Rehabilitation Robot in Primary Walking Pattern Training for SCI Patient at Home

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Abstract**—**Recently attention has been focused on incomplete spinal cord injuries (SCI) to the central spine caused by pressure on parts of the white matter conduction pathway, such as the pyramidal tract. In this paper, we focus on a training robot designed to assist with primary walking-pattern training. The target patient for this training robot is relearning the basic functions of the usual walking pattern; it is meant especially for those with incomplete-type SCI to the central spine, who are capable of standing by themselves but not of performing walking motions. From the perspective of human engineering, we monitored the operator's actions to the robot and investigated the movement of joints of the lower extremities, the circumference of the lower extremities, and exercise intensity with the machine. The concept of the device was to provide mild training without any sudden changes in heart rate or blood pressure, which will be particularly useful for the elderly and disabled. The mechanism of the robot is modified to be simple and lightweight with the expectation that it will be used at home.

Keywords**—**Training, rehabilitation, SCI patient, welfare, robot.

I. Introduction

JAPANESE society is aging at an alarming rate. Fig. 1 shows current changes in the Japanese population. In the near future, almost 25% of the population will be over 65. In such a society, stroke is a serious problem. About 300,000 people suffer strokes every year. The total number of stroke patients in Japan is estimated to be 1,330,000. In addition, many elderly people suffer non-bony type cervical cord injuries as a result of falls. Therefore, expectations are high for robots to accelerate recovery for these individuals, reduce the load of therapists, and save medical and welfare costs.

According to a fact-finding survey of disabled people conducted by the Ministry of Health, Labor and Welfare, there are 1.76 million physically disabled persons, including 54 thousand with spinal cord injuries (SCI) in Japan. Slightly more than 5 thousand peoples suffer this disease every year as a result of traffic accidents, falls, and sports accidents. Physical therapy is designed to prevent orthostatic hypotension, muscle atrophy and contracture, and mental disorders.

Recently, attention has been focused on incomplete-type SCI to the central spine caused by pressure on parts of the white matter conduction pathway, such as the pyramidal tract. Middle-aged and elderly patients may suffer quadriplegia as a result of injury to this area from overextension of the spinal cord, in most cases caused by a fall. According to epidemiological data from new patients in 2005 and 2006 in the Fukuoka Prefecture in Japan collected by the Spinal Injuries Center, the incidence rate of incomplete SCI has shown a decreasing trend, from 33.7 to 27.6 per million on average in 2005 and 2006, respectively. However, the age of onset has been increasing. Forty-five percent of these patients are incomplete-type SCI to the central spine cases. In most of them the spinal cord is not completely severed, but muscle power and sensation in the extremities are poor. In such cases, paralysis may be present more strongly in the upper extremities than in the lower. The muscle power of the lower extremities will build gradually to a level sufficient for standing and walking. The muscle power of the hands and fingers, however, may not recover to a level where the patient can grasp or pinch sufficiently to manage the typical activities of daily living. Even so, three years of home training and outpatient services may be necessary for patients to recover walking functions. These repetitive and long-duration trainings create a heavy load for therapists. In addition, there is risk of losing the walking function again because of the danger of falling at home.

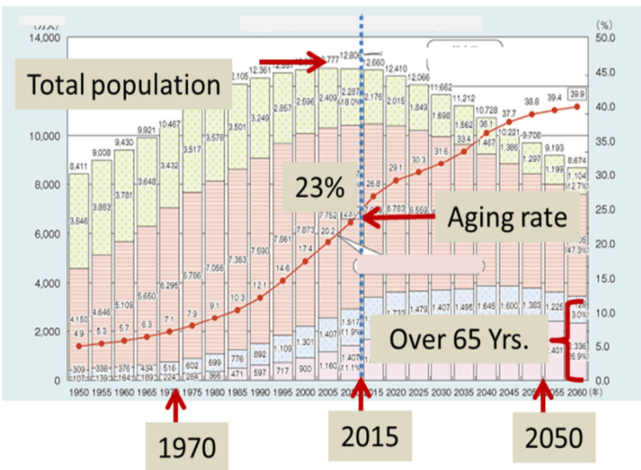

Fig. 1 Demographic changes in the Japanese population

The rehabilitation process for SCI comprises several steps, including: 1) basic training for extending the range of motion of joints and muscle strengthening; 2) training to maintain a seated posture; 3) training in standing up and sitting down; 4) training to relearn the primary walking pattern; and 5) training in

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practical walking.

Over the last decade, a variety of rehabilitation robots and robotic assist devices for physical therapy have been developed [1]-[4]. In particular, BCI (brain computer interface technology), neuro-rehabilitation techniques, wearable robot technologies, and neuro-rehabilitation robotics have been actively studied [5]. Recent gait rehabilitation robots, such as the Lokomat, the Lopes, the PamPogo, the ALEX, and the GaitTrainer have been studied and used in locomotion training for SCI or CNS (central nervous system) patients [6], [7], [13]-[15]. These therapies are based on neuroplasticity at the spinal and supraspinal level, and achieved by physiological multisensory input to reshape the locomotor pattern of the spinal circuitry. The physical constraints of conventional manual-assist training can be overcome using robotic training to activate the CPG (central pattern generator) with the BWSTT (body weight supported treadmill training) mechanism of a robot [8], [9], [12], [16], [17].

We have been developing a series of robots to apply to every step of training for patients with incomplete SCI to the central spine. In this paper, we focus on a robot that assists with primary walking-pattern training.

A. Conventional Methods for Walking Pattern Training

Circular walkers, canes, and parallel bars are the most popular tools used in rehabilitation. The problems with these tools are the high risk of falling, and the difficulty of maintaining a normal trunk posture, leading to the need for extensive monitoring, care, and advice by a therapist. Also, the patient usually cannot exercise for a long period of time with these rehabilitation aids, as it is very tiring to do so.

Several training machines for lifting the trunk have been developed for SCI and other types of patients. The Lokomat and the KineAssist provide partial body weight support and postural torque on the torso [7], [10]. Their features include a lifting mechanism for the trunk to decrease the weight a patient must lift, a mechanism that drives the lower extremities, and a treadmill. However, these machines cannot train a patient for practical walking in a real environment, achieved by voluntary motions such as body weight transfer and swing-phase motion. A wearable training machine that is mounted on the lower extremities has been developed at Tsukuba University [5]. The features of this device include a driving mechanism to actuate the hip, knee, and ankle joints with motors; commands for the device are calculated with sensors responding to inputs such as EMG or leg motions. The machine, however, is not able to support a patient's weight. The risk of falling with this machine is therefore greater than with other types of training machines, since a mechanism for supporting the trunk is not provided.

Circular-wheel-type training machines with electric motor wheels have been developed by the Hitachi Co. The features of this type of machine are a maneuvering mechanism mounted to a circular wheel, automatic control of the maneuvering system that leads the patient to walk, and a supporting mechanism for the waist, trunk, and upper extremities. Most of these machines do not provide a mechanism to directly drive the legs. The problem with the machines is that there is, again, a risk of falling. It is difficult trying to learn the correct posture and walking pattern again, and there is no mechanism for taking advantage of the voluntary movements of the patient.

In summary, the conventional machines and tools have the following problems: 1) risk of falling; 2) difficulty in achieving the right posture of the body and obtaining practice in practical walking in a real environment; 3) lack of a mechanism for taking advantage of the patient's voluntary movements; 4) fewer degrees of freedom (d.o.f.) of movement because the patient's body is fastened to the machine; and 5) very large size and heavy weight.

II. Training Robot for Primary Walking Pattern

The target patient for this training robot is one who is relearning the basic functions of the ordinary walking pattern, especially those who have suffered an incomplete-type injury to the central spine who are capable of standing by themselves but not capable of performing walking motions. The primary walking pattern with voluntary motion for body weight transfer and swing phase leg motion will be a preparation to the recovery of practical walking in the real environment.

A. Training Robot for Rehabilitation Center and Its Experimental Results

We have proposed a training machine that assists patients in relearning the walking pattern and executing preliminary dynamic walking, as shown in Fig. 2 [11], [18], [19]. Specifically, this robot provides three kinds of assistive motions with a sliding mechanism according to the recovery level of the patient's lower extremities. The passive reciprocal motions of the feet are provided in the case of poor muscle power of the lower extremities. In addition, other assistive motions are provided while sensing the reciprocal movement of foot pressure or when sensing foot pressure movement and lifting motions of the foot during the swing phase. The whole mechanism of the robot can travel forward coincident with the sliding mechanism motion, which provides quasi-walking actions. The sliding motion does not simulate a completely natural gait in the swing phase. The patient, however, could be trained by quasi-walking motions with voluntary body weight transfer and lifting of the leg in the swing phase monitored by the machine.

This robot has both a slide mechanism and a maneuver mechanism. The sliding mechanism provides reciprocal forward and backward sliding motions of the patient's feet to achieve a quasi-walking pattern. Each foot is fixed on the foot plate mounted on the chain actuated by the servo motion of one stepping motor servo system (Cool Muscle CM1-C-23L20A, 30W, 2000rpm, Muscle Corporation), which includes a stepping motor, angular sensor, and servo amplifier.

The pressure sensor mounted on the footplate measures foot pressure. According to the sensor information, the microcomputer, Arduino, delivers the motion command to the motor. The actuators of the Cool Muscle system, which are connected to each other and controlled by the Arduino, are used in the sliding mechanism.

The waist pad and the belt support the patient's body to prevent falling. The body supporter, waist supporter and supporting belt allow the patient to move freely and safely within the small confines surrounded by those supporters; sidebars prevent falling without harnesses. To compensate for the poor muscle power of the upper extremities, the hands can be fixed with a belt to the hand sticks if necessary.

The robot can provide three-step training functions according to a patient's walking ability, as follows:

1) 'Passive walking-pattern training' is the primary level. The robot allows completely passive motion for the patient with severely reduced ability that can stand by him/herself but cannot perform any body weight transfer motions. Here, the footplates move reciprocally as automatic motions.
2) 'Static walking-pattern training' is the middle level. It can be used with patients who still have a poor ability to transfer their body weight. Sensing the transfer of the load by the pressure sensor on the foot plate, the foot plate moves reciprocally according to the load amount. The sliding motion stops when there is no change in foot pressure by transferred body weight. This function provides feedback to the patient, thus facilitating voluntary body weight transfer.
3) 'Semi-dynamic walking pattern training' is the highest level. It will be utilized for patients with poor swing phase motion but with sufficient ability to transfer body weight. Sensing the foot pressure and the motion of the leg lifting in the swing phase detected by the micro switch on the top of the foot plate, the foot plate moves reciprocally. The sliding motion will stop when there is no change of these two motions. This function will provide feedback to the patient, facilitating voluntary body weight transfer and swing phase motion.

The motion, activity of muscles, and exercise intensity of the lower extremities were measured using the proposed robot [19]. The hip joint angle vibrated at 17 degrees as a center point. The angle extended by approximately 5 degrees, and flexed by approximately 8 degrees, which constituted 1/3 of the walk pattern of a healthy person. The ankle joint changed repeatedly, with approximately 15 degrees of plantar flexion and approximately 8 degrees of dorsiflexion, almost the same pattern as that of a healthy person. In addition, calf circumference changed repeatedly during the same period as the joint angle motions. The change in blood pressure and heart rate during exercise were small. Thus, the particular characteristics of this device are: 1) the load by the standing position depends on the foot bottom that does not support the load; 2) reciprocal stepping motion of both legs is available; 3) assistance is provided when the center of gravity movement to the right and left is detected; 4) the swing phase motion of the leg is partially realized; 5) the range of motion of the hip is 1/3 that of a healthy person, and that of the ankle is the same as that of a healthy person; 6) flexion and extension of the muscle spindle and tendon spindle of the calf is expected to affect the afferent deep reflex.

Considering these experimental results, comments of staff such as physical therapists, and medical science papers, some of the current technical problems are being addressed as follows: 1) implementation of a swing phase leg motion that is closer to the movement of a healthy person, in particular the pulling-up motion of the toes (emphasized by the therapists); 2) modification of the transfer process to make it easier and more certain; 3) improvement of the feedback system to provide information regarding the results of training to the user; 4) redesign of the operation panel so as to make it easier for the elderly to utilize [19].

B. Training Robot for Home-Use

According to the experimental results and the comments from the physical therapists, we have also developed the next-step robot for rehabilitation at home, as shown in Fig. 3. The new development target is a device with simple functions and low cost that is small and lightweight for home-use exercise to make possible the recovery of walking functions.

The former robot had high-level functions, and expensive mechanisms such as sensors and actuators. In the revised robot, the functions and mechanisms have been simplified, and the user interface is robust and easy to use. Light weight, low cost and safety are important for home use. The robot for hospital use is comprised of two motors to actuate the slide mechanisms with two kinds of sensors and a tablet-type computer to measure training data on the robot in order to evaluate the recovery level of the patient. The system is complicated to operate, and the flame mechanism is large.

Fig. 2 Rehabilitation center training robot for basic walking-pattern training. The robot has two motors for the two sliding mechanisms, two motors for maneuvering on the floor, and two kinds of pressure sensors on the steps, and touch switches on the step covers

On the other hand, the robot for rehabilitation at home should be small and lightweight. The system is simple for the user to operate. The robot comprises only one motor to actuate the slide mechanism, with a chain mechanism for the reciprocal motion of footsteps on the chain. The steps are not available to move independently, but the limited motion is sufficient for home rehabilitation. The four pressure sensors are mounted on the steps. The simple operating panel controlled by microcomputers is installed with dials and buttons, which are easy for the elderly to understand and operate. The mechanical flames are simplified, making the size and weight of the machine 2/3 and 1/2 that of the former one, respectively.

III. Preliminary Experiments for Training Robot for Home-Use

We tested the low-cost, home-use machine with normal subjects. Five 5 normal subjects (male, age: 20-23) joined the experiments. Subjects included two people with experience in robot training and three without.

The robot actuates the sliding mechanism driving the footsteps triggered by the change in foot pressure on the step. The state of the foot pressure is displayed on the front panel in real time. The display was intended to facilitate patient's recognition of foot motion, as well as to prevent lower back bending. The sliding mechanism moves about three seconds per step. Among the motions, the hip moves 5–15 degrees, while the knee moves 5–35 degrees.

Measurements include oxygen intake, heart rate, blood pressure and joint angles. Oxygen intake is measured by VO2000, and blood pressure is measured by tango+. Whole-body motion during training is monitored by video camera.

The subjects without experience in robot training were given guidance on how to use the device. They were given 1-2 min rests, were kept standing without moving for 1 min, and performed training on the robot for 10-min intervals. One-minute section averages were monitored and recorded for each subject on oxygen intake, heart rate, blood pressure and joint angles.

The time histories of oxygen intake and heart rate are shown in Figs. 4 and 5, respectively. Increase in those measurement values was moderate. The averages for oxygen intake and heart rate were higher in the training mode, but the increases were not significantly different from the values of the subjects at rest.

The experimental results for oxygen intake were compared to resting in a chair. Intake values in the training mode were taken for the 5th and 10th min for subjects with (W, n = 2) and without (WO, n = 3) experience in robot training. Oxygen intake at the rest was 223.3ml/min±16.7 for W and 225.9ml/min±29.9 for WO. Intake during the 5th min of practice was 332.0ml/min±20.0 for W and 347.4ml/min±50.1 for WO. Both groups thus showed an increase compared to at rest. Oxygen intake in the 10th min of practice was 362.3ml/min±12.5 for W and 307.4ml/min±53.1 for WO, again higher compared to the other measurements.

The METs (metabolic equivalents) in the 5th min of practice were 1.5±0.3 for W and 1.5±0.1 for WO. In the 10th min of practice, METs scores were 1.6±03 and 1.4±0.1, respectively, as shown in Fig. 6. The total METs of machine training was 1.5±0.2. The total of 1.5* METs is about equivalent to the METs of seated office work. Blood pressure, oxygen intake, and heart rate showed no rapid changes. Thus, the machine imposed only a small load on cardiopulmonary function even with long-duration training. This means the machine training is suitable for the elderly.

Energy consumption for each subject training on the device for 10 min was 0.26±0.03Kcal/kg. The amount of energy consumption by weight for subjects 1 and 2 was comparatively low. This suggests that individuals with robot training show better energy efficiency.

In order to check the similarity of the motions of machine training / walking, the joint angles of the lower extremities were measured by a motion-capture system. Again, five subjects normal subjects (male, age: 20-23) participated in the experiments. They had a 2-min rest interval before 10-min of training on the machine. The measurements included pelvic posture, hip joint angle, and knee joint angle. The motion patterns were arranged as normal walking across the floor, machine training with passive motion with the steps free, and active assistive motion with the steps free.

The overall trend of motion patterns showed similar changes in the time history. The knee angle made smaller changes in fixed step, larger changes in free step. Almost half of the angles were in a normal walking pattern. The active assistive motion showed larger knee angles than the passive case.

Fig. 3 The training robot for the basic walking pattern for home use. The robot has simplified functions and mechanisms, and a robust and easy to use user interface. The light weight, low cost and safety are important for the home use

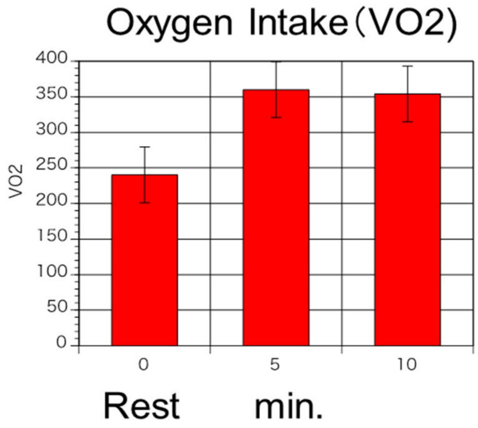

Fig. 4 Time histories of oxygen intake. The rise in the measurement values are moderate. The averages of the oxygen intake in the training mode were increased, but not significantly different than at rest

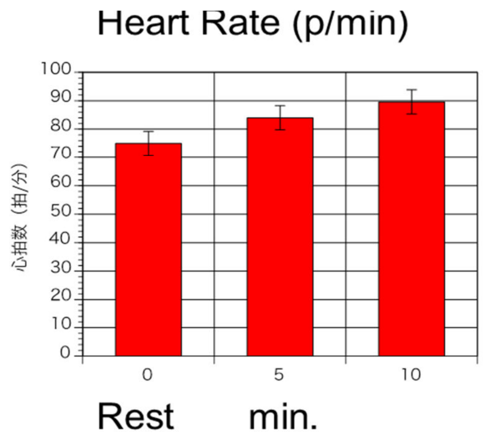

Fig. 5 Time histories of heart rate. The increase in the measurement values are moderate. The averages of the heart rate in the training mode were higher but not significantly different than at rest

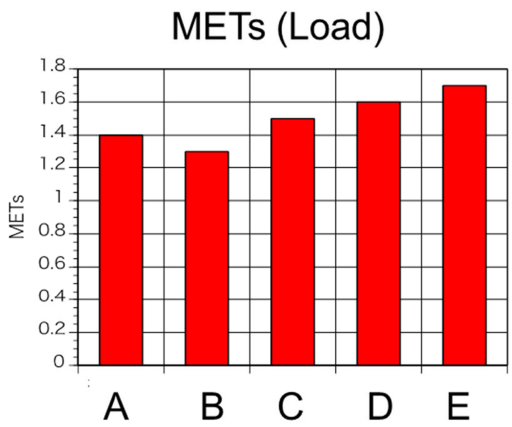

Fig. 6 The METs (metabolic equivalents) in the 5th min of practice for the five subjects on the training robot for home use

IV. Conclusions

We have developed two types of training robot, one for rehabilitation centers and the other for home use. The concept of these devices is to provide mild training without sudden increases in heart rate or blood pressure, which will be particularly useful for the elderly and disabled. Those functions were verified by experimental results with normal subjects. The machine imposes only a small load on cardiopulmonary function even during long-duration training. This means the machine training is suitable for the elderly. We next plan to test the training load for elderly subjects on the robots.

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