DEVELOPMENT OF GAIT ASSIST SYSTEM FOR UNDERWATER TRAINING

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Abstract: The aim of this study was to develop a pneumatic gait orthosis for underwater gait training. This orthosis was modified from long-leg orthosis based on the hip and knee joint angular motions. The special pneumatic actuator is similar to human leg muscular system. The prototype system of pneumatic gait orthosis was evaluated by the experimental test on land and underwater conditions. The results of experimental test indicated that the hip and knee joint movement patterns of both on land and underwater walking were quite similar with the kinematics of normal walking, and also the hip extensor muscle activity decreased during stance phase in underwater walking. The results of this study suggested this pneumatic gait orthosis might be effective for underwater training to several motor disorders.

Introduction

Some previous studies have been developing the body and gait support system for locomotor training on land as one of the rehabilitation method for several motor disorders. Dietz and Colombo's group has been developing from 90's the driven gait orthosis system used gait orthosis with DC motor, lift system for unloading of body weight and treadmill (Colombo et al. 2000; Colombo et al. 2001). Hesse's group has also been developing from 90's the gait trainer and partial body support system for locomotor training (Hesse et al. 1999, Hesse et al. 2000). Those studies have already been using those systems for several clinical studies and suggested the effectiveness for several motor disorders.

On the other hands, in Japan, the underwater exercises are very popular as one of the method of physical therapy for several motor dysfunctions. The buoyancy of water can decrease the vertical component of the ground reaction force (GRF) for walking, especially that of the impact force at heel contact (Nakazawa et al. 1994). Also, the joint moment of the lower limb is decreased during stance phase of the underwater walking (Miyoshi et al. 2004). Moreover, when walking underwater, propulsion forces against to water resistance. These properties for walking underwater have some advantages for rehabilitation methods as compared to several on-land exercises. It has been suggested that the underwater exercise improves the pulmonary function and blood-gas exchange in healthy subjects (Reilly et al. 2003) and in patient of chronic obstructive pulmonary disease (Kuribayashi et al. 1997). Therefore, we focused on the underwater environment instead of body support system on land. However, if the patient cannot perform voluntary movements (e.g., hemiplegia, paraplegic), it might also be difficult to walk underwater. Therefore, we attempted to develop an underwater gait assist system.

Materials and Methods

This gait assist system consists of a pneumatic gait orthosis and a waterproof treadmill. The pneumatic actuator used the "Air Muscle" (Hitachi Medical Co.) (Fig.1A). This pneumatic actuator is made from a rubber tube and a special reticular fiber. The actuator length can be shortened by 30 % maximum by air pressure. The long-leg orthosis was modified to two degree of freedom in the sagittal plane: the hip joint is movable in the flexion and extension direction, the knee joint is movable in the flexion direction, and the ankle joint is immobilized (Fig 1B). The number of actuators, the actuator position, and the moment arm of each joint in each actuator can be easily changed by the attachment of gait orthosis.

The electronic-pneumatic regulator is used to control the rubber tube actuator. The control procedure is defined on the basis of the normal gait pattern. This controller consists of an open-loop feed-forward system with a control frequency of 10 Hz.

Experimental test for pneumatic gait orthosis has

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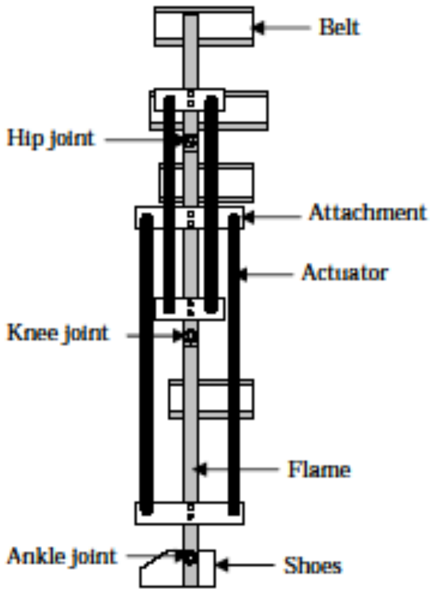
been performed by on land and underwater conditions. Five healthy male subjects (age: 22 – 26 yrs) agreed the informed consent for the experimental procedure and participated to this experiment.

A

B



C

Figure 1: A) The pneumatic actuator "air muscle". B) Schematic representation of the pneumatic gait orthosis. C) The pneumatic gait orthosis

To determine the heel contact in each step, a waterproofed foot switch was attached on the surface of the heel of right foot. Surface EMG activities were recorded from muscle belly of medial gastrocnemius (MG), tibialis anterior (TA), rectus femoris (RF), long head of biceps femoris (BF) and gluteus maximus of right leg by bipolar electrodes (Ag-AgCl, 8mm diameter) with inter-electrode distance of 3.0 cm. These electrodes were covered by microfilms for waterproof. All EMG signals were amplified and band-pass-filtered (30 Hz – 5 kHz) by a bio-amplifier.

On the land gait orthosis, the hip and knee angles were measured by electro-goniometer attached to the center of rotation axis in each joint. On the underwater gait orthosis, those angles were calculated from coordinates of center of rotation axis of the shoulder, hip, knee and ankle joint acquired by 3D motion analyzing system.

Walking speed was 1.2 km/h on land and underwater treadmill. The immersion level was 1.2 m (umbilicus level: 60 % body weight-reduced condition), and the water temperature was 34 ˚C. Two types of test compared: assist and non-assist by pneumatic actuator, to examine the effect of assist torque. The subject walked five sets (1 set: 10 gait cycles) after sufficient practice to walk with gait orthosis.

Results and Discussion

The average waveform of the hip and knee joint angle on land and underwater conditions were shown in Figure 2. In both case of on land and underwater conditions, the displacement of the hip and knee joint angles indicates a quite similar pattern between assist and non-assist walking. However, the range of motion and timing of flexion and extension were different between on land and underwater conditions and/or between assist and non-assist walking.

In case of on land condition, the hip joint displacement was relatively flexed during stance phase in assist walking as compared to that in non-assist walking. The timing of turning point from hip extension to flexion was earlier in assist walking than in non-assist walking. Also, the knee joint displacement was also relatively flexed during stance phase in assist walking as compared to that in non-assist walking. The timing of knee flexion was earlier in assist walking than in non-assist walking.

These results of on land condition indicate the pneumatic actuator of the hip and knee flexion is mainly effective to assist the leg swing of orthotic gait on land

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walking. However, in case of hip joint movement, the range of motion and the peak hip extension were decreased in assist walking as compared to that in non-assist walking.

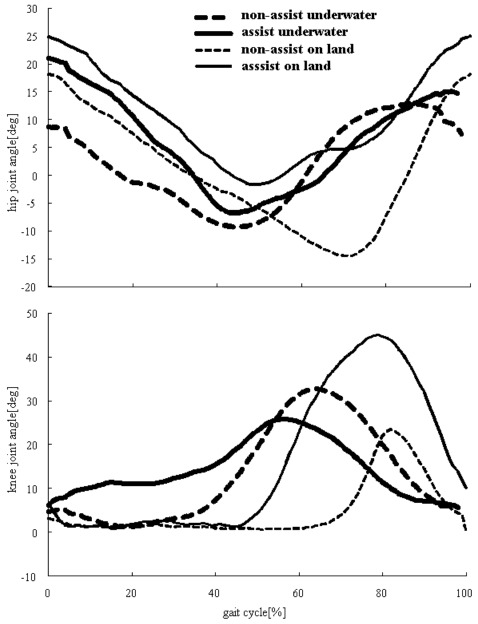

Figure 2: The average waveform of the hip and knee joint angle displacements. The abscissa was standardized from heel contact to toe-off by gait cycle (%). The plus quantity of ordinate represents flexion direction of each joint.

Dietz and Harkema (2004) suggested load- or hip joint-related afferent input are crucial importance for both the generation of a locomotor pattern and the effectiveness of the training for spinal cord injury. Therefore, it seems we have to improve our gait orthosis about the range of motion, especially hip extension, for the locomotor training for spinal cord injury.

In case of underwater condition, the hip and knee joint displacements were relatively flexed during stance phase in assist walking as compared to that in non-assist walking. Moreover, the hip joint angle of non-assist walking in underwater is not so flexed during stance phase as compared to those of other conditions. This result indicates the pneumatic actuators for hip flexion and knee flexion is effective in underwater. However, in case of underwater condition also, the hip extension is still not sufficient for locomotor training.

The average EMG waveforms of leg muscles in underwater condition are shown in Figure 3. The EMG activity of MG, BF and GM was significantly decreased in assist walking during stance phase as compared to that in non-assist walking.

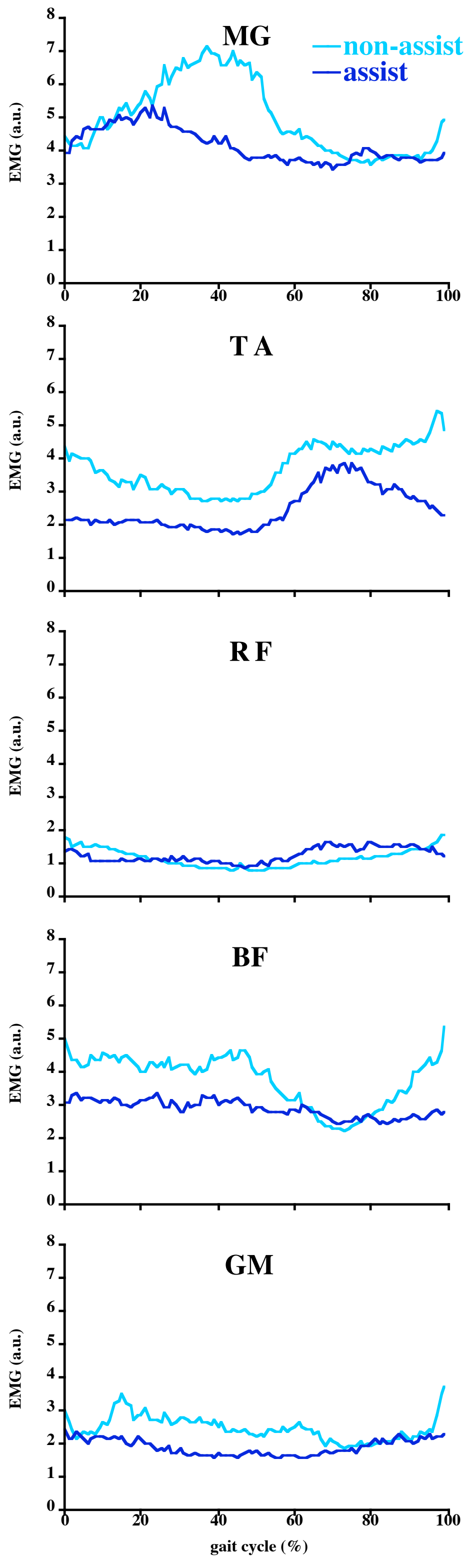

Figure 3: The average rectified EMG waveform of leg muscles in underwater walking. MG: medial head of gastrocnemius, TA: tibialis anterior, RF: rectus femoris, BF: Biceps femoris, GM: gluteus maximus.

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The EMG activity of TA was decreased in assist walking during all the gait cycle. Those reductions of EMG activity seem to be reasonable and functional. The GM and BF is one of the hip extensor muscles, and the MG is used for forward movement. In underwater walking, the body weight is deceased by buoyancy. On the other hand, the propulsion force is increased by water resistance. Miyoshi et al. (2004) indicated that the EMG activity of hip extensor muscle (BF) increased in underwater as compared to that on land walking, and suggested the BF EMG activity is necessary to generate the propulsion force for underwater walking. Therefore, in this study, the reduced EMG activity in assist walking suggests the effectiveness of gait orthosis to support the propulsion force in underwater walking.

The underwater locomotor training with pneumatic orthosis has several advantages, i.e.; natural body support, effect on breathing and body temperature, as compared to on land locomotor training. For the next model, it is necessary to improve the strategy of software program of pneumatic actuators (timing, combination of recruitment and so on) and the structure (number, position, moment arm of actuators and so on), especially for hip extension torque.

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