Paper:

Development of a Rehabilitation and Training Device Considering the Ankle Degree of Freedom

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While the number of people who need rehabilitation has been increasing because of the aging population, there are only a limited number of physical therapists engaged in rehabilitation, making it difficult to perform rehabilitation at a sufficient level. In this situation, various devices have been developed to replace physical therapists. However, no rehabilitation devices that can respond to the complicated degrees of freedom of an ankle joint complex (AJC) are commercially available. In the present study, we developed an AJC rehabilitation device using a Stewart platform parallel link mechanism. Using the device, we aim to measure and control the AJC with six degrees of freedom so that complicated composite motions of the AJC can be realized. To evaluate the device's usefulness, we investigated how the composite motion generated by moving the AJC along the trajectory the device reproduced could influence a crural muscle. Muscular activities of the anterior tibial, soleus, and gastrocnemius muscles, generated by a composite motion of plantar flexion and inversion, had a similar feature to those generated by plantar flexion. However, the muscular activity of the peroneus longus muscle generated in the composite motion was significantly different from that generated only in plantar flexion. In the composite motion of plantar flexion and inversion, based on the knowledge that activity to develop only back muscles while suppressing muscular activities of the anterior tibial and peroneus longus muscles is possible. Based on the knowledge, the device was used to perform isokinetic contraction for evaluating the device's usefulness for muscular training. We found a difference between the combination of active muscles during the composite motion and that during plantar flexion. A load can be applied to different muscles depending on the composite motion, which indicates that the device can be suitable for rehabilitation or training with high degrees of freedom.

Keywords: parallel link mechanisms, rehabilitation, training, EMG

1. Introduction

Sprains of the ankle joint complex (AJC) frequently occur in our daily lives, and recovery from them often requires rehabilitation. A sequela of apoplexy is hemiparesis, and its treatment requires recovery of athletic ability. However, compared to the number of patients who needs rehabilitation, the number of physical therapists who can assist with rehabilitation is low, which motivates the development of devices that can be used to replace physical therapists.

Among the various ranges of motion of the AJC, the dorsi and plantar range of motion are determined by the state of the talocrural joint, which is one of the joints that is most likely to be restricted, and affects our daily lives even if it is only slightly restricted. Therefore the range needs to be measured with high precision. The high-precision evaluation of the range of motion of a joint is essential to find a factor that restricts the joint motion and to establish a method for effective rehabilitation. Goniometers are widely used to measure the range of motion of a joint, but the precision depends on a visual check, and measurement errors conducted by highly skilled physical therapists remain $\pm 4^\circ$ [1].

The use of a rehabilitation device would realize not only the recovery of athletic ability but also the objective and high-precision measurement [2, 3]. Conventional rehabilitation devices include the JACE Ankle A330 CPM system, Optiflex Ankle CPM system, and A3 Ankle CPM, all of which perform rehabilitation around a fixed axis [4]. These devices can perform dorsi and plantar flexion around a fixed axis using a single motor. With some other device, inversion and eversion can be performed by changing the position of the motor. However, generating a composite motion, such as a combination of dorsi flexion and inversion, is impossible by using a single motor. Other rehabilitation devices are also being developed using balloons or artificial muscles, but AJC motion is restricted to the direction of dorsi and plantar flexion [5, 6].

In actual rehabilitation of the AJC at medical facilities, appropriate choices of the load to the AJC based on the condition of a patient and determination of the reaction from the patient are important. Continuous passive mo-

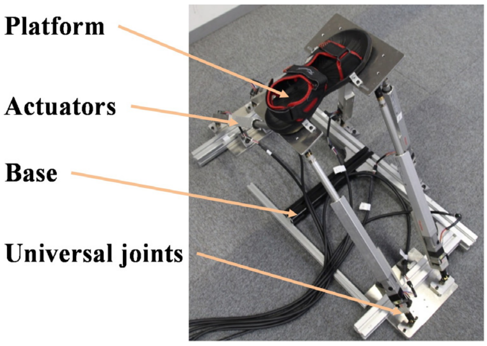

Fig. 1. Overview of the developed device.

tion (CPM) simply repeats motions along a predefined trajectory and cannot adjust rehabilitation by the state of the AJC [7]. One of the rehabilitation devices that consider the active motion of a patient is the Therapeutic Exercise Machine (TEM). However, most TEMs utilize single-axis rotation for the AJC, and the rotation direction of the AJC, as well as CPM, is limited.

In this study, we employed a Stewart platform parallel link mechanism with six actuators and developed the device that allowed control and measurement with six degrees of freedom, without limiting composite motions of the AJC. We designed the configuration of the cylinder based on the range of motion of the AJC. The device could realize a combinatory motion of dorsi and plantar flexion motion and inversion and eversion motion, that could not be realized using conventional devices. The cylinder output could be modified by controlling the force applied to each cylinder. Therefore, the load to the AJC could be modified based on the condition of the patient and the AJC can be controlled based on motions of joints and muscles.

In this study, using the developed device, we evaluated the influence of a composite motion of the AJC on the crural muscle based on surface myoelectricity. Isokinetic contraction was implemented using the device proposed to evaluate the effectiveness of muscle training including the composite motion.

2. Device Development

Figure 1 shows the device developed in this study (from now on referred to as the device). A Stewart platform consisting of a platform and a base, which are connected to each other by six actuators, was employed for the device. Because this structure allows motions with six degrees of freedom, including pitching, rolling, and yawing about x-, y-, and z-axes, and motions where these motions are combined, the device can respond to a range of motion of the AJC [8–10].

With a patient's leg placed on the movable link of the Stewart link, the device controls the length of a straight-moving actuator to move the AJC. We have the following three requirements to set the device.

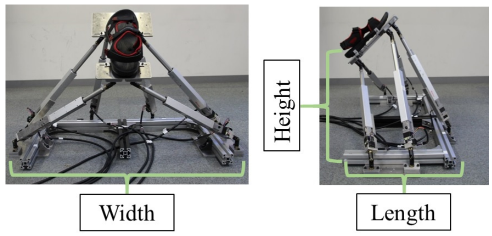

Fig. 2. Size definitions of the device.

Table 1. Device specifications.

Weight	14.8 kg
Dimension	
Length	450 mm
Width	900 mm
Height	350–450 mm
Actuator	
Maximum speed	150 mm/s
Thrust	50 N
Stroke	150 mm
Repeated positioning accuracy	±0.02 mm
Force measurement accuracy	±5 N

1. The device can be used in small areas, such as a hospital room.
2. A patient can use the device in a dorsal position.
3. The device meets the AJC's range of motion.

To meet the above three conditions, we employed electric cylinders for the actuators that did not require a compressor or hydraulic pump. The actuators used for the device were model EAC2F15AZAK (Oriental Motor). The stroke was 150 mm, and the position, speed, acceleration, and ratio of the force from the actuator can be measured and adjusted. The portable weight in the horizontal direction was 15 kg. Because the electric cylinder consists of a stepping motor and ball screws, high-level control of positioning can be achieved.

To meet conditions 1 and 2, the device was designed so that the width was $<$ 1000 mm, the length was $<$ 500 mm, and the height was about 400 mm (**Fig. 2**). Only the height is changeable. The dimensions were determined according to doctors' opinions, sizes of hospital rooms and beds, the number of hospital beds, and the distance between beds. The total weight and size of the device are given in **Table 1**.

We calculated the configuration of the cylinder to meet condition 3 and examined it through simulations. The AJC's reference range of motion specified by the Japanese Orthopaedic Association Corporation was employed for the range of motion of the device.

Modbus was used to control the device. The communication system of Modbus is of a single master- or multi-slave type with the computer being the master and the

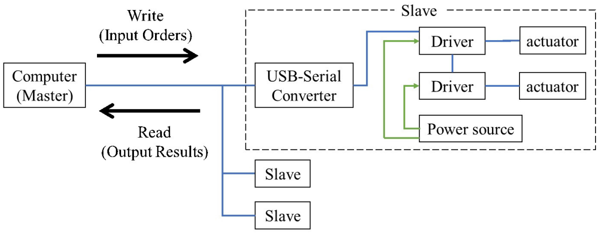

Fig. 3. System diagram of the device.

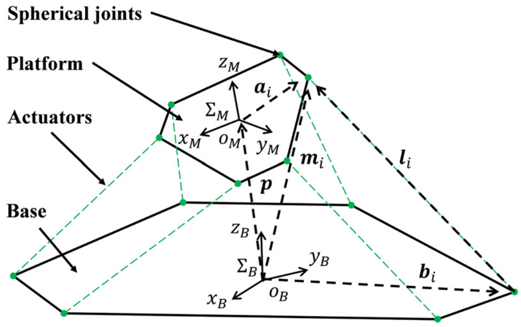

Fig. 4. Geometrical model of the device.

driver being the slave. The baud rate was 115,200 bps. For high-speed communication, we used three converters and connected two drivers to each converter. The system configuration is shown in **Fig. 3**. The driver that we used was AZD-KD (Oriental Motor), and the converter was Uport1130 (MOXA). The power supply of the device was HWS300-24 (TDK).

3. Device Control

3.1. Calculation of Actuator Length by Inverse Kinematics

Calculation of the forward kinematics for the Stewart platform of the straight-moving actuator type is not easy. Therefore, we used inverse kinematics to control the device. The actuator length was calculated for each posture of the Stewart platform in the following manner. **Fig. 4** shows a geometric model of the Stewart platform used in the study. Σ_B and Σ_M in **Fig. 4** are orthogonal coordinate systems of the base and the platform, respectively. Vectors connecting the fixed link and the actuators in Σ_B are $\boldsymbol{B} = [\boldsymbol{b}_1 \quad \cdots \quad \boldsymbol{b}_6]$ with $\boldsymbol{B} \in \boldsymbol{R}^{3\times 6}$, vectors connecting the movable link and the actuators in Σ_M are $\boldsymbol{a} = [\boldsymbol{a}_1 \quad \cdots \quad \boldsymbol{a}_6]$ with $\boldsymbol{a} \in \boldsymbol{R}^{3\times 6}$, and the actuator length is l_i. Also, the position of the origin o_M of Σ_M when viewed from the origin o_B of Σ_B is $\boldsymbol{p} = [x\ y\ z]^T$ and the rotation angles about the x-, y-, and z-axes are $\boldsymbol{s} = [\theta\ \phi\ \psi]^T$, respectively. Then, the generalized posture of the movable link can be defined as $\boldsymbol{P} = [\boldsymbol{p} \quad \boldsymbol{s}]^T$ with $\boldsymbol{P} \in \boldsymbol{R}^{6\times 1}$, and the following relation is satisfied:

$$\Sigma_B = \boldsymbol{p} + \boldsymbol{R}\Sigma_M. \qquad (1)$$

Here, $\boldsymbol{R}$ is a rotation matrix that affects the rotational transformation of the orthogonal coordinate system of the fixed link to that of the movable link. Eq. (2) shows that the vector $\boldsymbol{m}_i$ connecting the movable link to the actuator viewed from the origin o_B can be obtained from

$$\boldsymbol{m}_i = \boldsymbol{p} + \boldsymbol{R}\boldsymbol{a}_i, \quad i = 1,\ldots,6. \qquad (2)$$

Equation (3) calculates the actuator length l_i from

$$l_i = \|\boldsymbol{p} + \boldsymbol{R}\boldsymbol{a}_i - \boldsymbol{b}_i\|, \quad i = 1,\ldots,6. \qquad (3)$$

As shown above, the lengths of the six actuators of the device can be calculated by the inverse kinematics if the posture of the movable link is known. From the above calculation, we set the posture as the input and the cylinder length as the output. With this calculation, we can reproduce the defined posture repeatedly.

3.2. Calculation of Position and Posture by Updating the Jacobian Matrix

The posture was calculated by updating the Jacobian matrix [11]. In the experiment, the position and posture of the platform were regarded as that of the AJC. The platform's position and posture $\boldsymbol{P}$ and the length of each actuator $\boldsymbol{L}$ satisfy a relation expressed by

$$\dot{\boldsymbol{P}} = \boldsymbol{J}^{-1}\dot{\boldsymbol{L}}. \qquad (4)$$

Here, the Jacobian matrix $\boldsymbol{J}$ of the device can be calculated using Eq. (5):

$$\boldsymbol{J} = \begin{bmatrix} \boldsymbol{d}_1^T, (\boldsymbol{b}_1 \times \boldsymbol{d}_1)^T \\ \boldsymbol{d}_2^T, (\boldsymbol{b}_2 \times \boldsymbol{d}_2)^T \\ \boldsymbol{d}_3^T, (\boldsymbol{b}_3 \times \boldsymbol{d}_3)^T \\ \boldsymbol{d}_4^T, (\boldsymbol{b}_4 \times \boldsymbol{d}_4)^T \\ \boldsymbol{d}_5^T, (\boldsymbol{b}_5 \times \boldsymbol{d}_5)^T \\ \boldsymbol{d}_6^T, (\boldsymbol{b}_6 \times \boldsymbol{d}_6)^T \end{bmatrix} \qquad (5)$$

The directional vector of each actuator $\boldsymbol{d}_i \in \boldsymbol{R}^{3\times 1}$ is as expressed by

$$\boldsymbol{d}_n = \frac{\boldsymbol{b}_n - \boldsymbol{a}_n}{\|\boldsymbol{b}_n - \boldsymbol{a}_n\|}, \quad n = 1,\ldots,6. \qquad (6)$$

By updating the actuator length L_n from the n-th search to the $(n+1)$-th search, the length is made closer to the value measured with the actuator, and then the position and posture $\boldsymbol{P}_{n+1}$ are calculated using

$$\boldsymbol{P}_{n+1} = \boldsymbol{P}_n + \boldsymbol{J}_n(L - L_n). \qquad (7)$$

The actuator length L_{n+1} is calculated again from the equation using the position, and posture $\boldsymbol{P}_{n+1}$ is obtained to decrease the difference of the position and posture to the measured length L with the updated Jacobian matrix $\boldsymbol{J}$. The actuator length can be measured when the magnetic excitation turns off. Because magnetic excitation is turned off, the movable plate can be moved manually, and the trajectory of the manual movement of the movable plate can be obtained inside of the area that the Jacobian matrix can

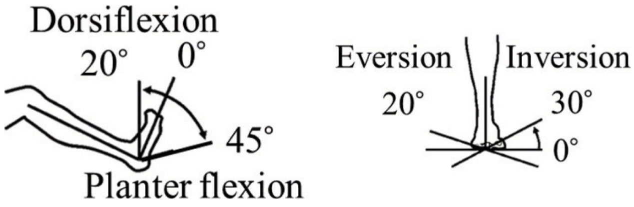

Fig. 5. Ankle motion.

be calculated. A motion matching the motion of the subject's ankle can be obtained by moving the device along the obtained trajectory.

4. Experiment to Measure Activity of the Crural Muscle

4.1. Overview of the Experiment

Five subjects (young, healthy males of 24.4 ± 1.5 in age) participated in the experiment. None had experienced damage to their lower legs in the past or sprains of the AJC in the past six months. The experiment was conducted for three types of AJC motions (plantar flexion with $-35°$, inversion with 30°, and inversion and plantar flexion with 20° and $-35°$, respectively) to evaluate the active muscles of the tibialis anterior (TA), peroneus longus (PL), soleus (SOL), medial gastrocnemius (MG), and lateral gastrocnemius (LG) by using electromyography (EMG). Dorsi and plantar flexion motions and inversion and eversion motions are shown in **Fig. 5**. Generally, the range of motion of the AJC is larger than that in the present experiment. However, because the range of motion of the subject's AJC differed from subject to subject, the range of motion in the experiment was unified to the smallest one. **Fig. 6** shows the position and posture of the device when it is working. The position and posture of the device were measured with a motion capture system. The trajectories of the position and posture measured with the system are shown in **Fig. 6**. The motion capture system that we used was OptiTrack (Acuity). OptiTrack is an optical-type motion capture system consisting of a camera with an infrared LED and three-dimensional tracking software. Three or more markers were put on the object to be measured, and the software constructed a rigid body by connecting the markers with each other by straight lines. Then, the motion of the object was recorded to acquire tracking data for the six degrees of freedom of the rigid body. The position and posture of the device were measured with four markers pasted on the movable link at the positions shown in **Fig. 6**. For the measurement, we used 11 cameras for 30 s with the frame rate of 250 frames/s. In the figure, we see that the motions from the reference posture to each target posture could be reproduced repeatedly. The pitch, roll, and yaw in the figure do not change depending on the subjects, but translation in the x, y, or z direction is subject dependent. The reason is that the rotation center of the device was changed for different subjects. In the experiment, the subject's malleolus direction was considered as the x-axis, the toe direction was the y-axis, and the tibia direction was the z-axis. The crossing point of an extended line of the z-axis and the platform of the device were chosen as the origin of the x-y plane. The rotation center was considered to be a point that was moved in parallel along the z-axis from the origin to the height of the ankle.

We measured the active muscles of TA, PL, SOL, MG, and LG during motions of the subjects [12, 13]. **Table 2** lists the muscles that become active under dorsi flexion, plantar flexion, inversion, or eversion [14]. The electromyograph that we used was a TRIGNO EMG System (Delsys). The bandwidth was 20–450 Hz, and the sampling rate was 2000 Hz. To determine the electrode position, we referred to the position recommended by the SENIAM project [a]. The electromyograph pasting positions recommended by the SENIAM project and the positions where the electromyographs were pasted are shown in **Figs. 7** and **8**, respectively [13]. The central figure in **Fig. 8** shows that the gastrocnemius muscle is removed from the left figure. Because muscle positions change between subjects, each muscle position was inspected by hand to paste the electromyographs to the subjects. Before the experiment, the subjects were asked to move each muscle to check the presence of the muscle potential.

Myoelectricity sensor for each crural muscle was placed at the following locations.

- TA: $1/3$ on the line from the head of the fibula to the medial malleolus.
- PL: $1/4$ on the line from the head of the fibula to the lateral malleolus.
- SOL: $2/3$ on the line from the medial condyles of the femur to the medial malleolus.
- MG: Most protruding point.
- LG: $1/3$ on the line from the head of the fibula to the ankle.

Maximal voluntary contraction (MVC) was measured to standardize muscle activities obtained from the experiment. MVC measurement on each muscle was performed in the following way [14, 15].

- TA: The subjects perform dorsi flexion of the AJC, and the measurer applies an external force to the plantar flexion direction.
- PL: The subjects perform eversion of the AJC, and the measurer applies an external force to the inversion direction.
- SOL: The subjects stand on tiptoes while sitting on a chair, and the measurer pushes and applies a force to their knees toward the lower legs.
- MG: The subjects stand on tiptoes, and the measurer pushes and applies a force to their shoulders toward the ground.

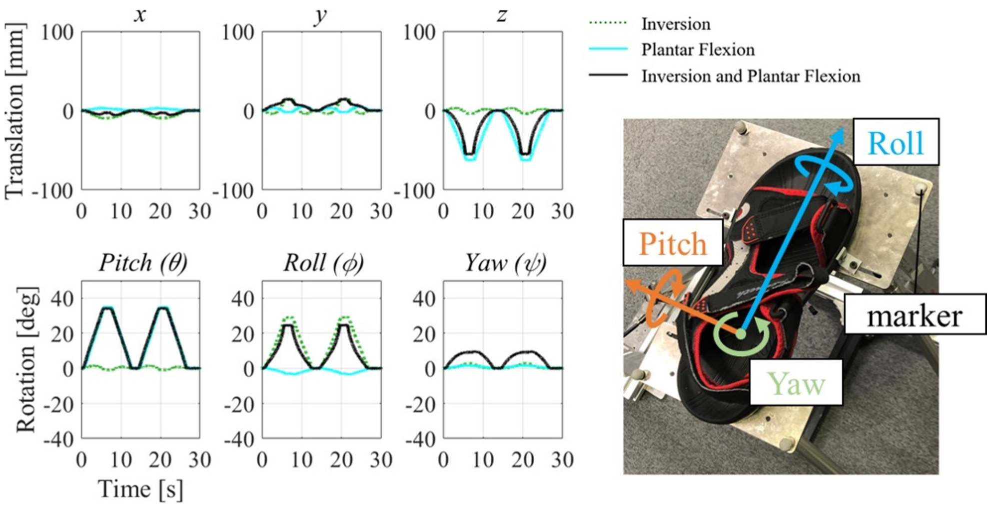

Fig. 6. Position and posture of the device during ankle motion of the device.

Table 2. Correspondence table of ankle motion and active lower leg muscle [14].

	Plantar flexion	Dorsiflexion	Inversion	Eversion
Tibialis anterior (TA)		○	○	
Peroneus longus (PL)	○			○
Medial gastrocnemius (MG)	○		○	
Lateral gastrocnemius (LG)	○		○	
Soleus (SOL)	○		○	

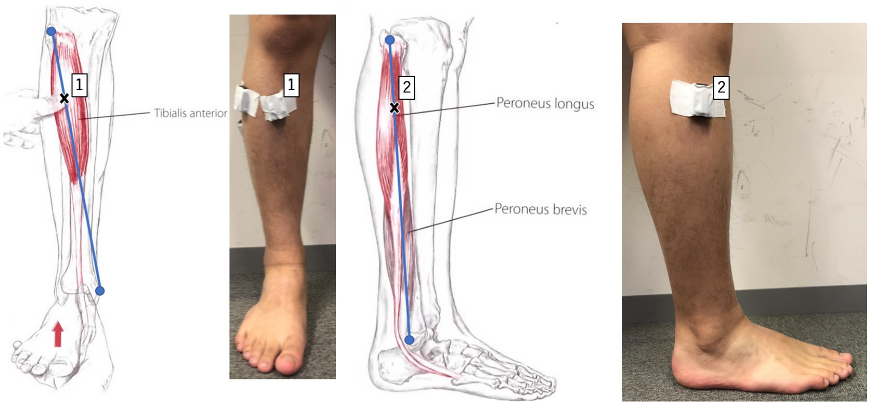

Fig. 7. Electromyographic location of the TA and PL [13].

LG: The subjects perform plantar flexion of the AJC, focusing on lifting up their heels rather than lowering their toes. The measurer applies a force to make the subjects lift up their toes and lower their heels.

The position at which the electromyography was placed was adjusted until the muscle activity could be measured with the action. If MVC could not be measured with the above method, the action with which the MCV was measured was changed by referring to **Table 2**.

The subjects placed their left legs on the device and changed their postures from a reference posture to the target posture. This change of posture was conducted in the experiments twice. The reference posture is the state where the leg is rotated by 45° to the x-axis. A movable plate that worked as CPM was used for the device to guide the subjects. The subjects were asked to press the plate by 30% of their full force and move their legs actively. The knee position was fixed at 90°.

The knees were loosely fixed, and therefore the subjects could react by moving their thighs or lower legs to a certain extent even when the device functioned erroneously. In addition, the subjects had a switch to stop the device so that they could stop it by pressing the switch when a malfunction occurred.

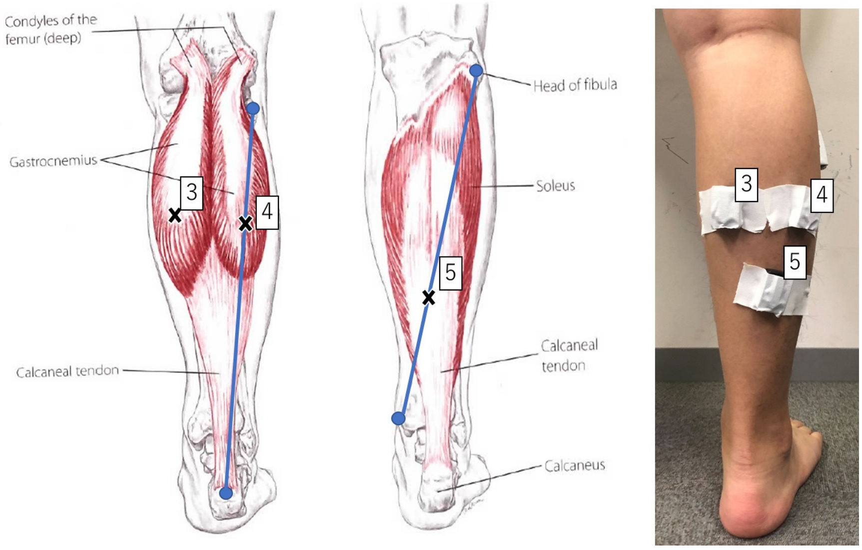

Fig. 8. Electromyographic location of the MG, LG, and SOL [13].

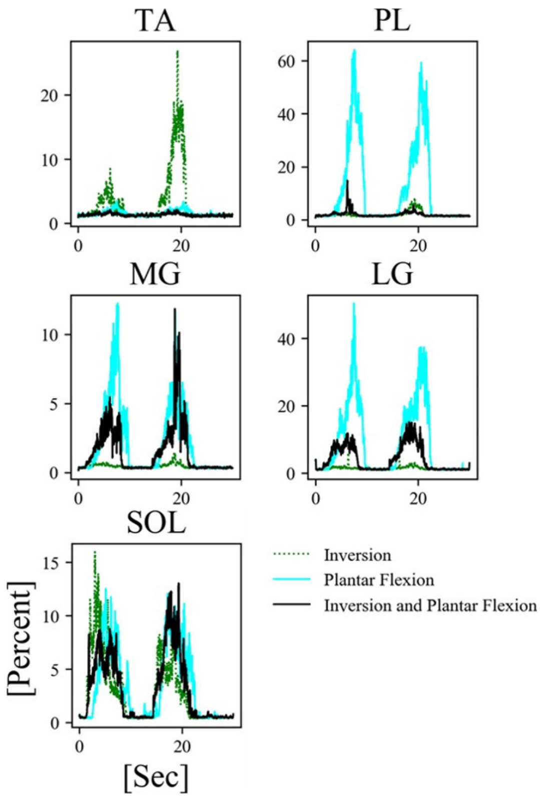

Fig. 9. Normalized EMG and position of EMG.

The muscle action potentials of the five subjects were measured and normalized. We used the 100% MVC method as the normalization. The normalized muscle action potentials are shown in **Fig. 9**, and the average maximum muscle action potentials are shown in **Fig. 10**. The horizontal axis of the graphs presents the muscles measured. The vertical axis presents each ratio with the muscle action potential for the maximum muscle power being set to 100%. A t-test was used for testing the data.

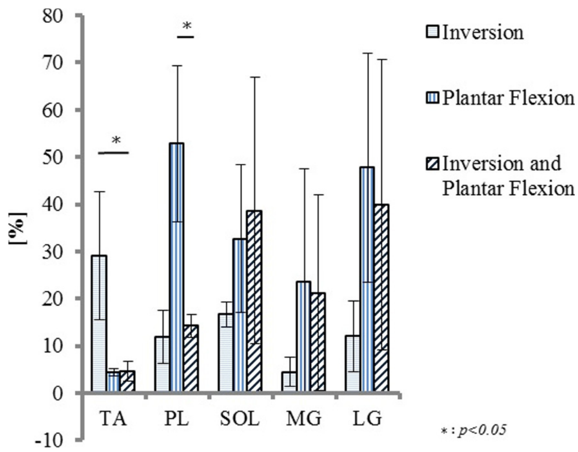

Fig. 10. Average of the normalized myoelectric maxima.

4.2. Results of the Crural Muscle Activity Measurement

For the TA, the average of maximum muscle action potentials were 29.2% with "inversion" and 4.7% with "plantar flexion and inversion," indicating that the average with "inversion" is significantly large ($t = 3.10$, $df = 6$, and $p = 0.021$). There was no significant difference between "plantar flexion and inversion" and "plantar flexion" ($p = 0.811$). For the PL, the average maximum muscle action potentials were 52.8% with "plantar flexion" and 14.3% with "plantar flexion and inversion," indicating that the average with "plantar flexion" is significantly large ($t = 4.01$, $df = 6$, and $p = 0.007$). There was no significant difference between "plantar flexion and inversion" and "inversion" ($p = 0.526$). For SOL, MG, and LG muscles, there was no significant difference between the composite motion of "plantar flexion and inversion" and the single motion of "plantar flexion" ($p = 0.760$, $p = 0.900$, and $p = 0.740$). Further, there was no significant difference between the composite motion and the single motion of “inversion” ($p = 0.226$, $p = 0.217$, and $p = 0.178$).

4.3. Discussion of the Crural Muscle Activity Measurement

In the composite motion of plantar flexion and inversion, the activity of triceps surae muscles (inner gastrocnemius muscle, outer gastrocnemius muscle, and soleus muscle) had the same tendency as that in the activity of plantar flexion or inversion. The reason is that triceps surae muscles also work in the plantar flexion motion and the inversion motion. Moreover, in the composite motion, the PL muscle in the plantar flexion and the TA muscle in the inversion work little. From the result in the composite motion, we found that the composite motion of plantar flexion and inversion can suppress the activity of the TA muscle and the PL muscle and activate the muscles at the backside only. This result indicates that the muscles activated by the single motion and those by the composite motion are different from each other. If a person who has damage in a portion of the front muscles of the lower legs and cannot use the ankle CPM, the proposed device can be used for the rehabilitation of back-side muscles of the lower legs, such as the gastrocnemius and soleus muscles. The training to develop one specific muscle is available by moving their legs actively during the composite motion [16]. The proposed device can realize not only active motion but also passive motion without reducing the degrees of freedom of the AJC.

5. Training by Contraction Exercise

5.1. Muscle Contraction Type and Problems

The range of joint motion can be expanded by CPM, but muscles cannot be developed by transitive motion. However, to move a joint, muscles to move the joint by contraction need to be developed. Therefore, muscle contraction is essential for exercise therapy. Muscle contraction motion includes isometric contraction, isotonic contraction, and isokinetic contraction.

Isometric contraction is a motion to contract the muscle without moving a joint. An advantage of isometric contraction is that it can apply a maximum load. However, because it does not move a joint, a muscle pump effect is not easily realized, and the blood stream is obstructed [17]. Moreover, the effect on muscle power to move a joint is small.

Isotonic contraction is a motion that moves a joint and applies a certain amount of resistance as a load to contract the muscle. Because the training is dynamic, its speed can be adjusted, and the blood stream is less obstructed. Also, training of both shrinking and extending motions can be achieved. However, training with maximum load cannot be achieved because the training is performed with a load that the users can handle. Further, the load quickly changes from inertia if the speed is increased. Furthermore, the load can change if the joint angle changes [18].

Isokinetic contraction is a motion that solves the problems of both isometric and isotonic motions and can offer resistance in accordance with the muscle power generated to all areas with a constant-speed rotation motion. Because the training is dynamic, the blood stream is not obstructed, and resistance suitable to muscle power that changes during joint motion can be generated. Therefore, efficient training for the entire range of motion can be achieved.

To conduct an isokinetic motion, a device that can work at a constant speed is necessary. One of the devices used to perform isokinetic contraction is the Biodex dynamometer system [19]. This system can perform isokinetic, isometric, isotonic, and passive motions. However, for the AJC, it works only in the direction of dorsi and plantar flexion and does not work for inversion, eversion, or composite motion. In addition, users need to sit on chairs, which can be a safety problem. Moreover, the device weighs 360 kg and is difficult to carry. Therefore, the proposed device that isokinetic contraction can work with the present device can solve for the disadvantage of conventional devices.

5.2. Isokinetic Contraction with the Device

In Section 4, the proposed device guided the subjects to make a motion along the trajectory that the device made at a constant speed. Because we could confirm that the crural muscle worked even when using the device in this way, the device would be effective for training. However, if the leg movement is slower than the speed of the device’s guidance, the device only makes a passive motion, and no training effect is obtained. Moreover, because the leg needs to be moved according to the speed of the device, users require to get off the proposed device. Therefore, we require a control under which the device works only when the users exert a force and stop otherwise. A view of a subject who undergoes isokinetic contraction with the device is shown in **Fig. 11**. For isokinetic contraction, the device changes the posture from the reference posture to the target posture, returns to the reference posture, and then changes the posture again from the reference posture to the target posture. When the device first returns to the reference posture, calibration is performed, and isokinetic contraction is achieved when the second change of the posture from the reference posture to the target posture is made.

When the subjects first change their postures to the target posture, the device measures the moment M_{motion1} [N·m] necessary for the device to rotate their AJC with no force applied by the subjects. When they change the postures back to the reference posture, the device is stopped every time it rotates by a certain angle and measures the moment M_{stop1} [N·m] necessary for the device to support their AJC with no force applied by the subjects.

In the second change of the postures of the subjects to the target posture, isokinetic contraction is performed.

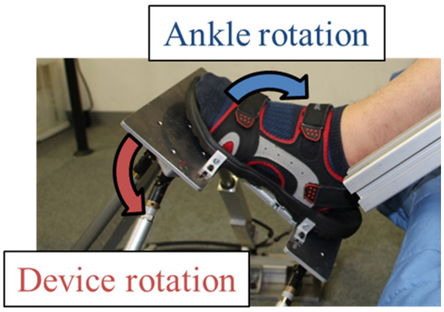

Fig. 11. Isokinetic experimental setup.

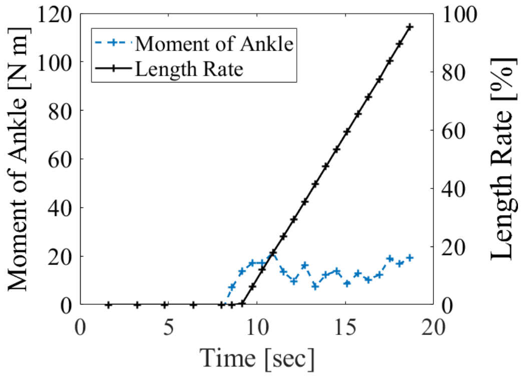

Fig. 12. Moment of the ankle and length rate of the cylinder.

The speed was set to take 8 s for the posture to change from the reference posture to the target posture. During this motion, the subjects rotate their legs in the opposite direction to the device's movement. In **Fig. 11**, the device rotates in the direction of plantar flexion while the subject rotates his leg in the direction of dorsi flexion.

For isokinetic contraction, an arbitrary threshold value α needs to be set in advance. During the isokinetic contraction, the device measures the moment M_{motion2} [N·m] necessary for the device to rotate the AJC with force applied by the subject, and the device works if the following equation is satisfied:

$$M_{\text{motion2}} - M_{\text{motion1}} > \alpha. \quad (8)$$

The device stops when Eq. (8) is not satisfied. Then, with the subject exerting the force, the device measures a moment M_{stop2} [N·m] that is needed to support the AJC of the subject. The device restarts when the following equation is satisfied:

$$M_{\text{stop2}} - M_{\text{stop1}} > \alpha. \quad (9)$$

Figure 12 shows the moment during isokinetic contraction. The left y-axis shows the moment applied by the legs. The right y-axis shows the length rate of the cylinder with the cylinder length in the reference posture being set to 0% and the length in the target posture set to 100%. **Fig. 12** also shows that the length rate increases linearly with a constant gradient, indicating a constant speed increase. Because the variation of the load due to the change

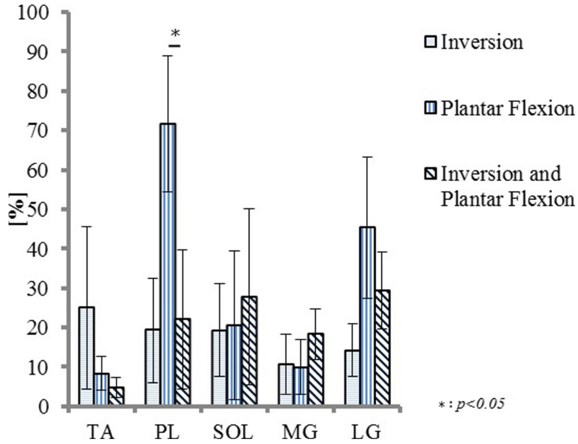

Fig. 13. Average of the normalized myoelectric maxima.

of the joint angle is small, the moment applied from the leg is almost constant. Therefore, the ankle motion can be performed under the same force irrespective of the joint angle. If the device is used for training, it is necessary to control the force that the device exerts by using a load from the leg. Since the aim of the proposed device was to evaluate how the composite motion with the subject exerting a force of a specific force affected the crural muscle, we employed a control method in which the subjects could exert a force of the same magnitude irrespective of the joint angle.

5.3. Experiment on Isokinetic Contraction

Three subjects (young, healthy males of 24.3 ± 0.58 in age) participated in the experiment. None had experienced damage to their lower legs in the past or sprains of the AJC in the past six months. The experiment was conducted with isokinetic contraction for three types of AJC motions (plantar flexion with $-35°$, inversion with $30°$, and inversion and plantar flexion with $20°$ and $-35°$, respectively) to evaluate active muscles of TA, PL, SOL, MG, and LG by using surface myoelectricity. The device stops when the force from a subject in isokinetic contraction motion is small. The experiment is regarded as a failure when the device stops. In this case, the threshold value was lowered, and the trials were repeated until the target posture was achieved without termination of the device. After the measurement, the data were normalized using the 100%MVC method as done in Section 4, and an average of the maximum values of the muscle action potentials was obtained. The results are shown in **Fig. 13**. A t-test was used for testing the data.

5.4. Results of Isokinetic Contraction

For the TA, the average maximum muscle action potentials were 25.0% with "inversion" and 4.8% with "plantar flexion and inversion," indicating no significant difference ($p = 0.242$). There was also no significant difference between the composite motion and "plantar flexion" ($p = 0.376$). For the PL, the average maximum muscle action potentials were 71.6% with "plantar flexion" and 22% with "plantar flexion and inversion," indicating that the average is significantly large with "plantar flexion" ($t = 2.85$, $df = 4$, and $p = 0.046$). There was no significant difference between the composite motion and "inversion" ($p = 0.578$). For SOL, MG, and LG muscles, there was no significant difference between the composite motion of "plantar flexion and inversion" and the single motion of "plantar flexion" ($p = 0.664$, $p = 0.333$, and $p = 0.144$). There was also no significant difference between the composite motion and the single motion of "inversion" ($p = 0.750$, $p = 0.281$, and $p = 0.332$).

5.5. Discussion of Isokinetic Contraction

As in Section 4, in the composite motion of plantar flexion and inversion, the activity of the triceps surae muscle (MG, LG, and SOL muscles) had the same tendency as that of plantar flexion or inversion. In the composite motion, the activity of the PL muscle that worked in the plantar flexion motion was suppressed. The muscle activity of each motion was similar to the one obtained in Section 4. This result indicates that using muscle contraction by the composite motion of "plantar flexion and inversion," special training is available that cannot be reproduced with the single motion of "plantar flexion" or "inversion." Therefore, the use of the composite motion in training with isokinetic contraction is effective for high degrees of freedom training.

6. Conclusion

In this study, we developed a device for rehabilitation that can control the AJC with six degrees of freedom, and we examined motions with no restriction on the AJC's degrees of freedom and applicability of the device to training. The examination showed that the device could achieve not only motions such as dorsi and plantar flexions or inversion and eversion motions but also composite motions combining them and that the single and composite motions were different in the combination of active muscles. Furthermore, the result of a surface myoelectricity showed that the device was useful not only for rehabilitation but also for training based on isokinetic contraction. The knowledge elucidated and the device obtained from this study would be applicable to future exercise therapy.

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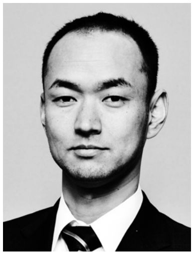

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