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Walking Assistance Apparatus Using a Spatial Parallel Link Mechanism and a Weight Bearing Lift

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Abstract— **A prototype for a walking assistance apparatus for the elderly or motor palsy patients was developed as a next-generation vehicle or movable neuro-rehabilitation training appliance, using a novel spatial parallel link mechanism and a bearing lift. The flat steps of the apparatus move in parallel with the ground; the apparatus can support entire leg alignment (including soles) and assist; walking behavior at ankle, knee and hip joints simultaneously. In order to respond the variation of equipped person's walking velocity, the length of stride and walking cycle while walking with wearing the apparatus were compensated by using the relation of walking ratio. Therefore the apparatus can be controlled in response to equipped person's will. Motor palsy and muscle weakness patients can walk by themselves by using the apparatus; patients who have ambulation difficulty can use the apparatus with weight bearing lift that we developed. Using the apparatus with the weight bearing lift prevents stumbling and enables input of walking movement to the brain motor area. It is very effective for rehabilitation to use the apparatus with the weight bearing lift. This newly developed system facilitates motor palsy and muscle weakness patients in the rehabilitation program.**

Keywords-walking assistance; spatial parallel link mechanism; walking ratio; neuro-rehabilitation

I. INTRODUCTION

Japan has experienced a rapid grown in elderly population in recent years. As people ages, their muscle strength tends to decrease. Therefore, even if they can walk by themselves, they become fatigued easily, and their walking motion is different from a healthy person's. As a result, they are more susceptible to stumbling and falling down, even though there may be only a slight step involved. With these accidents, they experience a lapse in confidence and the fear of sustaining serious injuries. This can decrease their quality of life.

In response to these actual conditions, we developed a walking assistance apparatus for elderly or rehabilitants to promote their independent lives and regain their muscle strength. Up until now, walking equipment was generally used for walking support. However, these equipped people became tired very quickly, because the equipment fixed the joints of the knees and ankles. And, the patient had to turn his/her body to swing their leg to the front. For this problem, the walking-support equipment with a joint drive system of the body-worn type was developed by Yamamoto, Sankai, and others [1] [2] [3] as shown in Fig. 1(a). These walking-support equipments support the knee and hip joints, which need an especially large torque while walking, and does not support the ankle joint.

However, during long periods of walking, fatigue appears in the tibialis anterior muscle (TA) making the ankle capable of dorsiflexion and causing stumbling [4]. In recent years, neuro-rehabilitation that repairs the neural circuit by inputting walking movement to the legs directly has attracted attention and training machines have been developed (e.g. Lokomat®, developed by Hocoma co. [5]). However, most of those machines have the problem that rehabilitants tend to be bored, and are not able to move while using them.

Therefore, a new walking assistance apparatus as a next-generation vehicle or movable neuro-rehabilitation training appliance is being developed. The purpose of this research is to develop a walking assistance apparatus to support the entire leg which includes the ankle in addition to knee and hip joints while walking [6], and to assist walking behavior at the ankle, knee and hip joints simultaneously. Furthermore, we developed an apparatus as a training device to exercise the neuro-rehabilitation of walking for a patient who cannot walk and has gait problem. The developed prototype was experimented on and effectiveness was confirmed by electromyography (EMG) measurement.

II. Walking Assistance Method

In this research, the walking assistance method in which the flat steps always follow the soles of each foot structurally was proposed. That is, the equipped person loads his/her legs on the flat steps and is assisted by the walking movement of the entire leg from the sole of the foot as shown in Fig. 1(b). The main joints and the main procedures used in walking are as follows:

a) Hip joint: The turn in the direction of the right or left side motion, the swing in the direction of back and forth

b) Knee joint: The swing in the direction of back and forth

c) Ankle joint: The swing in the direction of back and forth

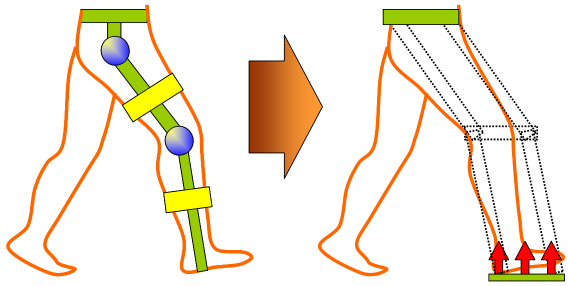
Among these, the developed apparatus specifically supports the operation of the swing of back and forth motion which influences the direction of movement. As shown in Fig. 2, the steps are driven so as to keep parallel to the ground. Therefore three joints can be supported at the same time. When the phase of the walking is a stance phase, the steps connect to the ground, and at a swing phase, they are driven according to the lowest position of the sole of each foot. Because posture is controlled when the equipped person stands, this prevents tumbling by attaching the apparatus.

III. Designing The Walking Assistance Apparatus

A. The Application of the Spatial Parallel Link Mechanism

The spatial parallel link mechanism is proposed as the mechanism allowing the walking assist method which was previously described. This mechanism has the structure which connects two parallelograms lengthwise on the front and the side. The step can always maintain translational motions of three degrees of freedom to the body of the equipped person as shown in Fig. 3. This mechanism was applied to the walking assistance apparatus as shown in Fig. 4. The structure to have the link of the parallelogram correspond to the femoral and crural parts of the leg respectively was made as shown in Fig. 4. The actuator to the direction of the operation on both sides wasn't attached, and the equipped person can move in any direction freely himself/herself. The mechanism has taken into account the twisting motions of the ankle by using a flexible link as shown in Fig. 4. This link is made with a stainless steel plate and rubber, so it can be bent and twisted with moderate elasticity. However, the link must not buckle; i.e., it is hard enough to be elastic in the direction of the link length.

By taking into account the necessary torque and angular velocity, each actuator's rating power and gear ratio were selected as shown in Table 1, and the apparatus can drive under the conditions same as the torque and angular velocity of walking for an able bodied person. And the structure of the mechanism which was manufactured is shown in Fig. 5.



(a) Conventional structure (b) New proposal structure

Fig. 1 The difference between conventional and new proposal structures of the power assistance apparatus

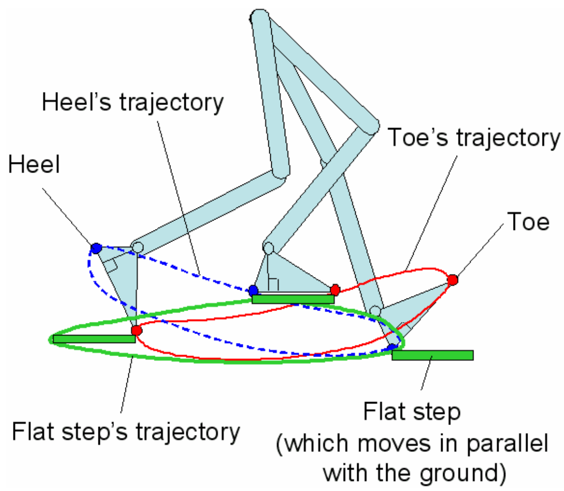


Fig. 2 Trajectory of the flat step of the apparatus

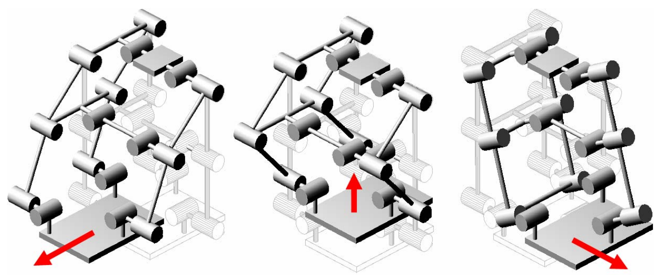


Fig. 3 Directions of three DOFs of the spatial parallel link mechanism (For the right leg)

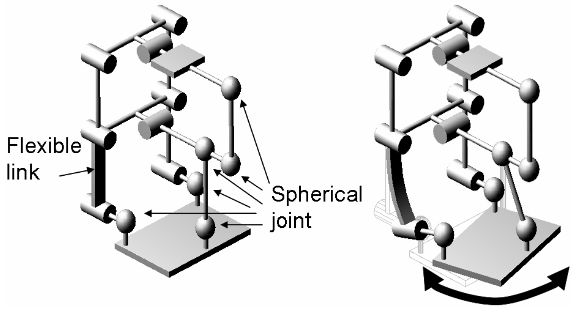


Fig. 4 Flexible link and spherical joints in the mechanism and twisting motion of the mechanism (For the right leg)

Table 1 Maximum output data of the actuator for each joint of the apparatus

Joint	Rating power (W)	Gear ratio	Pulley ratio	Max output of angular velocity (rad/s)	Max output torque (Nm)	Ratio with Max output torque and necessary maximum torque (%)
Hip	150	126/1	36/36	6.30	215	125
Knee	150	126/1	36/36	6.30	215	101

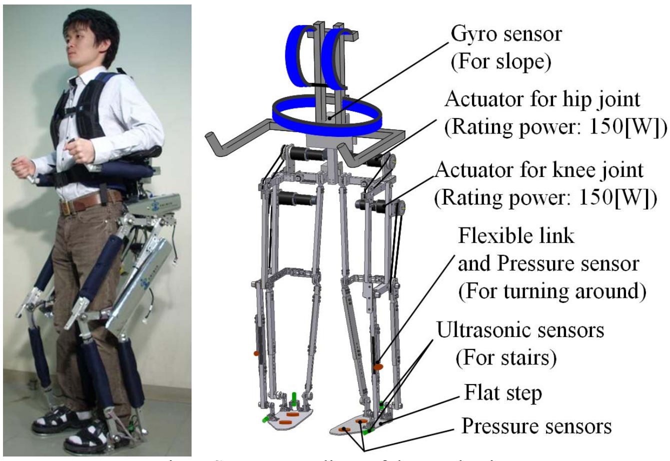


Fig. 5 Structure outlines of the mechanism

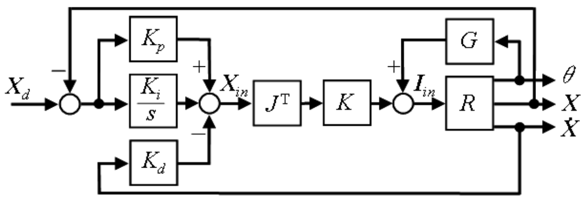


Fig. 6 Control System of the apparatus

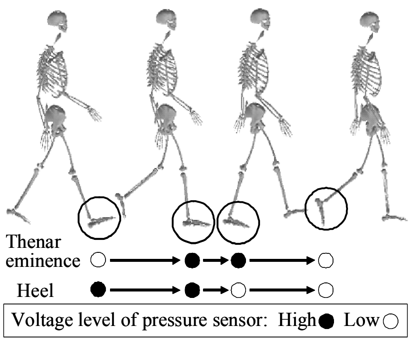


Fig. 7 Measurement of walking phase

B. *The control method of the apparatus*

The value of the torque for each actuator was calculated and controlled with a PID controller. The control deviation of the flat step is defined as $\boldsymbol{X}_{in}$, the electric current input value is defined as $\boldsymbol{I}_{in}$. $\boldsymbol{X}_{in}$ and $\boldsymbol{I}_{in}$ can be expressed as follows (illustrated in Fig. 6):

$$\begin{aligned} \boldsymbol{X}_{in} &= \left(K_p + K_i/s\right)\left(\boldsymbol{X}_d - \boldsymbol{X}\right) - K_d\dot{\boldsymbol{X}} \\ \boldsymbol{I}_{in} &= KJ^{\mathrm{T}}\boldsymbol{X}_{in} + G \end{aligned} \quad (1)$$

where $\boldsymbol{X}_d$ is the target value, $\boldsymbol{X}$ is the actual measurement value at the center of the flat step, K_p, K_i, K_d is each gain of the PID control, J is the Jacobian matrix from the center of the body to the center of the step, K is the diagonal matrix for the proportional coefficient with torque-electric current value, and G is the weight compensation which is taken into account the variation of the value by the difference between swing and stance phases.

Actually, it is necessary for a control law to consider inertial forces and the output forces created an equipped person. However, the each gain that an equipped person feels comfortable is different from each person, its fine adjustment to equipped person is required. Then, we use the simple control law such as the above for easy parameter tuning.

The coordinate $\boldsymbol{X}$ of the step is calculated with direct kinematics from the encoder value θ, which is attached to each motor, and the control signal $\boldsymbol{X}_{in}$ is obtained the tracking error $\boldsymbol{X}_d - \boldsymbol{X}$ with control gain K_p, K_i, and K_d. The values of torque which each joint needs are calculated by multiplying $\boldsymbol{X}_d$ by the transposed Jacobian matrix J^{T}. The electric current input value $\boldsymbol{I}_{in}$ taking into account the weight compensation is obtained to each motor driver. The motors are controlled through the motor drivers according to the value of $\boldsymbol{I}_{in}$. As a result, the apparatus can assist the equipped person by giving the force according to the value of the deviation. This control system is run with the SH-4 board. The operating system (OS) of the computer utilized ART-Linux, and the control interval was set to 1 milliseconds. Lithium-ion battery as the power supply was mounted on the apparatus, and the self-contained control system was realized.

C. *Estimation of the walking phase, the angle of slope and the distance of stairs*

To estimate the walking phase of each leg of the equipped person, pressure sensors were attached under the thenar eminence and the heel of the sole, and the pressure variation of each sensing point was measured. The sensor was made by sandwiching a pressure-sensitive and conductive rubber of 0.5 mm thickness in the thin copper sheet. Its output voltage is 0-5 V using the partial pressure circuit. Because the sensor is attached in the insole to use for shoes and so on, the pressure can be measured only while laying the insole in the footgear such as the sandal which the equipped person wears. Fig.7 shows the pressure conditions under the thenar eminence and the heel according to the walking phase. The stance phase is estimated grasped by dividing it into 4 steps as shown in Fig. 7. By specifying the target value of the step according to each phase, the control corresponding to the behavior of the equipped person, and this improved safety as well. For emergency, in case of system malfunction, a direct stop switch was also equipped. To recognize the equipped person's will of walking direction, the pressure sensor was also attached on the flexible crural link. A gyro sensor was attached on the back of the apparatus. Due to the parallel link mechanism, the sensor can measure the angle of the slope where the equipped person is standing. Furthermore, to measure the distance between the flat step and stairs, an ultrasonic sensor was attached both toe and heel of the flat step. If the foot in the swing phase is about to hit the edge of the stair, the sensor detects it and the foot is prevented from hitting the stair. Therefore, the equipped person can walk on the stairs safely.

D. Weight bearing lift

A person who can walk on their own, such as a healthy person or elderly person can use the apparatus independently. On the other hand, it is difficult for patients who have ambulation difficulty or who can not walk by themselves to use the apparatus independently. Because they are more likely to stumble, it is necessary to support the balance of the patient. Furthermore, to use the power of the apparatus effectively, a weight bearing lift is effective. Therefore, we developed a weight bearing lift with two arms labeled arm A and arm B which can bear both the combined weight of the equipped patient and the apparatus (Figs.8, 9). As shown in Fig. 8, this lift can be driven with a joystick for the direction where the helper or equipped person wants to proceed.

Arm A bears the weight of the apparatus. The apparatus is fixed on arm A, and the weight bearing lift is also equipped with wheels so that the apparatus and the weight bearing lift can be used while moving. A helper can control the weight bearing lift with electro operation from behind at a speed suitable to the patient's needs. Arm A can bear 150 [kg], which is sufficient to support the apparatus's total weight of 20 [kg]. The arm has actuators that can adjust to the height of the apparatus. Arm B bears the weight of the patient. Arm B is attached to arm A. The patient wears a harness which is hung from arm B's hook. Arm B was designed to bear up to 100 [kg], and can be adjusted to the patient's height up to 180 [cm].

The bearing weight of the equipped patient, $\Delta m_h g$ is calculated by

$$\Delta m_h g = f\frac{l_2 \cos\theta}{l_1} \qquad (2)$$

where f is tension that is measured by the spring balance, l_1 is the length from the arm B fulcrum to the point where the equipped patient hangs, l_2 is the length from the arm B fulcrum to the point which is connected to the spring balance, as shown in Fig. 9.

The weight bearing lift enables the patient to feel more secure in using the apparatus because the apparatus is fixed on arm A, and the patient is supported by arm B, thus keeping the patient free from stumbling.

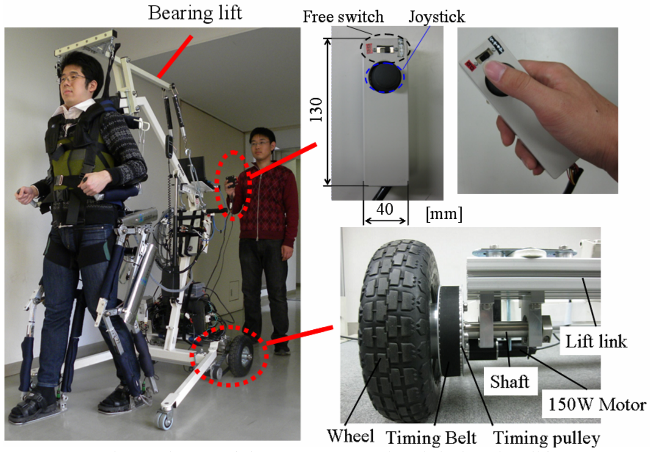


Fig. 8 Photos of the apparatus and weight bearing lift

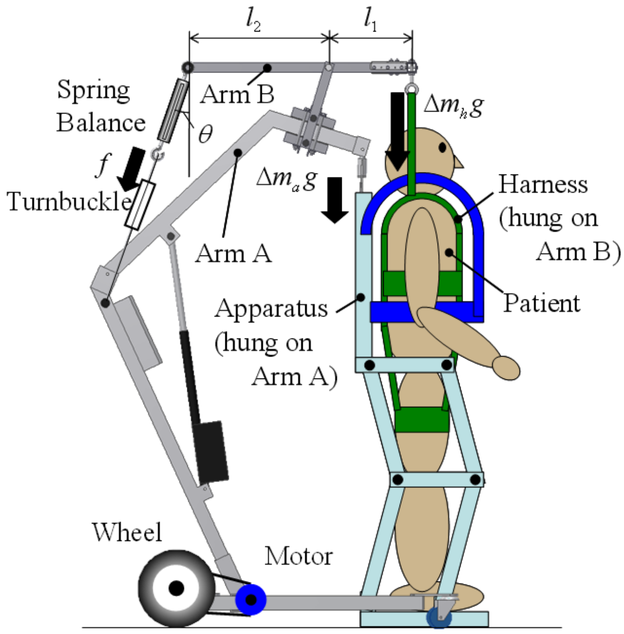


Fig. 9 Mechanism of the weight bearing lift

IV. THE COMPENSATED METHOD TO ADAPT ACCORDING TO THE VARIATION OF WALKING VELOCITY

A. Adoption of the relation of walking ratio

For elderly who can walk themselves, it can be said that it is important to promote walking for anti-aging. In response to this request, we suggested utilizing this apparatus as a next-generation vehicle for a walk in beauty spot, leisure venue and so on (Fig. 10), because almost these spots have a slop or stairs. To use this apparatus as a vehicle, it should be able to adapt according to the variation of walking velocity which the equipped person desires, therefore we developed a new compensated method using the relation of walking ratio.

Walking relation a can be shown as follows:

$$a = \frac{lp}{120} \text{ [m/step/min]} \qquad (3)$$

Fig. 10 Photos of an example of the apparatus utilizing as a vehicle

where l [m] is the length of stride, p [sec/step] is walking cycle, respectively. The value of a is generally known as a=0.006 [m/step/min][7]. By using this equation, we developed three control methods for adapting account for the variation of walking velocity as mentioned below. Here, we defined that p can be variable in the range from 1.08 to 2.16 [sec/step], because 1.08 [sec/step] is the average value of able bodied persons. And the maximum value of l was calculated from the target trajectory for each equipped person, which was calculated from the data of each length between the joints of equipped person and each angle variation data [8] by using direct kinematics.

a) l is measured while walking with wearing the apparatus, and the target value of p which is calculated from Eq. (3) is compensated.

$$p = 120 * a / l_{measured}$$

b) p is measured while walking with wearing the apparatus, and the target trajectory is compensated by multiplying by the ratio between target value l of which is calculated from Eq. (3) and maximum value.

$$l = 120 * a / p_{measured}$$

c) If the equipped person wants to walk faster or slower than now, the time while double stance phase T [sec] is varied according to the requested walking cycle. Therefore, the time while double stance phase T which the equipped person is measured, and adequate value of p is calculated from the linear relation between variation of T and p. And target p and l are compensated by using Eq. (3).

$$p = \alpha T_{measured} + \beta, \; l = 120 * a / p$$

B. Experiment of walking with wearing the apparatus

To confirm the validity of each compensated method, l, p and the walking velocity while walking with wearing the apparatus were measured. And somesthetic assisted power on the condition of each compensated method was interviewed. The test subjects were two healthy 23 and 25 year old men, and they had prior experience to walk using the apparatus. Subjects were given the instructions that they walked 12 steps (6 walking cycles); first 4 steps were accelerated, middle 4 steps were top speed which the subjects felt most suitable, final 4 steps were de-accelerated. The measured data of l, p and the walking velocity of two subjects are shown in Figs. 11 and 12.

C. Consideration of experiments of results

As compared to the results Figs. 11 and 12, there are similar tendency in three graphs. The result of without compensation is hardly varied in all graphs. The result of the compensated method a), the length of stride is longer than the other results, however, it is also hardly varied. It is considered that the target of l was constant; therefore l could not be diminished by the equipped person. Next, the walking cycle of the compensated method b) shows almost same pattern to the result of the compensated method c). However, the target of l was diminished according to the value of p, consequently, the walking velocity was also decreased. The variation ranges of the results of the compensated method c) were the largest in four condition's results. The method c) also had a best opinion of the result of interview about somesthetic assisted power in four conditions. Therefore, we concluded the method c) was the most effective. However, when the method c) is adopted in the control program, the variation range of T of each subject has to be measured and grasped the relation between T and p previously. As a future work, we are going to make the table of this relation according to the age, gender, weight, and so on.

V. EVALUATION THE EFFECTIVENESS OF THE WEIGHT BEARING LIFT

A. Experiment of walking with wearing the apparatus and using the weight bearing lift

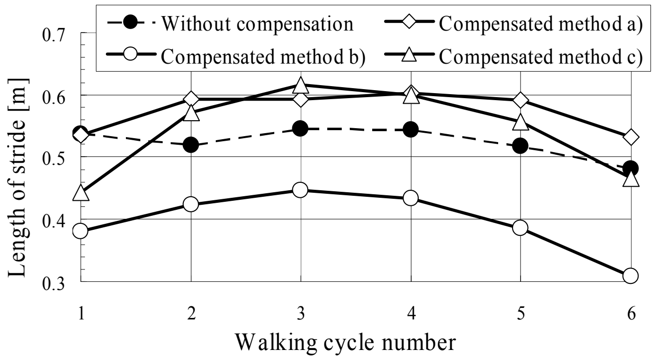
In order to evaluate the effectiveness of the developed weight bearing lift, the EMG data of one leg of the equipped person was measured while walking with wearing the apparatus and using the weight bearing lift. The test subject was a healthy 23 year old man; his height was 172 cm, weight was 66 kg, and he had prior experience to walk using the apparatus. He walked with the walking cycle at 1.30 [sec/step], which was comfortable for him using the apparatus and bearing lift. The conditions of the experiment were as follows:

a) Walking with wearing the apparatus (without the lift)

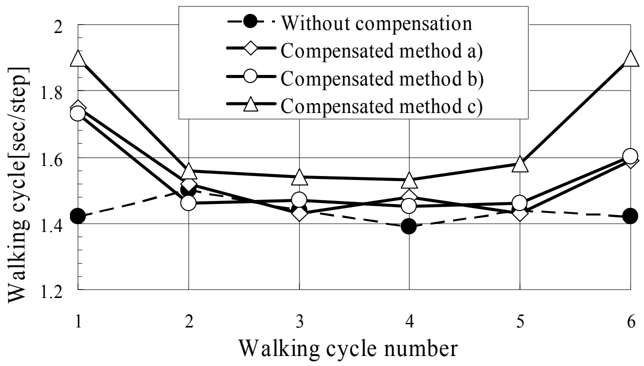
b) Walking with wearing the apparatus and using Arm A of the bearing lift (bearing by 60 [%] of the apparatus's weight (22 [kg]))

c) Walking with wearing the apparatus and using both arms of the bearing lift (bearing by 60 [%] of the apparatus's weight (22 [kg]) and by 30 [%] of the subject's weight (66 [kg]))

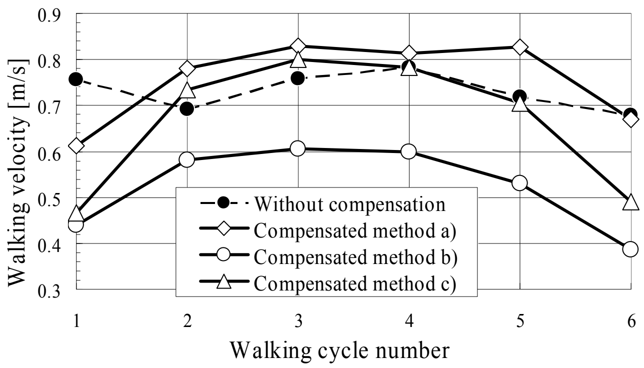
He walked straight ahead with constant velocity, and the EMG was measured while walking 10 steps. The measured data was collected from four points on the right leg (Tibialis Anterior muscle: TA, Medial Head of Gastronemius muscle: GMH, Rectus Femoris muscle: RF, Long Head of Biceps Femoris muscle: BFL). The distance between the electrodes of



(a) Variation of the length of stride

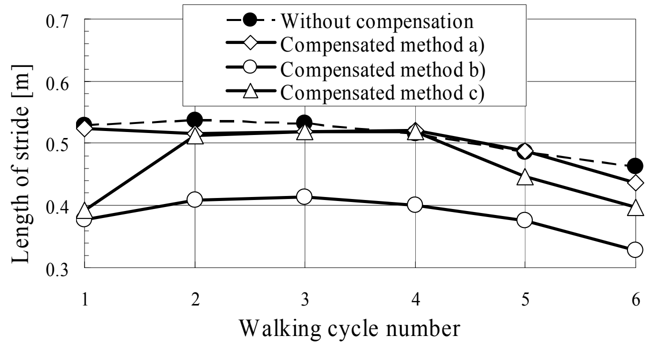


(b) Variation of the walking cycle

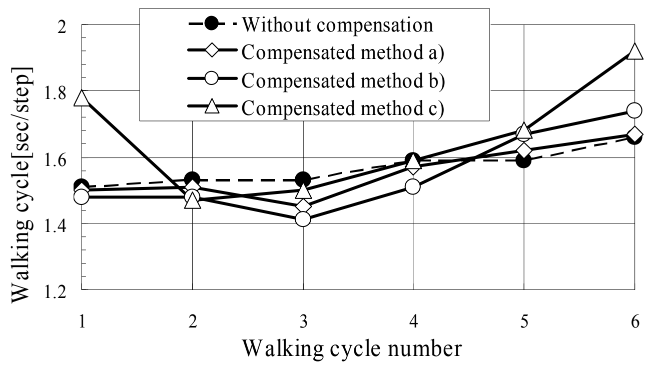


(c) Variation of the walking velocity

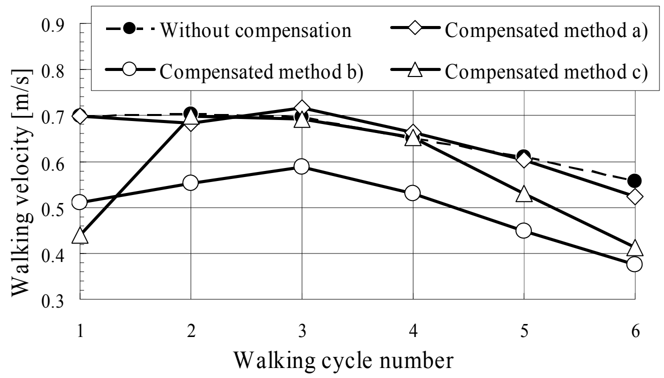
Fig. 11 Comparison of measured data under the condition of each compensated method (Subject A)



(a) Variation of the length of stride



(b) Variation of the walking cycle



(c) Variation of the walking velocity

Fig. 12 Comparison of measured data under the condition of each compensated method (Subject B)

the EMG sensor was 34 [mm]; the signal amplified by 1000 times was converted from analog to digital signal whose sampling time was 1 [kHz], sent the signal by wireless, and recorded with a PC. IEMG (integrated EMG) at intervals of 0.1 [sec] was calculated from the EMG data, and the maximum values of IEMG in each steps were averaged, and the averaged value was compared with MVC (maximum voluntary contraction), therefore the %MVC (percentage of MVC) of each condition was derived as shown in Fig. 13.

In the case of this subject, it should be said the crural muscles (TA and GMH) are used more actively than femur muscles (RF and BFL), and the muscle activity can be decreased by using the weight bearing lift from the results in Fig. 13. The activity of BFL was especially decreased by using both arms of the weight bearing lift. By using the Arm B, the floor reaction force arise from equipped person's weight was decreased, he did not have to kick the ground so strongly, the activity of BFL was also decreased. Therefore, the weight bearing lift can be utilized to adjust the equipped person's load for training. However, the behavior of kicking the ground is important for walking rehabilitation, the setting of the bearing force for the equipped person adequately is important. Hence, we will augment the number of subjects and confirm the relation between bearing force and the activity of the BFL, the

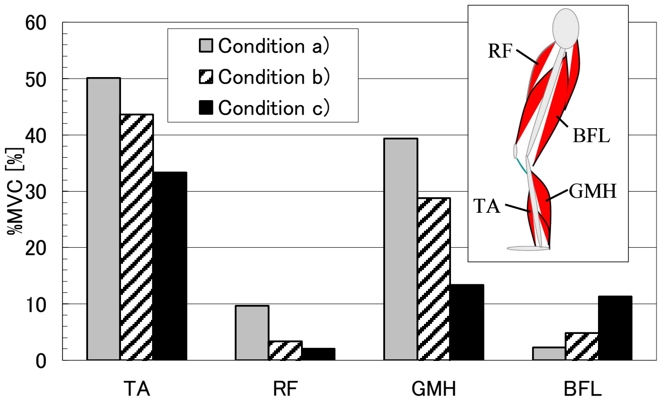


Fig. 13 Comparison of the %MVC data of each condition

apparatus will be able to use effectively in the clinical experiment for motor palsy patients.

VI. CONCLUTIONS

We developed a new walking assistance apparatus for the elderly or motor palsy patients, as a next-generation vehicle or movable neuro-rehabilitation device. In order to adapt the variation of walking velocity the concept of walking ratio was adopted for control the apparatus. For patients who cannot walk themselves, the weight bearing lift which can adjust bearing both the apparatus and equipped person. It can be shown the validity of the weight bearing lift from the results of measured %MVC.

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