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A Robotic Gait Training System with Stair-climbing Mode Based on a Unique Exoskeleton Structure with Active Foot Plates

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Abstract: This paper introduces a newly developed robotic gait training system for lower-limb rehabilitation of stroke patients. The system (Cyborg-Trainer L; Cyborg-Lab Co., Korea) provides a stair-climbing mode in addition to the conventional level-walking mode by leveraging a unique exoskeleton structure with separately operable foot plates. Unlike conventional end-effector type gait training robots, the subject's feet are not constrained by foot plates, but are free to emulate the ground or a set of stairs. The ground reaction force is measured by force sensors in the foot plates and utilized to compensate for the vertical movement of pelvis. The exoskeleton structures are connected at hip, knee, and ankle joints, and these can support a patient's weight to ensure a normal gait pattern. The system has four control modes with different levels of assistive or resistance force. To show the feasibility of the developed training mode, a series of experiments measuring muscle activity were conducted during 1) level-walking with the robot, 2) level-walking on a treadmill without a robot, 3) stair-climbing with the robot, and 4) actual stair-climbing without a robot. The muscle activation from the rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius medialis of the dominant leg of five healthy adults were measured and analyzed. Results showed that all muscles had a rhythmic muscle activation pattern. Even though muscle activation patterns were different between gaits using the robotic gait system and those not using it, reduced amplitudes and phasic muscle activations were observed during the training in the robotic system. The developed system is a new type of robotic gait training system that could induce phasic lower limb muscle activation patterns, and its clinical efficacy will be validated in clinical trials after regulatory approval.

Keywords: Exoskeleton, gait training, lower-limb rehabilitation, rehabilitation robot, stair-climbing.

1. INTRODUCTION

Stroke is the leading cause of acquired disability, such as hemiplegia, in adults [1]. One of the main goals of stroke survivors to return to their daily activities is the recovery of their ability to walk by themselves. This often requires essential locomotion training for patients. Traditional therapies are usually performed on a treadmill with partial body-weight support in order to restore the functional mobility of affected limbs. Body-weight supported treadmill training (BWSTT), which is a task-specific training system, has reported improvements in the walking function in individuals with locomotor disorders, such as stroke patients [2]. However, BWSTT therapies require a lot of effort and cause fatigue in the therapists, so more than two therapists are often required to support a single patient. For these reasons, various robotic locomotion therapy systems have been developed and used to train the patients.

Gait rehabilitation robotic systems can be classified into two types: exoskeletal type and end-effector type [3, 4]. Representative exoskeletal rehabilitation systems are the Lokomat (Hocoma AG, Switzerland) [5], the ReoAmbulator (Motorika, Israel) [6], and the Walkbot (P&S mechanics, Korea) [7]. These systems all consist of a treadmill and exoskeleton with a body-weight support. These exoskeleton structures are attached to a patient's hips, knees, and ankles using cuffs, and they are able to assist with the

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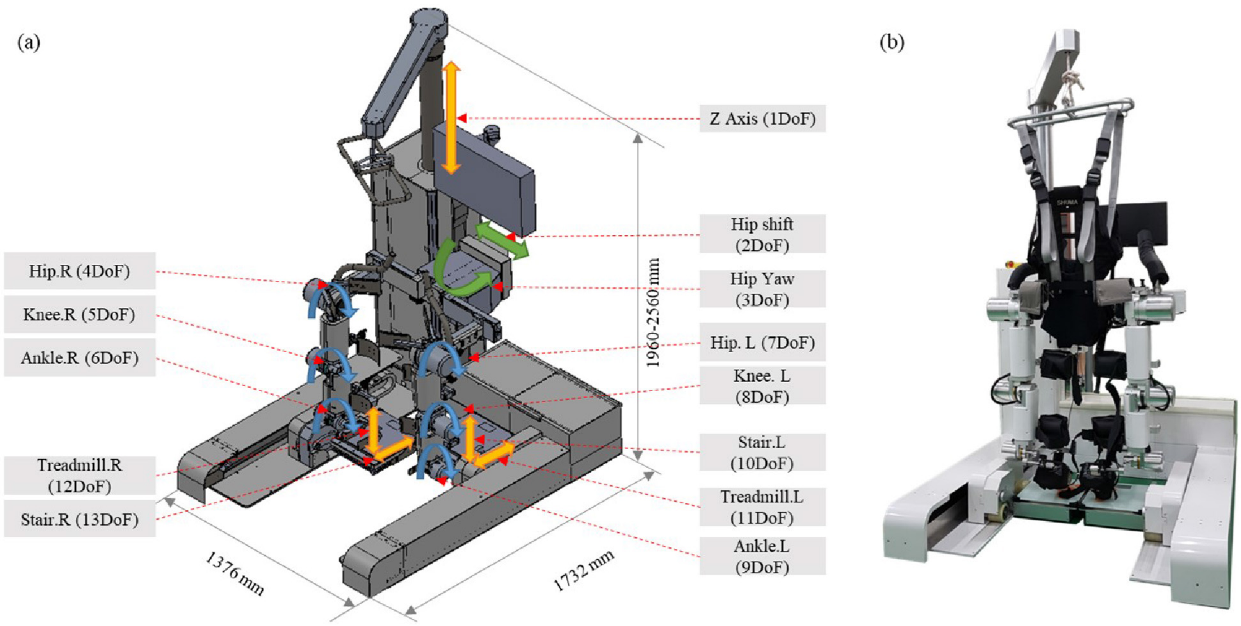

Fig. 1. Design of the robotic gait training system: (a) a three-dimensional model and (b) robot prototype.

establishment of a normative gait pattern while the patient walks on the treadmill. Due to their mechanical structure, these types of robots are generally limited to training on a level platform.

Stair climbing is an important part of daily activities for many people. Training stair climbing is an effective to improve and restore gait abilities in patients with low-severity impairments, or those who are in the recovery phase. In cases where the patients perform a stair-walk training course, they can use an end-effector type robotic system, such as the G-EO (REHA technology, USA) [8], and the Morning Walk (CUREXO, Korea) [9]. In these robotic systems, patients' feet are firmly bound to the foot plates, which are able to generate the necessary gait trajectories. The advantage of this type of robotic trainer is that it is easy to apply to patients, but it has a limited capacity to control the ankle, knee and hip angles of the patient, as these joints are not linked to any mechanical structure. LokoHelp has end-effectors with a fixed foot binding structure to ensure that the ankle is maintained at 90° during walking training [10].

Although not in a whole lower limb robotic system, active foot orthoses were applied on the user in both walking in a treamill and over ground settings. Compared to traditional passive orthoses, active foot orthoses were designed as actuated exoskeletons to assist and control ankle positions. Anklebot (Interactive Motion Technologies Inc., USA) is commercially available for stroke rehabiliation [11, 12]. It could compensate for weakness and deformities of ankle, but stroke patients who are not able to control balance are not suitable for wearing only orthoses because there could be safety issues without proper body-weight support.

In this paper, we develop a lower-limb rehabilitation robotic system on which a stroke patient can experience both stair-walk and level-walk training courses. Our approach combines the foot plates of an end-effector system with an exoskeleton that will help patients generate a normative gait pattern.

2. DESIGN OF THE ROBOTIC GAIT TRAINING SYSTEM FOR LEVEL-WALKING AND STAIR-CLIMBING

2.1. System concept

We have developed a lower-limb rehabilitation robotic system, the Cyborg-Trainer L, which takes advantage of both end-effector type and exoskeletal type robotic systems. Our system uses both a foot plate and an exoskeleton to provide effective gait training for stroke patients (Fig. 1). The feet of the subject are positioned on separate foot plates. Unlike conventional end-effector gait training robots, the feet are not connected to foot plates, but instead the patient's ankles are bound to the exoskeleton. The ankle of the patient moves along the programmed trajectories for the stance and swing phases of the gait training. At the same time, the foot plates follow the trajectories, with the patient able to provide the force to move them forward. The ground reaction forces acting on the patient during stance phases are measured by force sensors in the foot plates. The exoskeletal structures for the lower limbs are equipped with adjustable-length hip-to-knee and knee-

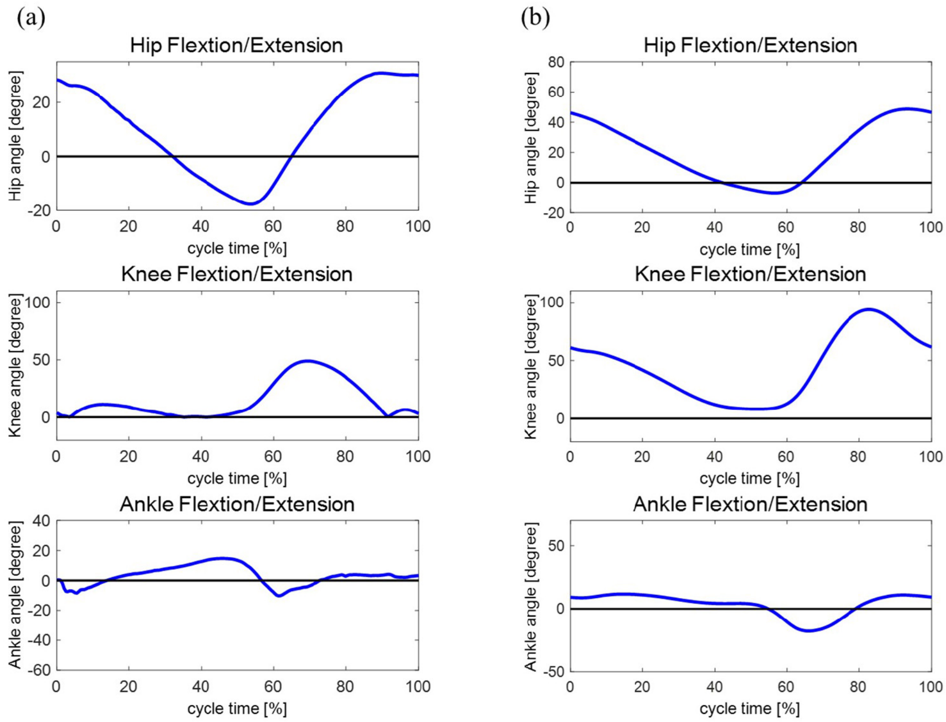

Fig. 2. Angular trajectory of each joint: (a) level-walking and (b) stair-climbing.

to-ankle structures, allowing the fit to be tailored to individual subjects. These structures are attached to the hips, knees, and ankles of the patient with cuffs. The foot plates and exoskeleton structure are moved simultaneously along programmed trajectories. This system is designed to implement both level-walking and stair-climbing patterns using robotic linkages and separated foot plates. The mechanical system consists of three parts: two (the exoskeleton and foot plates) targeted at gait control and one (the trunk control system) that compensates for pelvic motion.

2.2. Leg movement design

Our gait rehabilitation robot is composed with two bilateral exoskeletons that consist of a hip-to-knee segment and a knee-to-ankle segment. Because the segments are attached to the body of the patient, the lengths of the segments have to be adjustable to fit a range of body sizes. We determined the lengths of these exoskeletal components, as well as the widths achievable by the exoskeleton arms, based on statistical values for Korean adults, as measured by the Korean Agency for Technology and Standards [13]. The appropriate range selected for the hip-to-knee segment was 40-53 cm and the range for the knee-to-ankle segment was 30-42 cm. The hip portion of the exoskeleton was designed to accommodate patient widths of 27-51 cm.

In order to generate the normative gait patterns required for effective rehabilitation, motion parameters that included locomotion features were implemented for controlling the exoskeleton. Some significant motion parameters for this system are the range of motion (ROM) in each joint, and the gait speed. Ideal parameters were selected based on kinematic human motion data, such as joint angles, of a normal gait pattern, which were obtained from healthy subjects. We recorded position data of subjects' locomotion with a Prime41 optical motion camera system (Optitrack, Natural Point Inc., USA), focusing on the angle data associated with hip, knee, and ankle joints movements. In this experiment, six subjects performed level-walking, stair-ascent, and stair-descent movements. A five-step laboratory staircase was built for this test, with 17-cm risers and 28-cm tread depths, to conform with Korean building standards [14]. Using the position data gleaned from these observations, we calculated the proper joint angles for the robotic system to achieve.

Fig. 2 presents the mean variation in joint angles from healthy people during level-walking and stair-climbing. As shown in Fig. 2, the ROMs of the joints were different among the three motions observed. Establishing correct ROMs, in response to observations of normal gaits, was critical to prevent the rehabilitation robot from establishing or reinforcing abnormal gait behavior in recovering patients.

Our robotic gait training system for level-walking consists of 3 degrees of freedom (DoFs) of two gait control parts with 2 DoF of separable foot plates and exoskeleton (hip joint, knee joint, ankle joint), and 2 DoF of one trunk control part for compensating of pelvic motion. The separable foot plates are designed to have reduced the weight and size by using a fixed actuator. The width of each foot plate is 700 mm and the maximum velocity is limited to 1500 mm/sec. The height of the stair is set to 200 mm. The mechanical design used to simulate the trajectories of ankle movement is shown in Fig. 3, with one MSMD082S1S motor (Panasonic, Japan) and one AB090-006 reducer (Apex Dynamics, USA) used for control. The angular trajectories of the foot plates during stair-walking and level-walking were taken from the same observations used to define the joint angles. Both the foot plates are synchronized with the exoskeletal structures and are moved to fit with the gait cycle.

The exoskeleton uses light-weight, unified actuator modules, which consist of three motors each, to transfer power to the lower limbs of the subject (Fig. 4). Three gear reducers (K089050, K064050, and K064025) were used for each hip, knee, and ankle joint in order to reduce the weight of the machine and enhance its mechanical strength.

The ranges of motion and maximum velocities of the exoskeleton are shown in Table 1. These values are based on the kinematic observations of healthy subjects.

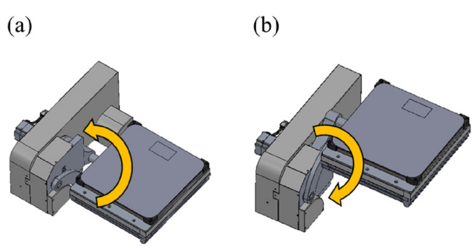

Fig. 3. Foot plate elevation mechanism: (a) down position and (b) up position.

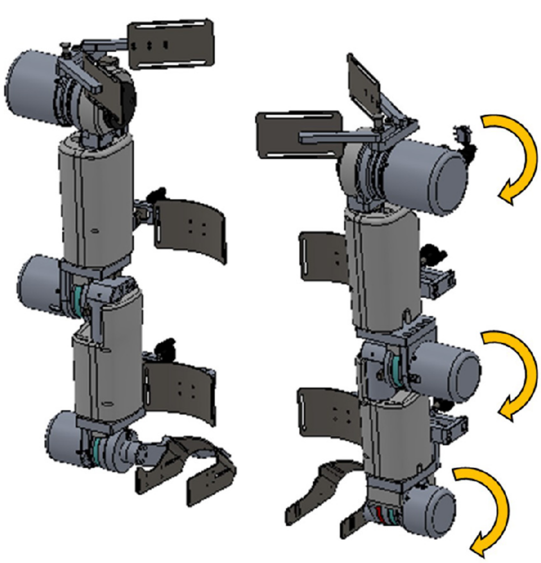

Fig. 4. Design of the exoskeleton.

Table 1. Range of motion and maximum velocity of exoskeleton.

Axis	Range of motion	Maximum velocity
Hip joint	-12°-55°	120°/sec
Knee joint	0°-90°	170°/sec
Ankle joint	-30°-25°	70°/sec

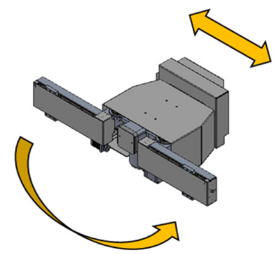

Fig. 5. Design of the pelvis compensation component.

In order to deliver vertical force to patients who are lifted up by the harness, up-down actuation is applied to support the desired trajectories of the hip joints. By detecting the vertical movement of the pelvis and the ground reaction force on the foot plates, we were able to reflect height changes during each walk. The motor force (MSMD082S1T, Panasonic, Japan) is transferred through a ball screw (BTK_2010) and is guided by an linear motion guide (HSR25). To assist the rotation of the pelvis, a parallel linked structure is used (Fig. 5). One motor (MSMD041S1S, Panasonic, Japan), reducer (AE090-090, Apex Dynamics, USA) and main shaft bearing (6007ZZ) are used in this subsystem.

2.3. Motion control modes

Our rehabilitation robot is designed so that a patient can be trained in four training modes. These four modes are distinguished by the degree of assistive or resistance force imparted by the system. The modes with assistive force are the passive mode and the guidance mode, while the modes that impart resistance are the resistance mode and the active mode. In passive mode, patients can move according to a predetermined normal gait pattern. This mode is for training people who cannot move their lower limbs by themselves, such as severe stroke patients. In guidance mode, a therapist can adjust the ratio of assistive force used to support patients who do not have enough power for a normal gait. The resistance mode gives the patient a feeling of walking through water by applying forces to the legs in opposition to the direction in which the person must move to achieve a normal gait pattern. Lastly, the active mode can be selected if patients need to walk by themselves, without any assistance from the robotic system.

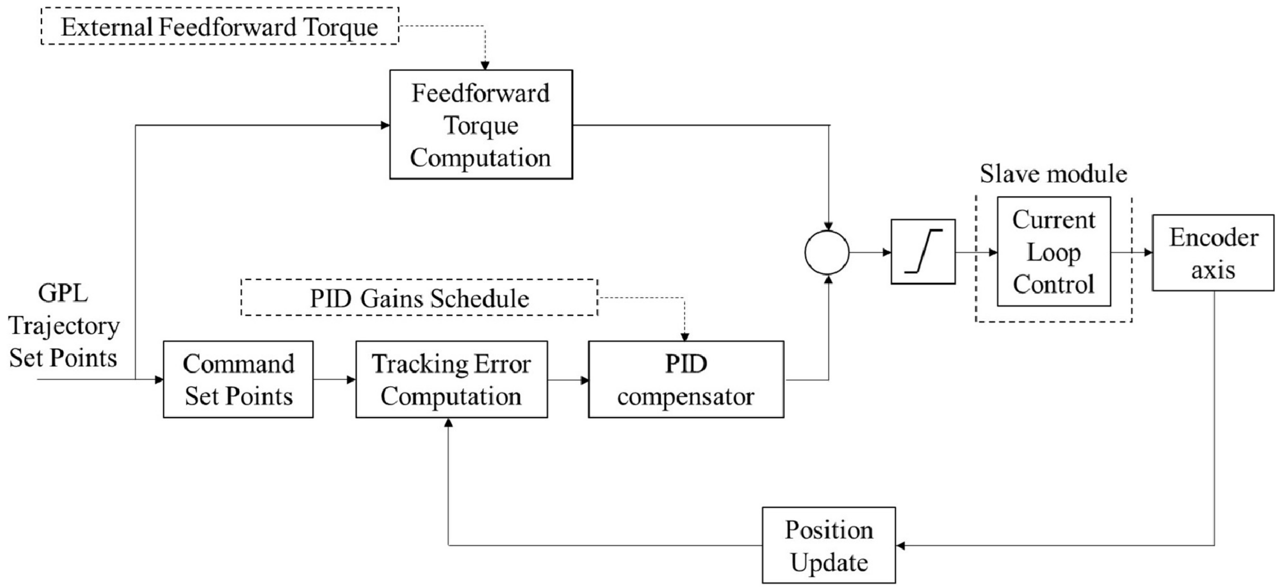

Fig. 6. Block diagram of the control strategy.

2.4. Control system

We developed a unified control system to combine the master control and the slave control. The master controller performs trajectory control, which determines the position control of each axis. The transmission unit is per 1 millisecond. A block diagram of the trajectory-compensation mechanism is shown in Fig. 6. Driving torque is calculated by feedforward and feedback torque, and a feedforward torque compensation control module was developed to regulate position, velocity, acceleration, and friction torque. In addition, the torque of gravity-compensation was adapted to enhance control ability. The output of the feedforward system is low-pass filtered and limited by the feedforward torque rate.

Error tracking is completed on-the-fly by calculating the difference between the predefined trajectory and the actual trajectory, which is fed back from the encoder. The error of the position, velocity, and acceleration at any given time is transferred to the PID compensator. The feedback torque compensation is calculated by the PID compensator, and the sum of feedforward and feedback torque output is transferred to the slave and then the slave control motors using current loop control.

3. EXPERIMENTAL VERIFICATION

3.1. Experimental procedure

A preliminary test was designed to verify that the muscle activation achieved during training on the Cyborg-Trainer L could mimic real-world training. The experiment consisted of four conditions: 1) level-walking with assistance from the robotic training system, 2) treadmill-walking with a speed similar to that of the robotic training, 3) stair-climbing with assistance from the robotic training system, and 4) real-world stair climbing with self-selected speed. Experimental setup and each condition are depicted in Fig. 7.

Five healthy subjects (four males, one female; aged 29.00 ± 3.81 years) participated in this experiment. Subjects were excluded if they had experienced or suffered

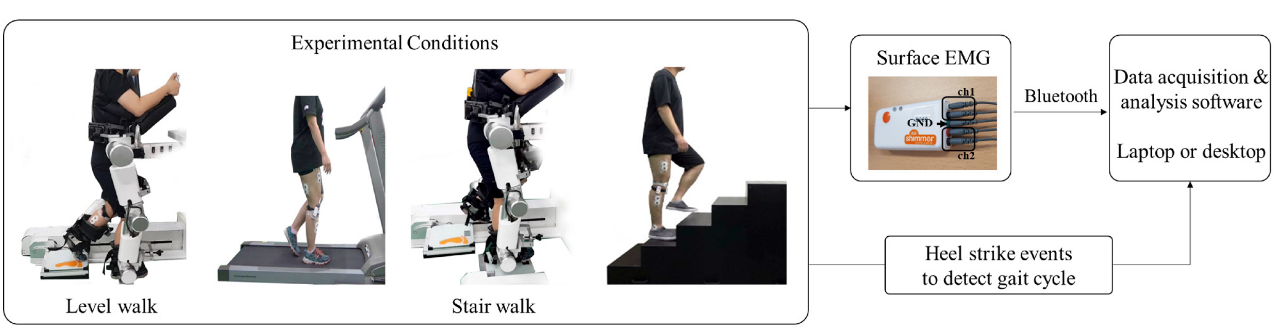

Fig. 7. Experimental setup.

from neurological injuries or gait disorders. All subjects were right-side dominant. Prior to the experiment, an event button connected to an electromyogram (EMG) system was installed to detect heel strikes during all trials, and the maximum voluntary contraction (MVC) of each muscle was measured to normalize the EMG signal.

Muscle activation during each activity was recorded for 1 minute, and at least five cycles of each condition were recorded. Muscle activation was measured using a Shimmer EMG with self-adhesive electrodes (Ag/AgCL). Before the electrodes were attached, skin was cleansed with alcohol to improve the conductance of the electrodes. The electrodes were placed on the four muscles of the dominant leg: tibialis anterior (TA), gastrocnemius medialis (GCM), rectus femoris (RF), and biceps femoris (BF). The electrode placement followed SENIAM recommendations [15]. Data were collected at a sampling frequency of 512 Hz.

The raw EMG results, EMG_{raw}, were the composite of the raw EMG data from each of the muscles with an electrode:

$$EMG_{raw} = [TA_{raw},\ GCM_{raw},\ RF_{raw},\ BF_{raw}]. \tag{1}$$

The amplitude of EMG_{raw} is stochastic, with a gaussian distribution [16]. As such, absolute values of EMG_{raw} were digitally filtered with a low-pass filter ($f_c = 5$ Hz) to remove noise. The MVC value, M, related to each muscle, can be calculated as

$$M = [mvc_{TA},\ mvc_{GM},\ mvc_{RF},\ mvc_{BF}], \tag{2}$$

where each component refers to the MVC data from one of the observed muscles.

Because the amplitudes of the EMG signals depend on the individual and the muscle, the absolute values of EMG_{raw} can be compared to each other only by normalizing them with MVC values. the normalized dataset, EMG_{norm}, was calculated as [17]

$$EMG_{norm} = \frac{|EMG_{raw}|}{M}. \tag{3}$$

Due to participants' own habits in walking, the lengths of one gait cycle were different among subjects. Therefore, it was necessary to normalize the data with respect to time by unifying the length of the data into 1000 divisions using an interpolation algorithm. Finally, we used these datasets, which were normalized with respect to time, to analyze the EMG signals. Gait cycles were segmented using the heel strike events and cycle parameters were averaged across three strides. All signals were processed with MATLAB software (Mathworks Inc., USA)

Cross-correlational analysis was performed to identify similarities in the shape and timing of EMG results between conditions [18]. The coefficient of correlation, R,

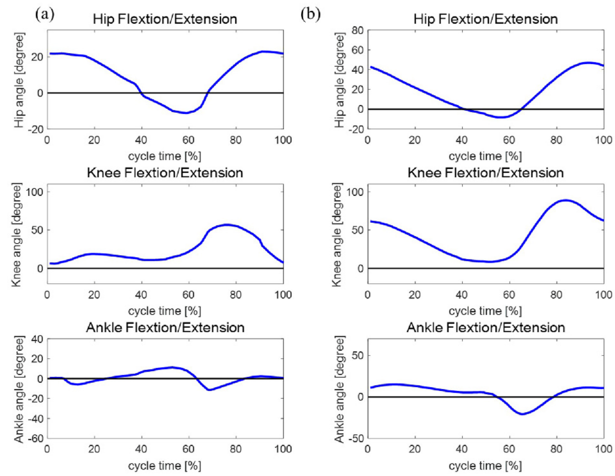

Fig. 8. Derived angles of each joint: (a) level-walking and (b) stair-climbing on robotic systems.

was calculated as follows:

$$\mathrm{R} = \frac{\sum x_i y_i}{\left(\sum x_i^2\right)^{1/2}\left(\sum y_i^2\right)^{1/2}}, \tag{4}$$

where x_i and y_i are the two signals.

3.2. Results of angle of exoskeleton structure

Fig. 8 shows the measured results from one subject with the robot system during the level-walking and stair-climbing conditions. The angles of each joint are similar to the previous experimental data from healthy subjects. Because these experiments were performed in passive mode, same variations of each joint's angle were repeatedly observed. The correlation coefficients of the angles of the hip, knee, and ankle during level-walk training were 0.94, 0.84, and 0.59, respectively, which reveals strong similarities. During stair-climb training, the coefficients of the angles of the hip, knee, and ankle were 1.00, 1.00, and 0.99.

3.3. Result of EMG analysis

Fig. 9(a) and (b) show the grand mean EMG for all five subjects during level-walking training on a treadmill and on the robotic gait system. The cadence of the robotic system during level-walking was 45 step/min, with a stride length calculated depending on the lengths of each of a subject's limb segments. The speed of the treadmill was between 1.4 and 1.5 km/h. The correlation coefficients of RF, BF, TA, and GCM between walking on the treadmill and on the robotic system were 0.06, 0.13, -0.32, and 0.79, respectively. Only the GCM showed the similar shape and timing of the EMG signal. Fig. 9(c) and (d) show the result of the grand mean and standard deviation of the EMG during real stair climbing and stair-climb training on the robotic gait system. The cadence of the robotic

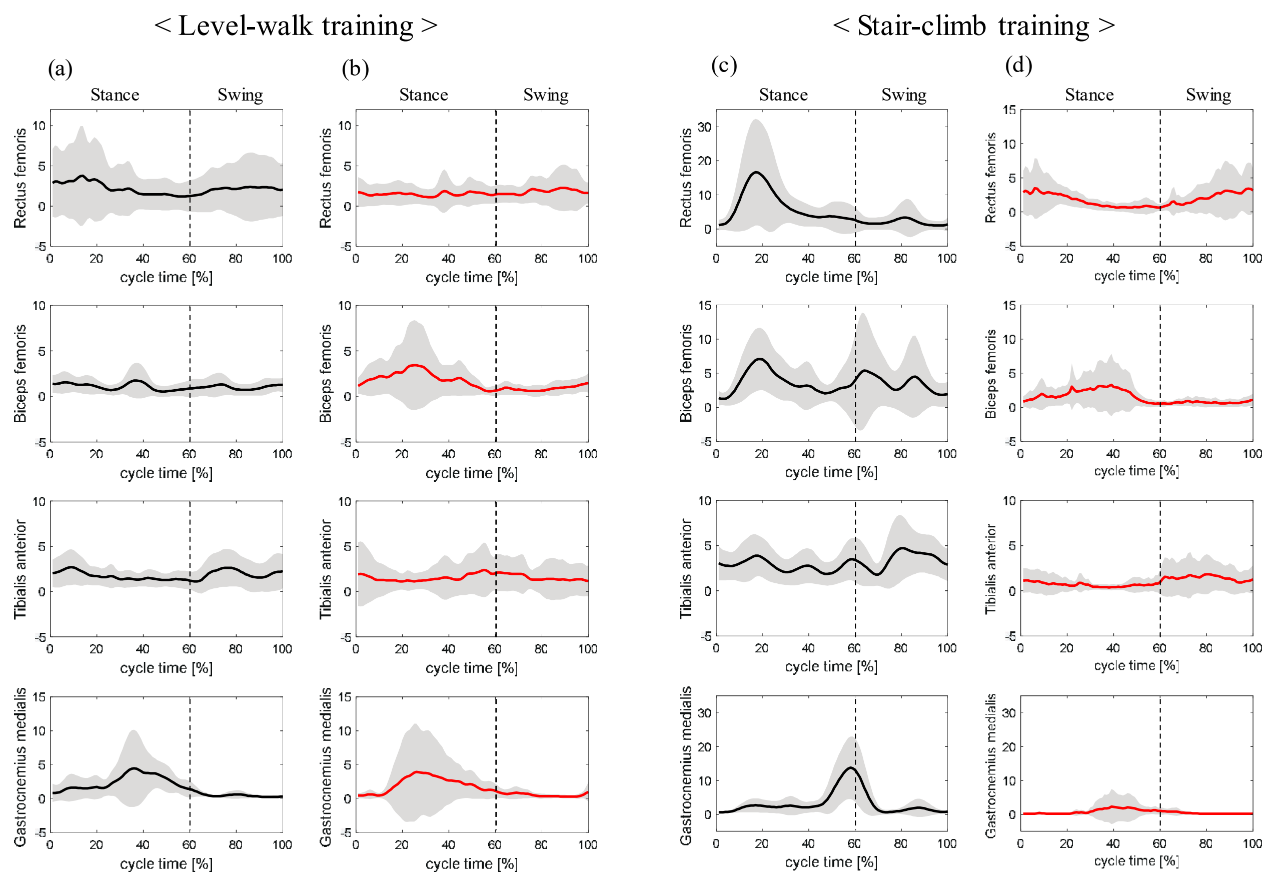

Fig. 9. Grand mean and SD of EMG during level-walk training: (a) on treadmill and (b) on robotic gait system, and (c) real stair climbing and (b) stair-climb training on robotic gait system.

system was set to 20 step/min. On the real stairs, subjects climbed with self-selected speeds. The cross-correlation coefficients of RF, BF, TA, and GCM were lower than 0.50, which means the muscle activations of real stair climbing and robotic stair climbing were different.

4. DISCUSSION

The results of the drived joint angles of the exoskeletal structures during each task were highly correlated with thouse of the previous experiments. It demonstrates that the proposed robotic system could generate the desired angles for the normative gait pattern. During walking and stair climbing on the robotic system, phasic muscle activations were observed. However, the activation patterns between level-walking on a treadmill and on the robotic gait system were different. Significant increases in the activation of the gastrocnemius medialis in the stance phase and light increases in muscle activation of the bicep femoris were observed in same phase. In case of the exoskeletal robot, Lokomat, increased activation of quadriceps and hamstring muscle have been reported due to restriction of leg movement during the swing phase and reduced ankle flexor and extensor motion observed throughout the gait cycle [19, 20]. Another exoskeletal robotic system, LOPES, showed closed muscle activities in lower limbs, as compared to free treadmill walking, under zero-impedance control mode [21]. In end-effector based gait rehabilitation robot systems, the feet of the subject are fixed on the programmable foot plates, and knees and hips are free to move without restriction. In the case of a patient who has weak muscle strength, a therapist must manually stabilize knee motion. Due to their movable foot plates, these kinds of gait robot could train stair-climbing. As compared to level-walking, stair-climbing requires additional muscle strength and standing balance abilities [22]. In a comparison between treadmill walking and HapticWalker [23] training, the activation of ankle extensor and flexor muscles were found to be reduced, and the activation onset of thigh and erector spinae muscles were slightly delayed.

The results presented in this study showed reduced amplitude of muscle activation of ankle extensor, GCM, and ankle flexor muscles, TA, during stair-climbing with the robotic system, as compared to real stair climbing. Even though the overall similarity index of the correlation coefficient was low, rhythmic patterns of muscle activation were observed in the stair climbing with the robotic system. In stance phase, RF started to activate and BF and GCM was activated at the same time and in the swing phase, light activation of the TA muscle followed sequentially by RF. RF, TA, and GCM muscle activations resembled those of stair-climbing muscle activation reported in other studies [24–26].

The robotic gait training system presented in this paper provides a stair-climbing mode in addition to the conventional level-walking mode by leveraging a unique exoskeleton structure with separately operable foot plates. There are exoskeleton robots with active foot plates of simiar configuration as the robot system in this paper. However, the binding structure of patient's feet and the foot plates is different from ours. Unlike conventional end-effector type gait training robots, the subject's feet are not constrained by foot plates, but are free to emulate the ground or a set of stairs in our system.

Although the results of muscle activation with robotic system, in passive training mode, were not exactly same patterns as found in normal treadmill walking and stair walking, but rhythmic muscle activations were induced in muscles, especially shank muscle. Several robotic gait training systems showed the overall reduced muscle activation and lower activation on shank muscle in case of end-effector type robotic gait training systems. In the developed robot, we have shown that the separable foot plates, which were not connected to subjects' feet, could conntribute to the increase in shank muscle activation for better training outcome. The activation patterns would be changed depending on subject and control modes (training modes). It will be further investigated in future study.

Current study has limitation in that the experiments with the robotic system were performed only in passive mode. Subjects were affixed to the exoskeletal lower limb structure and moved by following the programmed trajectories of each joint. Because of restriction of leg movement on the sagittal plane, excessive thigh muscle activation was observed during robot movement. Especially in the case of patients, it is essential to add assistive force that is capable of moving subjects forward. In this robotic gait training system, three more training modes other than the passive mode with differenct combination of assistive force and resistive force - active mode training, guidance training, and resistance training - were implemented. Different muscle activation patterns would be generated depeding on the training mode and it will be further studied in clinical research under prepration for regulatory approval.

5. CONCLUSION

We presented the newly developed robotic gait training system for lower-limb rehabilitation for stroke patients. This system, called Cyborg-Trainer L, provides the stair-walking and level-walking training by applying separable foot plates as end-effectors. To compensate for the forces involved, and to control the normative gait patterns on each joint, an exoskeleton structure and trunk control structure for pelvic movement were combined. Even though muscle activation patterns were different with and without the robotic gait system, reduced amplitudes and phasic muscle activations were observed during the training with the robotic system. This demonstrates that this new type of robotic gait training system can generate phasic lower limb muscle activation patterns. The efficacy of this robotic system will be validated in clinical trials on patients.

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