Gait Rehabilitation System for Stair Climbing and Descending

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Abstract

This paper describes the development of a gait rehabilitation system with a locomotion interface (LI) for stair climbing or descending. The LI consists of two 2 DOF manipulators equipped with footpads. These can move the user's feet while his or her body remains stationary. The footpads follow the prerecorded motion of the feet of a healthy individual. For gait training, the user progresses iteratively through successively more advanced modes. In this study, three modes, enforced stair climbing/descending, semi-voluntary stair climbing/descending, and real stair climbing/descending were used. Comparisons were made between the modes for healthy individuals and a patient. The effectiveness of the system was examined using EMG and foot pressure data.

Index Terms: H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Training, help, and documentation; H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Haptic I/O;

1 Introduction

In gait rehabilitation, physical therapists describe the motion of walking to patients in words or by physically handling the patient's body. However, there are an insufficient number of physical therapists for the number of patients to be treated, which increases their workload. It is difficult to teach patients attractive motion of the leg, even if the patients have the capability to do this. In addition, the development of motion assist systems is becoming more crucial as we plan for an aging society.

To solve these problems, some systems using robotics have been developed. Hitachi.Ltd commercializes rehabilitation systems using two belt type treadmills [2]. These are already being used in many hospitals. However, the motion they generate is only in a horizontal direction. Jezernik et al has developed a gait training system with a treadmill and 4 DOF rehabilitation robots called Lokomat [6]. This system can teach patients the correct motion. However it is cumbersome and complicated for the user to put on and take off. Hesse et.al has developed a gait trainer [3] and the HapticWalker [9]. These systems have two footplates which move the user's feet. They made a stair climbing training system [4]as well as flat surface training by using the HapticWalker.

Such systems help physical therapists reduce their manual labor and allow them time to provide quality support while helping patients get more exercise in the hope of attaining a higher level of recovery. Since 2000, the authors have been developing an efficient training system employing a locomotion interface which uses virtual reality technology, to directly move the patient's feet with a manipulator [11]. We have applied the system to various patients and have confirmed its effectiveness [10].

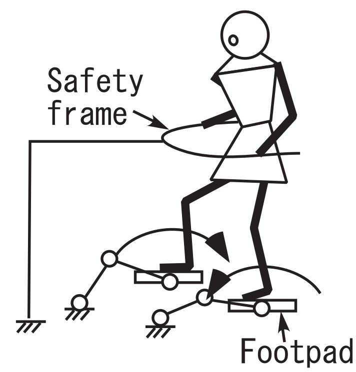

Figure 1: Basic concept of the system

Usually, for rehabilitation for climbing/descending stairs, real stairs, a mock-up of real stairs or a specialized treadmill such as StairMaster [1] are used. Since there is a risk of falling with all these methods, they are performed only with patients who have acquired stable walking skills. Our system, however, can support the patient's body safely by using footpads and a safety bar placed around the system (Fig.1). A safe stair-climbing/descending training system can be realized with this feature.

In this study, gait rehabilitation methods for climbing/descending stairs are proposed. Patients who could walk unattended and had a low risk of heart problems could use our system. A compact gait rehabilitation system that could be used with a commercial unweighing system has been developed. Using this system, two stair climbing training modes were developed. An evaluation was carried out to examine the effectiveness of the proposed methods.

2 System Configuration

2.1 Design Concept

Gait rehabilitation is usually applied to patients who develop problems walking, due to damage to bones, joints, nerves or muscles through accident, injury or disease. In general, gait rehabilitation begins with training to distribute the weight evenly on both feet. Then, the patient learns how to move his or her body and how to walk by him or herself. Usually, the physical therapist describes the walking motion to the patient in words or by physically handling the patient's body. These methods are based on the concept of relearning and also on the idea that alternative nerves can be activated even though the nerves usually used are injured. However, it is difficult for physical therapists to repeat the same motion for a long period of time, since they become tired and also have insufficient time to thoroughly train each patient. If this movement can be realized using equipment, the physical therapist can regulate

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the motion of the patient's foot with less fatigue. The other advantage of such equipment is that physical therapists who aren't strong enough to manipulate the patient's body can train them using the equipment. To realize the above, the equipment should be able to repeatedly move the user's foot through any trajectory and to do so for a long period of time.

The motion presented by the system can be belt-driven, such as in a treadmill, or can be an exoskeleton, such as in Lokomat [6]. The belt-driven technique has more advantages in that it allows a more liberal selection of walking styles; however, it provides very little restraint for the legs and demands certain skills in order for user to keep a constant position on the belt. On the other hand, exoskeletons, with actuators arranged along the physical joints, can accurately repeat the same motion, but they need to be adapted to each individual because of differences in walking style. Furthermore, attaching and detaching the devices that restrain the joints is a complicated operation.

In our research, we have adopted a system to move each foot with a manipulator with two degrees of freedom (back and forth and up and down), that allows repeated walking cycles, can easily be attached and detached, and moderately restrains the body. Given the range of movement of human joints, the device is designed so as to move only the feet, leaving the user to choose the movement of the joints in the legs, hips, and other parts of the body. If a user tries to stay upright on the footpads, his/her body will be shaken because of the motion of the footpads. To avoid this, the user must move his/her whole body. Since the trajectory of the footpads is prerecorded from a healthy individual, the body movement adopted by the user will resemble the movement of a healthy individual. With this design, we have achieved compatibility in the amount of exercise and provided moderate restraint.

2.2 Hardware

We developed a locomotion interface, which we call the GaitMaster5 (GM5, Fig.2). The size of GM5 is 965mm(H) X885mm(W) X1200mm(D). It is a manipulator type locomotion interface with two footpads that trace a virtual floor beneath the feet. When the user moves one of his or her feet forward, the footpad (under the foot in the swing phase) follows it like a shadow on the virtual floor. At the same time, the other footpad (beneath the foot in the stance phase) moves back the same distance as the other foot moves forward. Repeating this motion, the user can walk on an infinite uneven virtual terrain, while his or her body remains stationary in the real world.

The GM5 consists of two 2DOF motion-platforms (Fig.3), which have a linear guide and a slider-crank mechanism. To increase the stiffness of the slider-crank linkage, a parallel linkage is attached on the driving link of the slider-crank. A linear actuator that can move up and down is fitted at the end of the mechanism. The actuator consists of a linear slider, KR45H10A+440L (THK), and an AC servomotor, MQMA041P1S (Panasonic), and has a vertical working range of 315mm.

Each motion-platform has 300 mm x 270 mm footpads on top. The footpads can move 700 mm horizontally and 315 mm vertically. The maximum walking speed on the GM5 is 1000 mm/s and the maximum payload of each motion-platform is approximately 80 kg. The position of each footpad is measured using an optical rotary encoder on the AC servomotor, an MQMA041P1S made by Panasonic. The servomotors are driven by a PC through a controller (HCRTEXsd, made by HPtech) at 1ms intervals. The trajectories of the footpads can easily be changed by changing the motion data.

To fix the user's foot to the footpad, we use the binding used for a snowboard. The foot joints are fixed in such a manner that the toes and heels can move freely (Fig. 4), so that the dorsal flexion and plantar flexion of the foot joints are free. In order to detect the shift in weight, each footpad is equipped with 2 FlexiForce pressure

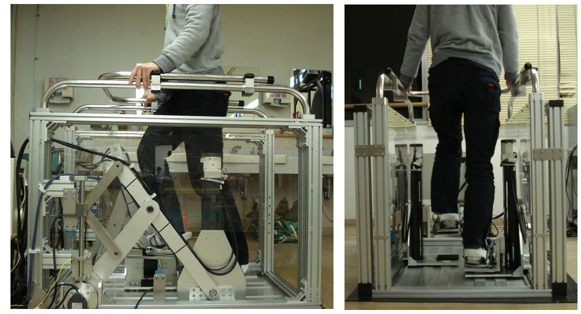

Figure 2: Overview of the system (Left:side view, Right: back view)

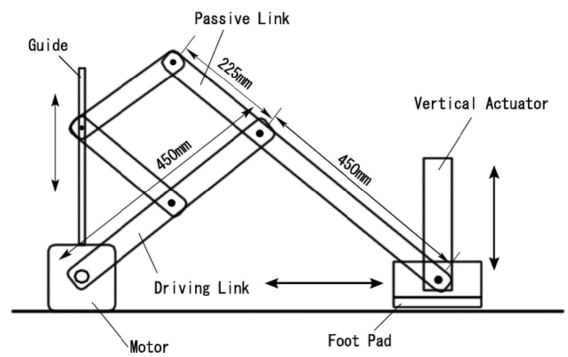

Figure 3: Mechanical configuration of the GM5

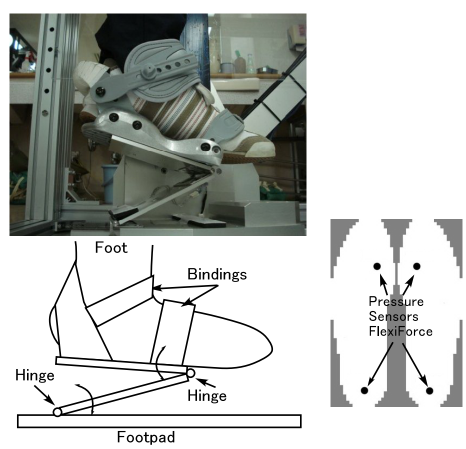

Figure 4: Overview of the footpad

sensors, made by NITTA. The sensors are placed under the heel and toe, based on the assumption that the user puts his/her weight on the heel and toe when the foot lands on the stairs.

3 Gait Rehabilitation for Climbing or Descending Stairs

3.1 Climbing stairs

We developed a gait training system using the GM5. The GM5 follows the trajectories of the feet of a healthy individual walking. First, the trajectory of the ankle of a healthy individual climbing a staircase was prerecorded using a motion capture system (Stereo labeling Camera, made by CyVerse). Fig.5 shows the captured data. By using this data, a trajectory can be generated from relative position of a foot from the waist which means the coordinate system is fixed to the walker's body (Fig.6).The data was smoothed to avoid instabilities in the control. Some healthy individuals experienced this trajectory with the GM5.

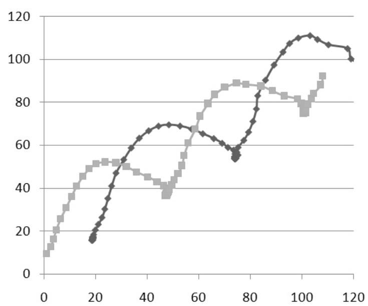

Figure 5: Original trajectories of both foot during stair climbing

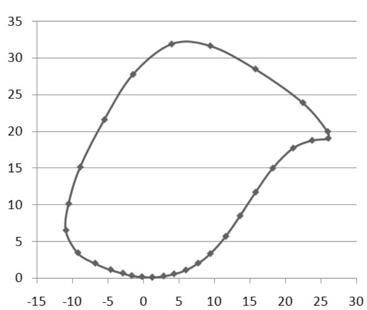

Figure 6: trajectory generated from relative position from waist in climbing stair.

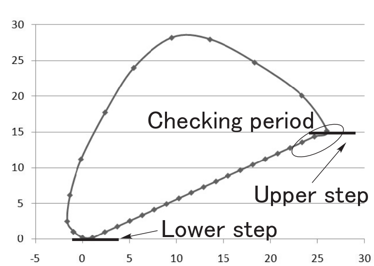

Figure 7: Displayed trajectory for training of stair climbing.

They, however, felt something was wrong about pullback motion. When we asked them in more detail, it seemed that they felt unnatural acceleration when the footpads pulled back to bottom position in the stance phase. To avoid the unnatural acceleration, the footpads pull back in constant speed in the stance phase and move up along with captured position in swing phase. Fig.7 shows the modified trajectory.

In this study, 2 training modes were developed.

One is the **"EnForced-gait"** mode (EF for short), in which the patient's feet involuntarily follow the prerecorded trajectory.

The other is the **"Semi-Voluntary gait"** mode (SV for short), in which pressure sensors data are used to detect the weight shift. Through a trial and error process, to detect of the intention of climbing stairs, the movement of user's body to upper step is important. The weight shift to the foot on the upper step is used to detect the motion in this system. When a user applies more than 25 % of his/her weight to the footpad beneath the foot at landing position on the next step, the footpad begins to move the foot backwards and the footpad beneath the foot on the lower step moves it forward. In addition, if the check point of weight shift is only one point, the users often fail to weight shift and then the footpad stops suddenly. This causes unnatural feeling. In this system, 0.15 seconds checking period is set to detect the weight shift so that the user can continue to climb virtual stairs without sudden stop. Therefore the timing of the movement is determined by the patient.

By using these modes, the user can learn the stair climbing motion of a healthy individual.

3.2 Descending stairs

In a similar way, the algorithm of descending stairs was developed. At the beginning, the ankles' trajectories of a healthy individual were captured with same motion capture system. The trajectories of both ankles is shown in Fig.8. Relative trajectory of a foot from the waist can be generated as shown in Fig.9.

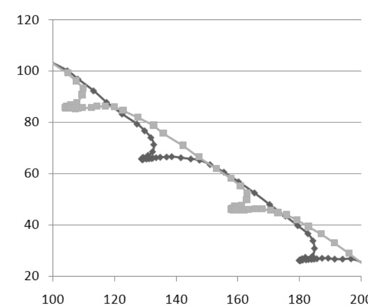

Figure 8: Original trajectories of both foot during stair descending

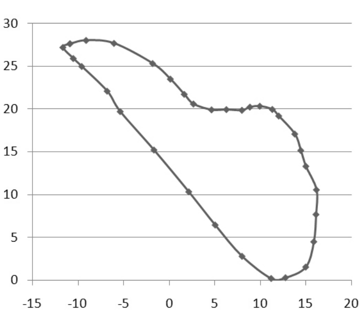

Figure 9: trajectory generated from relative position of each foot in stair descending.

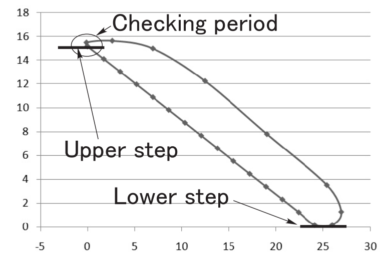

Figure 10: Displayed trajectory for training of stair descending.

As you can see, there is a shelf area in the swing phase. Since the waist begins to move downward while the swing phase, that causes the shelf area. Some healthy individuals experienced this trajectory and reported to feel something was wrong at the shelf area. Also they felt unnatural acceleration in the stance phase which means pulling up area. After some trial and error, we use a modified trajectory which is made from a reduced to 2 times original trajectory and a constant speed data connected to each step (Fig.10).

As same as stair climbing, 2 modes, EF mode and SV mode are provided for descending stairs. In the SV mode, detection of transition from stance phase to swing phase is important to detect the user's intention of descending stairs. Therefore we use timing of weight reduction of foot on the upper step. When the weight of foot on the upper step reduces under 1.0 kgf, the footpads begin to move. The checking period is set to 0.15 seconds as same as the stair climbing so that the user can continue to descending virtual stairs without sudden stop of the footpads.

4 EVALUATION OF THE PROPOSED METHOD

4.1 Experimental Conditions

Experiments were conducted in order to assess the effectiveness of the proposed methods for training patients to climb/descend stairs. We compared training in the EF mode, the SV mode and real stair climbing/descending (RS for short). The size of the stairs in each mode was 260 mm depth and 150 mm height, the same as a real step in a hospital. The cadence in stair climbing test was 42 steps/min in the EF mode, 40-46 steps/min in the SV mode, and 60 steps/min in the RS mode. Also the cadence in stair descending test was 45 steps/min in the EF mode, 44 steps/min in the SV mode, and 42 steps/min in the RS mode. These cadences were providing the physical therapist considered training could be safely executed.

The pressure applied to the feet and the muscle activities of the subjects were measured during each trial. As a pressure sensor, the F-Scan II made by NITTA. The sensors are 0.15 mm thick and placed underneath each foot. The sensor can measure 955 points of pressure data in real time. The time resolution of the measurement was 33 ms in stair climbing experiment and 5ms in stair descending experiment. An electromyograph, the MEG-6108 made by Nihon Kohden, which has 16 EMG channels was used for measuring the muscle activities of the subjects.

Five trials were conducted with 6 healthy individuals in their 20s, a 59-years-old hemiplegic patient for stair climbing and a 50-years-old hemiplegic patient for descending stairs. Although it is prefer that same patient experienced stair climbing and descending, we asked 2 different patient due to some schedule conflicts.

The healthy individuals' weights were between 59 kgf and 70 kgf.

The patient in stair climbing had right hemiplegia and visits hospital regularly as an outpatient for rehabilitation. He developed cerebral infarctions 2005 and 2008. He has a moderate degree of paralysis of the upper limb and a low degree of paralysis of the lower limb. He can undertake a circumduction gait without canes or ankle foot orthosis in the case of stair climbing. The duration of his stance phase is longer and the duration of his swing phase is shorter on the affected right side than on his normal left side. The patient weighs 58 kgf.

The patient in descending stair had right hemiplegia and visits hospital regularly as an outpatient for rehabilitation. He developed cerebral infarctions in 2009. He has a low degree of paralysis of the upper limb and the lower limb. He can undertake a independent gait without canes or ankle foot orthosis in the case of stair descending. The patient weighs 65 kgf.

In the EF and SV modes, a 15s rest, 30s stair climbing/descending and a further 15s rest were applied, the same conditions as in Miyai's paper [7]. The RS task was limited to 11 steps by the length of the cable to the EMG used to measure the muscle activities of the subjects. Since all subjects were novice users of the GM5, they walked on it for about 90 s before the experiment.

The following sections describe the results and analysis.

4.2 Foot Pressure in Stair Climbing

Table 1 shows a comparison of the average weight applied to the F-Scan by each foot during the task.

In the healthy subjects, the weight in SV mode is heavier than those of EF and RS. There are significant differences between SV and others in 1 % of critical rate.

Fig.11 shows a typical time series variation of weight shift of a healthy individual puts on his feet in each mode. The gray area means the stance phase of the right foot. The subjects stepped harder to avoid sudden stop of the footpads in the SV mode. This caused the above result. Also, there are different weight shift patterns of the RS mode that has a peak at right side of each hump, while the EF mode and SV mode have a peak at left side of each hump. The system checked the weight shift to the upper step in the SV mode. However, most of healthy individuals kicked the lower

Table 1: Comparison of average weight in each mode. (unit:kg)

Healthy	SV (33.825)	>	EF (28.156)	=	RS (28.400)
Patient	EF (29.063)	=	SV (29.071)	=	RS (28.582)

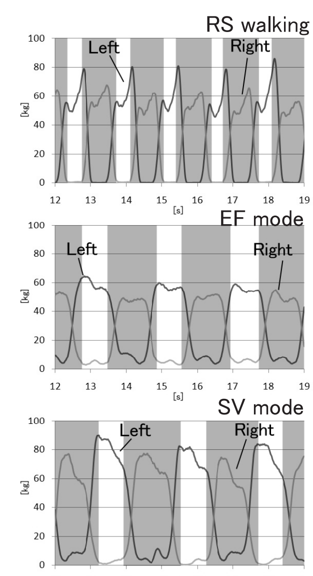

Figure 11: Time series variation of weight on each foot of a healthy individual in climbing stairs (Top: Real stairs, Middle: Enforced, Bottom: Semi-voluntary)

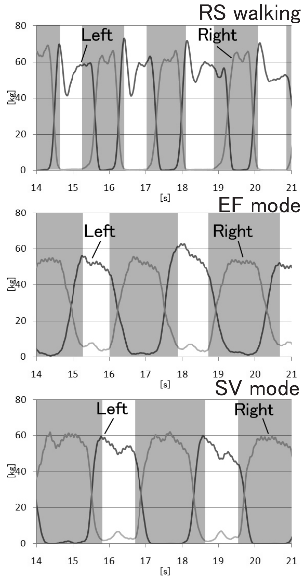

Figure 12: Time series variation of weight on each foot of the patient in climbing stairs (Top: Real stairs, Middle: Enforced, Bottom: Semi-voluntary)

Table 2: Comparison of the ratio of period A to period B for the patient in each mode.

Patient	RS(0.67)	$<$	EF(0.95)	$=$	SV(1.01)

footpad when they were climbing up the stairs. There is a room to improve the algorithm.

On the other hand, no significant difference among the average weights of the patient in the EF, SV and RS modes were found by using ANOVA.

Fig.12 shows a typical time series variation of the weight of the patient puts on his feet in each mode. He had tried the flat surface walking a few months ago. This experiment was second time of using this system for him. He might get used to this system. Therefore he can shift his weight proper.

We compared the ratio of the time spent in the stance phases of the left and right feet in each mode. Period A is the time spent in the stance phase of the right foot, and period B is that for the left foot. The ratio of period A to period B for each step in each mode was acquired. We compared the ratio for the 3 modes. In healthy individuals the ratios of each mode are usually about 1.0 and we found no significant difference between each mode. However, in the patient, a significant difference between the RS mode and other modes was found (Table 2). The GM5 provides moderate restraint, and the patient was able to move his body in symmetrical (Fig.13).

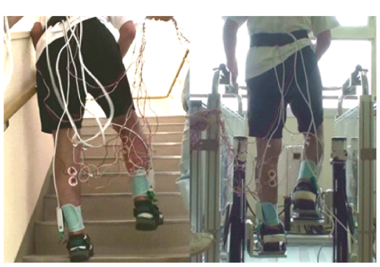

Figure 13: Figure of the patient of climbing stairs

4.3 EMG in Stair Climbing

Muscle function with electromyograms was measured to evaluate the effect of the stair climbing training. An electromyograph, the MEG-6108 made by Nihon Kohden, was used in this experiment. We measured the electromyograms of 4 types of muscle. These were the gluteus medius muscle, the hamstrings, the medial vastus muscle and the gastrocnemius muscle.

The gluteus medius muscle is one of the muscles attached to the hip, which is in charge of rotation and flexion of the hip joint. It maintains the standing posture during walking. The hamstrings are the muscles at the back of the thigh, which are in charge of extension of the thigh and rotation of the lower thigh. They decelerate the lower limb of the swinging side when the gait switches from the swing phase to the stance phase. The medial vastus muscle is a knee muscle, which is in charge of absorbing the shock when the foot lands on the ground. The gastrocnemius muscle is a sural muscle that is in charge of flexion of the lower thigh and the flinging-up motion used to obtain acceleration [8][5].

We measured both healthy subjects' and the patient's normal and paralytic sides. Fig.14 shows electromyograms of each leg of the healthy individuals in RS, EF and SV modes. The gray area means the stance phase. The activation is decreased in RS and continues SV, EF mode. In SV mode, the profile of each EMG of each muscle is resemble RS walking in appearance. For example, the gluteus medius muscle activates in the stance phase so that it controls standing posture during stance phase. There is a peak at the gastrocnemius muscle on stance phase taking off from the ground. These mean the system can activate these muscles correctly. Although subtle difference between EMGs of left and right leg is found, there is no significant difference between left and right legs.

Fig.15 shows electromyograms of the patient's normal (left) and paralytic (right) side in RS, EF and SV modes. The muscles on normal side are activated than those on paralytic side in RS walking because of his right hemiplegia. However, SV mode on paralytic side is more activated than EF mode and it provides comparable activation with RS walking of paralytic side. This result means the SV mode at least provides equivalent effect with the RS mode for the paralytic patient. Moreover, the gastrocnemius muscle has a peak at the foot on stance phase taking off from the ground. This means the gastrocnemius muscle was activated at the right time. The system provides moderated constraint for feet, the patient can concentrate to move his leg by using our system.

4.4 Foot Pressure in Descending Stairs

As same as stair climbing, the pressure distribution was measured using pressure sensor, the F-Scan II.

Table 3 shows a comparison of the average weight applied to the F-Scan by each foot during descending stairs. In the healthy subjects, there are significant differences between EF and others in 1 % of critical rate.

Fig.16 shows a typical time series variation of weight a healthy individual puts on his feet in each mode. In RS walking and SV mode, the subjects weighed their whole weight on the foot of stance phase side. In the EF mode, however, the subjects tended to weigh their weight on both feet. Since the velocity of the footpad is slower than that of the subject's foot, the subjects put their weight on the footpad even though it is in the swing phase. This caused the above result. The profiles of weight on each foot look like a convex shape in the EF and SV mode. The profiles of the RS mode looks like concave shape. The subjects grasped the safety bar on the GM5. The

Table 3: Comparison of average weight of each mode in descending stairs. (unit:kg)

Healthy	EF (31.467)	$>$	SV (27.893)	$=$	RS (28.344)
Patient	EF (23.570)	$=$	SV (23.211)	$<$	RS (39.531)

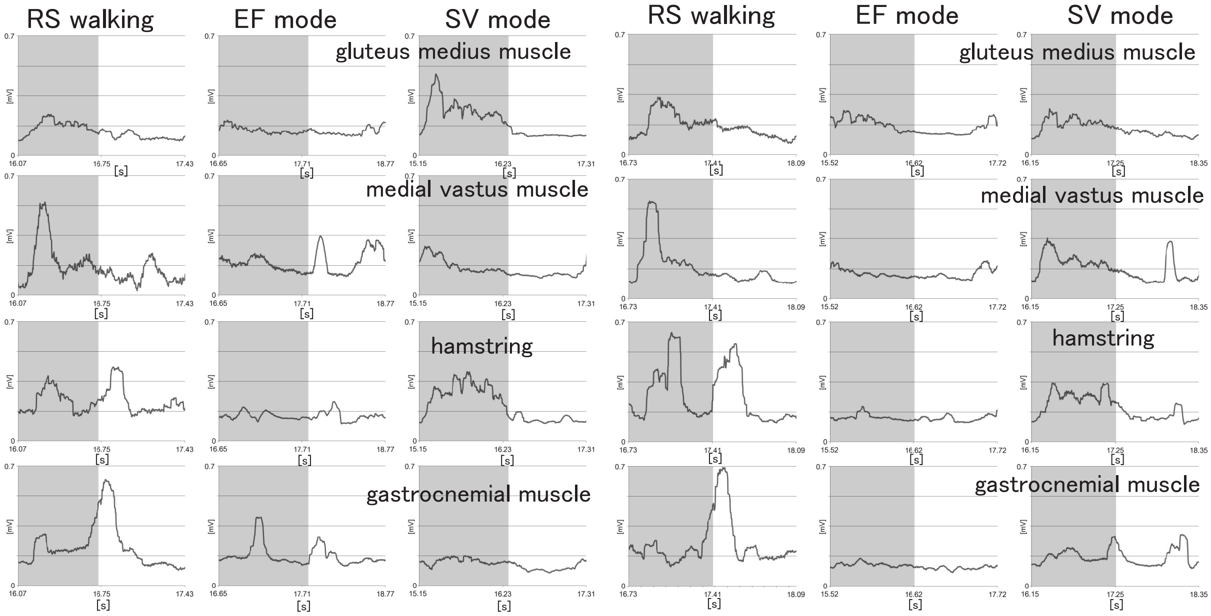

Figure 14: Electromyograph of a healthy individual's legs in stair climbing

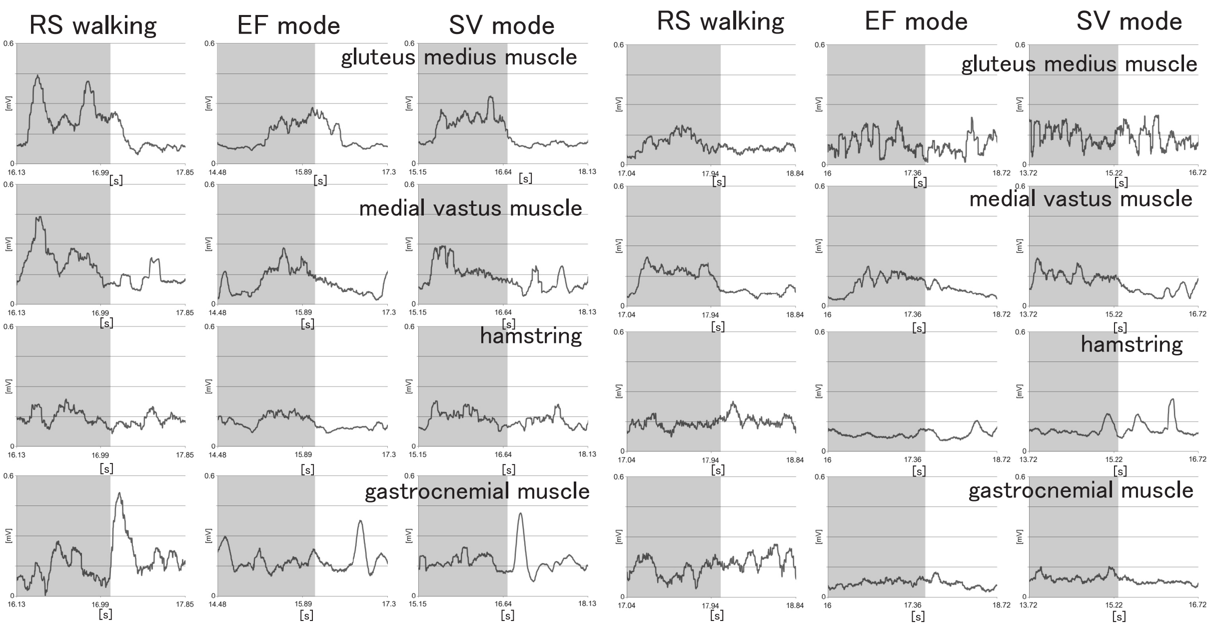

Figure 15: Electromyograph of the patient's legs in stair climbing

subjects tended to put their weight on the safety bar when landing and taking off the ground. This caused the shape difference.

On the other hand, significant difference between the RS walking and others in 1 % of critical rate is found in the patient. Fig.17 shows a typical time series variation of the weight the patient puts on his feet in each mode. In the RS mode, the patient used the handrail of the stairs at the left hand side. When he move his right leg (paralytic side), he tended to pressure on the handrail. Also the front part of the patient's feet run off the edge of the each stair, the pressure at the edge became large. To calculate foot pressure, the F-Scan integrated pressure values of each point. These may caused the above result.

We compared the ratio of the time spent in the stance phases of the left and right feet in each mode. In the patient, no significant difference among all modes was found (Table 4). This patient has low degree of paralysis so that the patient can move his legs in symmetrical.

Table 4: Comparison of the ratio of period A to period B for the patient on each mode in descending stairs.

Patient	RS(1.18)	=	EF(1.15)	=	SV(1.11)

4.5 EMG in Descending Stairs

Fig.18 shows electromyograms of each leg of the healthy individuals in RS, EF and SV modes in descending stairs. The gray area

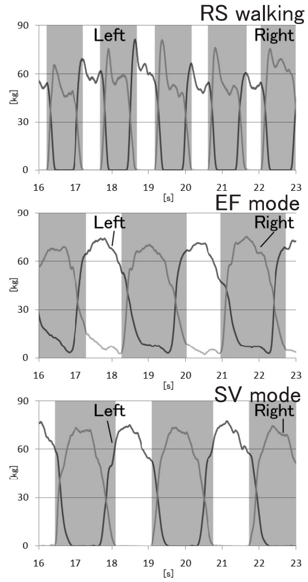

Figure 16: Time series variation of weight on each foot of a healthy individual in descending stairs(Top: Real walking, Middle: Enforced, Bottom:Semi voluntary)

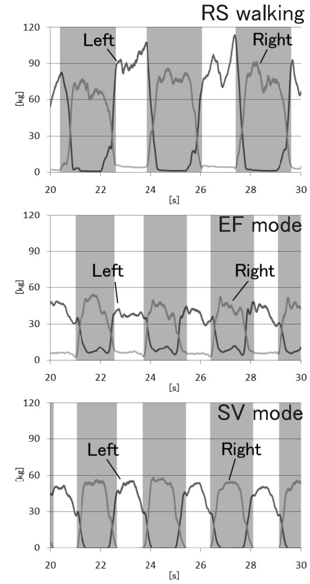

Figure 17: Time series variation of weight on each foot of the patient in descending stairs(Top: Real walking, Middle: Enforced, Bottom:Semi voluntary)

means the stance phase. The activation is decreased in RS and continues SV, EF mode. In SV mode, the gluteus medius muscle and hamstrings of left hand side are more activated than others. The subject might not get used to keep balance on the footpads. Therefore they prepare for sudden stop of footpad caused by the timing of weight shifting is off. Although subtle difference between EMGs of left and right leg is found, there is no significant difference between them.

Fig.19 shows electromyograms of the patient's normal (left) and paralytic (right) side in RS, EF and SV modes. Unfortunately, the EMG of medial vastus muscles are not measured normally because of the wire trouble of the electromyograph. We discuss by using remaining 3 muscles.The muscles on normal side are activated than those on paralytic side in RS walking because of his right hemiplegia. However, muscles on paralytic side in SV mode are more activated than RS mode. This caused symmetric motion of footpads. This result means the system has ability to bring out the patient's muscle activations on paralytic side.

5 DISCUSSION

We developed an enforced gait (EF) mode and a semi-voluntary gait (SV) mode. Each mode can present the trajectory of a healthy individual's feet to the user. However the EMG in the EF mode is less than in the SV and RS modes. This means the EF mode places less burden on the user's legs compared to the SV mode and the RS walking. Therefore the EF mode can be used for patients who lack physical strength. A patient can learn the whole body motion using the EF mode at a first level. At the second level, he/she can learn a semi-voluntary motion using the SV mode. After this training, the user can learn the motion for real steps using the LI mode of the GM5. The LI mode is the fundamental function of the GM5. By removing the bindings on the footpads, the feet of the user can move freely and the footpads follow the motion of the feet by adding foot position sensors.

By using our system, a virtual staircase can be realized, while the user's position is maintained constant. This is the same as for the StairMaster [1] which is a commercial step mill. Our LI, however, can realize staircases of arbitrary size. Therefore the GM5 system can be used for all the training modes required for climbing/descending stairs and normal walking on a flat surface. Moreover, since the stair climbing/descending modes can be used to increase the training work load, these might shorten the training periods required for normal walking on the flat. Meanwhile, until recently, it is necessary for patients to acquire/improve their gait before training of stair climbing/descending. Since the user's position is maintained, our system can reduce the risk of fall. Therefore, stair climbing/descending training with our system can provide opportunity to do such training for the patients who are in earlier stage of rehabilitation.

In the EF mode, some users reported that they felt as if they were walking on a soft surface. It was difficult for these users to completely synchronize their weight shift motion to the weight shift of the prerecorded data. The difference between these weight shifts gave rise to the above feeling. In the SV mode, some users often needed consciously to put weight on their feet. By using 2 pressure sensors at heel and toe of each foot, almost subjects can realize continuous walking in the SV mode. However the misjudge and stoppage of the footpads rarely occurred. Also foot pressure profile in RS looks like concave shape. Improvement of checking the weight shift is necessary.

6 CONCLUSION

In this paper, a gait rehabilitation system with a compact LI for training patients to climb/descend stairs was developed. An enforced gait mode and a semi-voluntary gait mode were implemented for the training. In an experimental evaluation, the capability of the system for training patients to climb/descend stairs was confirmed. The EF mode can be used for novice/ less active users and the SV mode can be used for more active users.

In future work, the long-term effects of our rehabilitation method will be investigated. We also plan to provide a more complex and realistic training environment with an immersive projection display.

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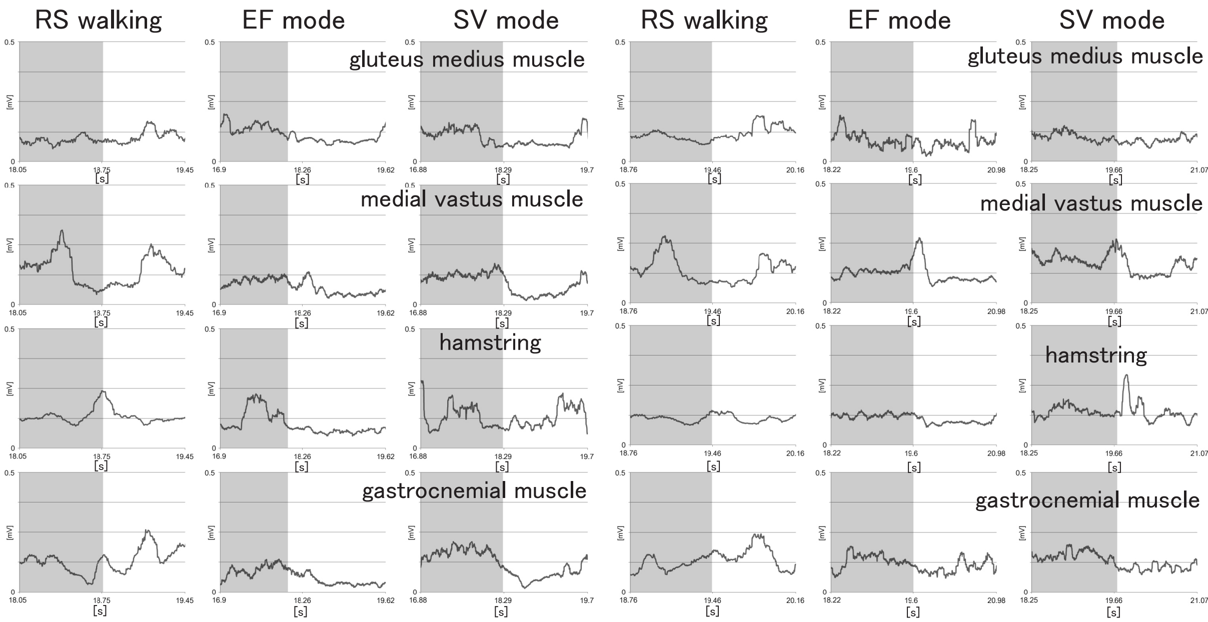

Figure 18: Electromyograph of a healthy individual's legs in stair descending

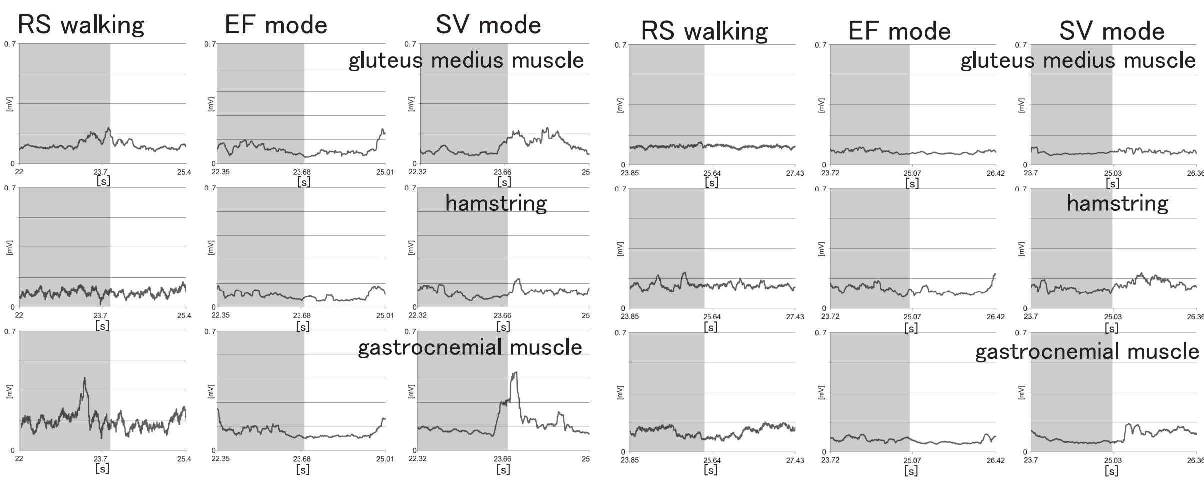

Figure 19: Electromyograph of the patient's legs in stair descending

search for Evolutional Science and Technology (CREST) from Japan Science and Technology Agency (JST).

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