoyancy; however, more force is required for walking in water than on land because of water resistance.

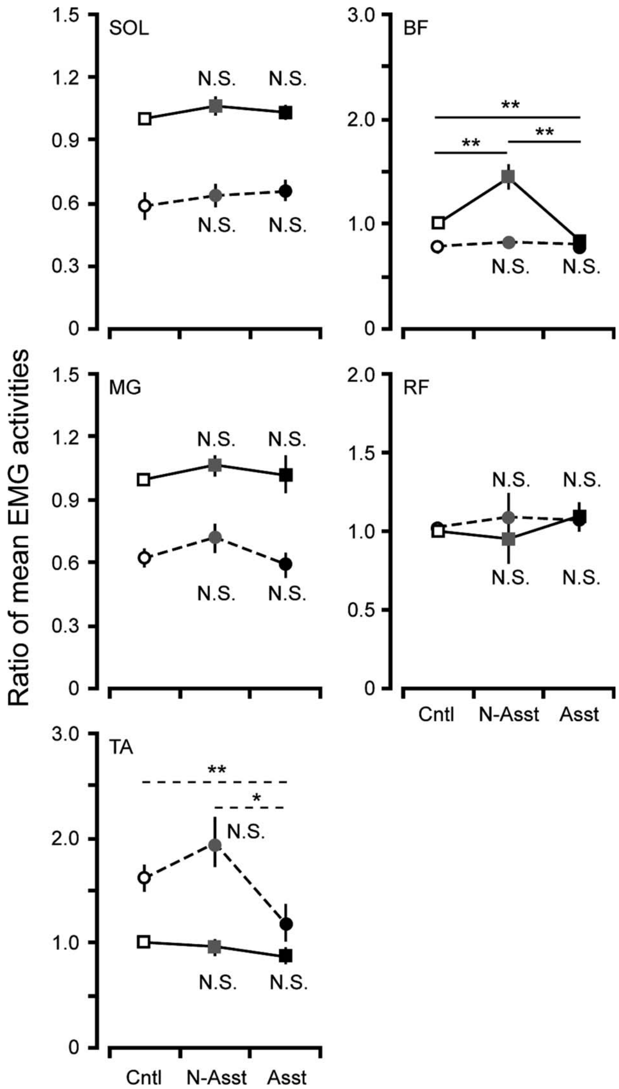

Figure 4. Mean EMG amplitudes at both the stance and the swing phases, normalized by the value of the stance phase under the control condition in each muscle. Using the RGTW while walking on a treadmill in water, the TA and BF EMG activities decreased more significantly than those under the control conditions and without an assist torque (* $p < 0.05$; ** $p < 0.01$).

The RGTW lacks a plantar-flexion and a dorsiflexion mechanism around the ankle joint. Therefore, the functional role of the enhanced TA EMG activities at the swing phase with the RGTW might exert dorsiflexion torque against the water resistance. Further research is needed on this point since the RGTW would need more actuators to decrease the TA EMG activities at the swing phase. The RF EMG activities did not change in the stance and swing phases with or without the RGTW. This was because the RF ENG activities are not needed while walking on a treadmill in water. Sadeghi et al. [9] demonstrated that the functional role of the hip flexion torque was an anti-gravity function. In this respect, the functional roles of the RF EMG activities while walking on a treadmill in water might create a difference in the hip flexion muscle group. One possibility is that the RF EMG activities while walking on a treadmill in water were given priority over the anti-gravity function, whereas the other hip flexion muscles resulted in the leg swinging against the water resistance. Further research will also be required on this point; however, the hip flexion assist torques with the RGTW would assist the hip flexion muscle group rather than the RF. Miyoshi et al. [10] reported that the hip extension moment was significantly more enhanced throughout the stance phase while walking in water than when walking on land and that it is necessary to activate the hip extensor muscle group to generate a propulsive force against water resistance while walking in water. In this sense, if the spatio-temporal patterns of the hip assist torques in the RGTW were successfully controlled, the enhanced hip extension moment and/or the hip extensor muscle group activities would be reduced. The decreased BF EMG activities with the use of the RGTW compared with those of the control condition indicate that we succeeded in controlling the spatio-temporal patterns of the hip assist torques.

Clinical relevance

The value of partial body weight support treadmill training (BWSTT) for disabled individuals has been well established, especially when initiated soon after an injury. Wernig et al. [11] had demonstrated that 25 out of 33 incomplete spinal cord injured persons learned to walk independently at the end of 3–20 weeks (median 10.5) with partial BWSTT. Wernig et al. [11] demonstrated that 25 of 33 individuals with spinal cord injuries learned to walk independently at the end of 3–20 weeks (median 10.5) with partial BWSTT. However, this treatment presents special challenges for the therapist. The passive moving of a disabled person's legs is ergonomically difficult since the individual being treated cannot support and/or move his legs by himself. In order to improve this therapy, Colombo et al. [12] developed a driven gait orthosis (DGO) that can be used on patients with varying degrees of paresis or spasticity for up to half an hour. Body weight can be controlled by the therapist during hydrotherapy by changing the depth to vary the load according to a patient's ability to maintain his upright posture against gravity. Variations in the immersion level can also be used to adjust for the static pressure of water to ease breathing while exercising. Reports indicate that breathing exercises during immersion improve the pulmonary function and blood-gas exchange in healthy subjects (for a review, see [13]) and in patients with chronic obstructive pulmonary disease

[14–16]. In other cases, passive body heat, such as that from a warm bath, effectively increased rectal body temperature, slow-wave sleep (deep sleep), and sleep quality in elderly with insomnia (for a review, see [17]). Hydrotherapy with the RGTW has at least three advantages over the partial body weight support treadmill training on land. First, the RGTW is electrically and mechanically safe since it consists of pneumatic actuators to prevent short circuits and the main frame is an exoskeleton type of the hip-knee-ankle orthosis that is used in general gait training. Second, the body weight is managed by changing the depth of immersion, which allows a patient to maintain an upright posture. Third, the intensity of breathing while exercising under static pressure of water can easily be controlled by changing the depth of immersion. In the future, investigations could be conducted to determine the effects of passive body heat as physically dysfunctional patients walk.

Conclusion

We developed a robotic gait trainer for use in water (RGTW) and evaluated its efficacy with EMG data as individuals walked in water. The RGTW reduces the activity of the hip extension muscle group. The RGTW may be used in partial body weight support training and for hydrotherapy, and it may be particularly valuable in therapy for hip joint movement dysfunctions.

Acknowledgements

We thank Keisuke Hotta for his preparation of the experimental device and Hideaki Hiramatsu for his help with the experiments. This study was supported in part by the Ministry of Health, Labor, and Welfare of Japan and by the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

References

1. Eitner D. Exercise in water. In: Kuprian E, editor. Physical therapy for sports. Philadelphia: Saunders; 1982. pp 155–157.
2. Miyoshi T, Shirota T, Yamamoto S-I, Nakazawa K, Akai M. Effects of the walking speed to the lower limb joint angular displacements, joint moments and ground reaction forces during walking in water. Disabil Rehabil 2004;26: 724–732.
3. Harkema SJ, Hurley SL, Patel UK, Requejo PS, Dobkin BH, Edgerton VR. Human lumbosacral spinal cord interprets loading during stepping. J Neurophysiol 1997;77: 797–811.
4. Dietz V. Proprioception and locomotor disorders. Nat Rev Neurosci 2002;3:781–790.
5. Kawashima N, Nozaki D, Abe MO, Akai M, Nakazawa K. Alternate leg movement amplifies locomotor-like muscle activity in spinal cord injured persons. J Neurophysiol 2005; 93:777–785.
6. Ivanenko YP, Grasso R, Macellari V, Lacquaniti F. Two-thirds power law in human locomotion: Role of ground contact forces. Neuroreport 2002;13:1171–1174.
7. Gottschall JS, Kram R. Energy cost and muscular activity required for propulsion during walking. J Appl Physiol 2003; 94:1766–1772.
8. Miyoshi T, Sato T, Tanizaki M, Nakazawa K, Akai M. Altered activation pattern in synergistic ankle extensor muscles in the reduced-gravity environment. Gait Posture 2006; 24:94–99.
9. Sadeghi H, Allard P, Duhaime M. Muscle power compensatory mechanisms in below-knee amputee gait. Am J Phys Med Rehabil 2001;80:25–32.
10. Miyoshi T, Shirota T, Yamamoto S-I, Nakazawa K, Akai M. Functinoal roles of lower-limb joint moments while walking in water. Clin Biomech 2005;20:194–201.
11. Wernig A, Muller S, Nanassy A, Cagol E. Laufband therapy based on 'rules of spinal locomotion' is effective in spinal cord injured persons. Eur J Neurosci 1995;7:823–829.
12. Colombo G, Joerg M, Schreier R, Dietz V. Treadmill training of paraplegic patients using a robotic orthosis. J Rehabil Res Dev 2000;37:693–700.
13. Reilly T, Dowzer CN, Cable NT. The physiology of deep-water running. J Sport Sci 2003;21:959–972.
14. Kurabayashi H, Kubota K, Machida I, Tamura K, Take H, Shirakura T. Effective physical therapy for chronic obstructive pulmonary disease. Pilot study of exercise in hot spring water. Am J Phys Med Rehabil 1997;76:204–207.
15. Kurabayashi H, Machida I, Kubota K. Improvement in ejection fraction by hydrotherapy as rehabilitation in patients with chronic pulmonary emphysema. Physiother Res Int 1998; 3:284–291.
16. Wadell K, Sundelin G, Henriksson-Larsen K, Lundgren R. High intensity physical group training in water – an effective training modality for patients with COPD. Respir Med 2004; 98:428–438.
17. Liao W-C. Effects of passive body heating on body temperature and sleep regulation in the elderly: A systematic review. Int J Nur Stu 2002;39:803–810.