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Ankle Stretching Rehabilitation Machine for Equinovarus: Design and Evaluation from Clinical Aspects

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***Abstract*—Three-dimensional stretching is needed to treat equinovarus, which deforms the patient's foot to plantarflexion, adduction, and inversion postures. We have prototyped a three-dimensional stretching machine that the patient can use for the treatment of equinovarus by him- or herself. By adopting a cable-driven mechanism with two independently controllable pneumatic actuators, the stretching machine can apply a force to the foot along the dorsiflexion direction as well as the direction combining abduction and eversion. In this study, we verified the effectiveness of a prototype stretching machine for healthy subjects. For evaluation, the muscle stiffness and maximum voluntary contraction (MVC) of plantarflexion were compared immediately before and after stretching and 10 min later. As a result, the MVC decreased after stretching, which is a clinical index for effective stretching.**

I. INTRODUCTION

Spastic paralysis after a stroke causes an increase in muscle tone. As a treatment for hypertonia, stretching is performed very often. In some previous studies, static stretching of foot improved the joint range and walking speed for stroke patients [1], [2], [3]. Stretching is major treatment in rehabilitation, and its effectiveness has also been shown for healthy subjects [4], [5], [6], [7].

The part targeted for stretching for spastic paralysis after a stroke is often the foot. This is because the foot deformation called equinovarus tends to occur easily by increasing the muscle tone of the lower limb. The gastrocnemius, soleus, posterior tibial muscle, flexor pollicis longus muscle, and flexor digitorum longus muscle become involved in equinovarus [8]. The gastrocnemius and soleus run parallel to axis of lower leg, whereas the posterior tibial muscle, flexor pollicis longus muscle, and flexor digitorum longus muscle run around the foot in a spiral; thus, equinovarus deforms the foot three-dimensionally.

Clinical stretching of equinovarus is often carried out by a physical therapist manually. The therapist stretches the muscle by applying the appropriate force while feeling the neurological and biomechanical response of the muscle during stretching. At the same time, while confirming the reaction of the subject, the magnitude of the applied force is adjusted to avoid causing pain. Furthermore, most therapists stretch the stroke patient's foot in a three-dimensional direction [9] In clinical practice, complicated controlled stretching is performed on equinovarus.

The above-mentioned prior studies [1], [2], [3] regarding stretching for after-stroke patients showed the results of continuous stretching on a daily basis. It has been reported that more than 40% of spastic paralyzed patients have spasticity after 3 months or more after the onset of a stroke [10]; therefore, stretching of the spasticity muscle should continue at home even after discharge. In practice, however, it is difficult for physical therapists to perform stretching closely in places other than hospitals. For this reason, a rehabilitation robot for the foot aimed at the automation of rehabilitation is beginning to be proposed. Saga et al. [11] proposed a foot rehabilitation device using a pneumatic actuator that is lightweight and capable of a large output. Waldman et al. [3], [12] developed a compact foot stretching device and showed the effect of stretching on stroke patients. However, these devices had only one motion axis for dorsiflexed and plantarflexed movement.

Equinovarus caused by a stroke deforms the foot three-dimensionally. Stretching for equinovarus is also performed three-dimensionally by physical therapists; thus, the machine that stretches the deformed foot needs to have a three-dimensional control system. Therefore, we have developed a three-dimensional stretching machine for equinovarus. In this paper, we propose a mechanism for the stretching machine and its clinical effects. Note that an automatic control method for this stretching machine is being studied in other research [13].

II. STRETCHING FOR EQUINOVARUS

A. Three-dimensional motion of a foot

As shown in Fig. 1, the upward movement around the axis connecting the inside and outside of the ankle is dorsiflexion, and the downward movement around this axis is plantarflexion. In the motion around the axis perpendicular to the foot sole, the movement to the outside of the toe is abduction, and the movement to the inside of the toe is adduction. Movement that turns the foot sole outward around the anteroposterior axis is

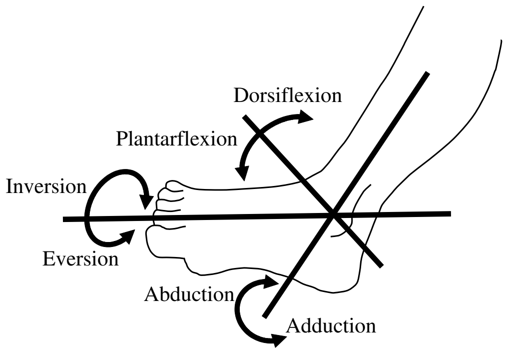

Fig. 1. Three-dimensional foot movement (right foot).

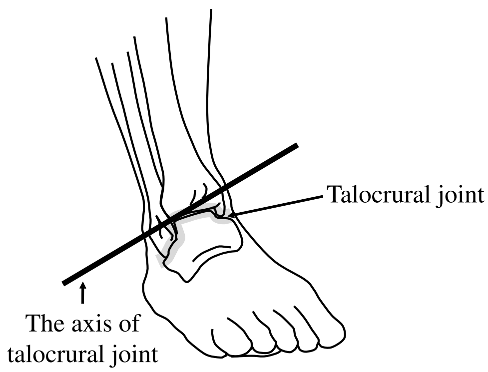

Fig. 2. The axis of the talocrural joint. The line indicates the anatomical axis mainly related to dorsi-/plantarflexion.

eversion, and the inward motion is inversion. Anatomically, the abduction movement is linked with the eversion movement and adduction is linked with inversion [14]. Dorsi-/plantarflexion mainly occurs at the talocrural joint, and ab-/adduction and e-/inversion occur at the subtalar joint. The anatomical axis of the talocrural joint is inclined, heading from the inside to the rear and outward (Fig. 2). Since the outer surface of the talus is slightly larger than the inner surface, as the dorsiflexion occurs, the talus rotates outward while rotating backward. For such anatomical features, the plantar surface rotates to the outside with the dorsiflexion motion; that is, foot abduction and eversion necessarily occur [15].

B. *Manual stretching by therapists*

When physical therapists perform manual stretching, they move the target parts along the directions in which the muscles run to induce appropriate articular movement. Therapists stretch the deformed foot three-dimensionally because the part of the muscle involved in equinovarus is in the spiral, as described above. Focusing on the articulation of the foot with dorsiflexion movement, the talus should rotate out, and the foot should be abducted and everted; thus, therapists correct the adduction and inversion deformation in advance for stretching the equinovarus foot. They perform such complex stretching on the basis of knowledge and experience. In order to perform effective foot stretching, it is also necessary to achieve such complicated control in a stretching machine.

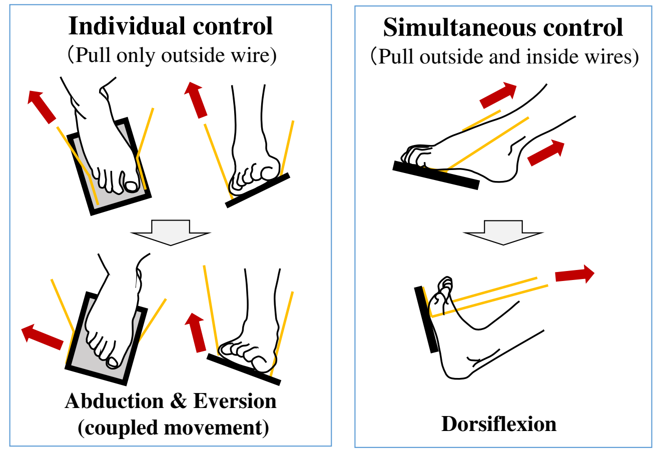

Fig. 3. Mechanism of double-wire control. The left figure shows the individual control of two wires, which are connected along the inside and outside of a footplate. When only the outside wire is pulled, the outside of the foot plate is moved outward and upward; thus, foot abduction and eversion, which are an anatomically coupled movement, occur. The right figure shows the simultaneous control of wires. When the inside and outside wires are simultaneously pulled, the front side of the foot plate is pulled upward; thus, the foot is dorsiflexed.

III. Design of the Stretching Machine

A. *Three-dimensional foot control by two actuated wires*

For foot control to dorsiflex after correcting inversion and adduction, a complicated mechanism is required in order to independently control all three directions. Therefore, in the prototype machine we have developed, we adopted a mechanism that performs three-dimensional control by pulling wires along both sides of a foot plate individually or simultaneously. As shown in Fig. 3, when only the outside wire is pulled, the outer side of the foot plate is moved outward and upward, and the foot is abducted and everted, which are an anatomically coupled movement. When both side wires are pulled at the same time, the upper side of the foot plate is moved upward, and the foot is dorsiflexed. In this way, it is possible to move the foot three-dimensionally by controlling the two wires.

Although an electromagnetic motor having a speed reduction mechanism is often used for the motion control of a rehabilitation machine, a pneumatic actuator was used for the wire control in the prototype machine. The force required to pull the wire is adjusted by changing the air pressure applied to the pneumatic actuator, which is connected to each of the two wires. Since the pneumatic actuator can easily exert a larger force than the motor, it is suitable for a stretching machine requiring a large output for correcting deformed feet.

B. *Safety consideration*

When using a geared motor to control the foot, it is necessary to transmit a force through a rigid part; however, with the use of a pneumatic actuator, it is possible that the design reduces the rigidity of the mechanism. Therefore, this prototype machine can maintain the flexibility of the mechanism and reduce the burden on the foot fixed to the device. For example, an exoskeleton-type mechanism using motors have

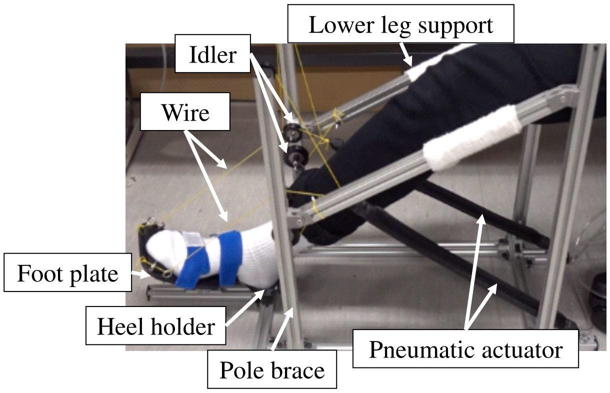

Fig. 4. Structure of the stretching machine.

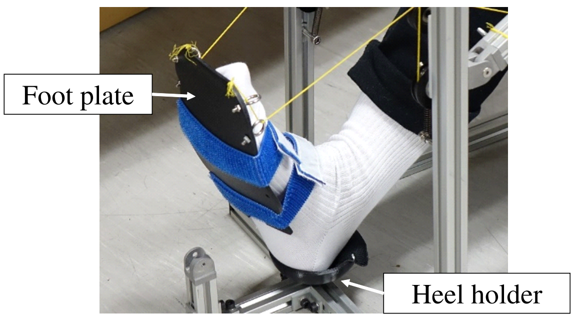

Fig. 5. Foot plate and heel holder.

its own centers of rotation that are separated from those of human joints, but by using a pneumatic actuator and the two-wire driving mechanism, the center of rotation of the human body is utilized effectively. Hence, it is possible to reduce the load on the human foot joints by joint misalignment.

When a large unexpected force occurs owing to a malfunction in the machine or the like, the power supply may be shut off for the purpose of protection or an emergency stop. At this time, if an electromagnetic motor with reduction gears is used, a dangerous posture is retained because of their friction and the risk of injury remains. On the other hand, if a pneumatic actuator is used, by shutting off the power supply and removing the air in the actuator, the load applied to the foot is removed, and a state of safety can be easily achieved. The prototype machine in this study has an emergency stop switch for removing the pressurization of the pneumatic actuator.

The amount of deformation of equinovarus depends on the degree of disability. To adjust for individual differences that cannot be compensated with the two-wire driving mechanism alone, a flexible sole plate is used. Moreover, the flexibility of the wires enables the prototype machine to accommodate individual differences.

IV. Apparatus

The prototype stretching machine consisted of a foot plate, heel holder, lower leg support, and pole brace (Fig. 4). The subject sat on a chair, and the heel on the target side was placed on the heel support. The foot plate was fixed using a belt to the foot of the subject, and the forefoot was supported from the bottom by the foot plate. Since the forefoot and heel parts were supported individually, the prototype could flexibly respond to three-dimensional foot deformation (Fig. 5). Two wires were passed one by one on the inside and outside toward the front of the foot plate. Each end of two wires was connected to a McKibben-type pneumatic actuator (Air Muscle, Kanda Tsushin Kogyo Co., Ltd., Japan) via an idler. The idler was used to adjust the direction in which the wire was pulled for each subject. The lower leg support part consisted of cloth similar to a hammock to support the lower leg of the subject. This made it possible to stabilize the lower leg during stretching and to reliably transmit the attraction force of the wire to the foot alone. Two idlers and two ends of McKibben-type pneumatic actuators were fixed to the pole brace. Two wires were drawn through the idler by pressurizing the McKibben-type actuator, and the foot was stretched (Fig. 6). Since the heel holder was cup-shaped, the heel could move slightly back-and-forth and right-and-left according to the foot movement.

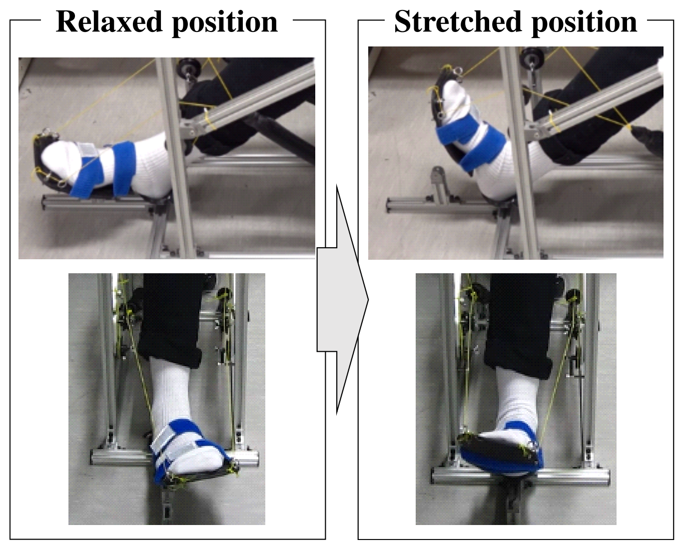

Fig. 6. Stretching motion. Left: Relaxed position before beginning stretching. Right: Foot position during stretching with the prototype machine instrumented with a double-wire mechanism.

An electropneumatic regulator was used for the pressurization of the McKibben-type actuator. In the prototype machine, the two electropneumatic regulators connected to the actuators were each controlled manually, and the pressure was individually adjusted. In order to perform stretching in a way to dorsiflex after braking the foot in the abduction and eversion direction, the actuator linked to the outer wire was first pressurized; then, the actuators on both sides were pressurized.

V. Clinical evaluation

A. Objective

In order to verify the three-dimensional stretching function and its clinical effects, we performed an experiment involving a healthy subject.

It is known that even healthy joints are affected by stretching, and its effects are investigated by examinations comprising joint stiffness and voluntary muscle contraction tests. Previous studies have shown that the ankle stiffness and maximum voluntary contraction (MVC) decrease immediately after static stretching [4], [5], [16]. Therefore, we also measured these two quantities before and after stretching.

B. Method

1) Procedure: A 22-year-old university student who provided informed consent participated. With the subject sitting on a chair, the right heel was placed on the heel holder, and the forefoot was fixed to the foot plate. At this time, the knee joint was flexed $55°$ from the straight extended position. In order to investigate the foot angle during the experiment, goniometers (SG110, SG110/A, Biometrics Co., Ltd., UK) were affixed to the lower leg and foot, and the dorsi-/plantarflexion, ab-/adduction, and ex-/inversion angles were measured. The anatomical basic limb position, i.e., the state where the toe is not twisted and faces the front and the foot is at a right angle to lower leg, is defined as $0°$ around all three axes.

Stretching by the prototype machine was carried out for 1 min. By applying pressure manually to the pneumatic actuators, the foot was abducted, everted, and dorsiflexed from the relaxed position, and it was held in a posture that reached maximum dorsiflexion. The subject was instructed to report when he felt pain during stretching. The ankle stiffness and MVC were measured before stretching, immediately after stretching, and 10 min after stretching. One experiment including stretching and the measurements of two values were repeated three times with 15 min of rest in between.

2) Measurement of the ankle stiffness: The stiffness was evaluated by indicating the relationship between the angle and the external force to dorsiflex a foot passively approaching a certain angle. For measurement of the external force, a handheld dynamometer (MT-100, Sakai Medical Co., Ltd., Japan) was used. The examiner pushed the subject's foot from the bottom of the foot to a certain angle ($0°$, $5°$, $10°$, $15°$, $20°$, $25°$) through the handheld dynamometer. The handheld dynamometer always contacted with the toe base during measurement. The force recorded by the handheld dynamometer when reaching each angle was recorded.

3) Measurement of the maximum voluntary contraction: The isometric MVC of the plantar flexors, gastrocnemius, and soleus was measured, which were the target muscles for stretching. For the measurement, a pull sensor (MT-150, Sakai Medical Co., Ltd., Japan) connected to the handheld dynamometer was used. During measurement, one of the belts of the sensor was placed on the bottom of the base of the toe, and the other was fixed to the chair. The subject's heel was placed on the heel holder of the stretching machine. The MVC was measured three times in one evaluation. A statistical analysis using a t-test was performed for the MVC.

C. Results

1) Foot control: Fig. 7 shows the results for the pressures applied to the two actuators and the angles of the foot posture during stretching in each of the three experiments. In all three trials, the foot was abducted, everted, and dorsiflexed while only the outer wire was pulled. By additionally pulling the inner wire, the dorsiflexion angle further increased. These results indicated that the prototype machine could perform stretching to dorsiflex after moving the foot for abduction and eversion.

While maintaining the maximum dorsiflexion for 1 min, for all three stretching operations, the dorsiflexion angle slightly increased regardless of the constant attractive force of the actuator. This suggests that the plantar flexor muscles were sufficiently stretched, and the viscoelasticity of these muscles had changed.

The abducted foot was slightly turned toward the inside when the inner wire began to be pulled. In this study, since the pressurization of the two actuators was controlled manually, it was only possible to delay the timing at which the pressure was applied. In the future, an automatic control system is required in order to adjust the amount and timing of the pressurization appropriately according to the change in the foot posture.

2) Ankle stiffness: The results for the ankle stiffness are shown in Fig. 8. The solid line shows the relationship between the passive dorsiflexion angle and the applied force for dorsiflexion before stretching, the dotted line shows the results immediately after stretching, and the broken line shows the results 10 min after the end of stretching. Owing to the nature of the nonlinear property of the muscle, a plot of the force versus the angle is generally a curve. From the results before stretching, as the angle increased, an exponentially larger external force was required. On the contrary, the applied force linearly increased immediately after stretching and after 10 min. Further, as compared to before stretching, a larger external force was required immediately after and after 10 min to reach the same angle. From these results, the stiffness slightly increased by stretching in this experiment, which was unexpected for us.

The external force for passive dorsiflexion was manually measured by using the handheld dynamometer, however, this measurement method is generally susceptible to error. In this study, the examiner was the same for all experiments, but the variance of the measured values became larger as the angle increased; thus, manual measurement might have led to the inaccuracy of measurement.

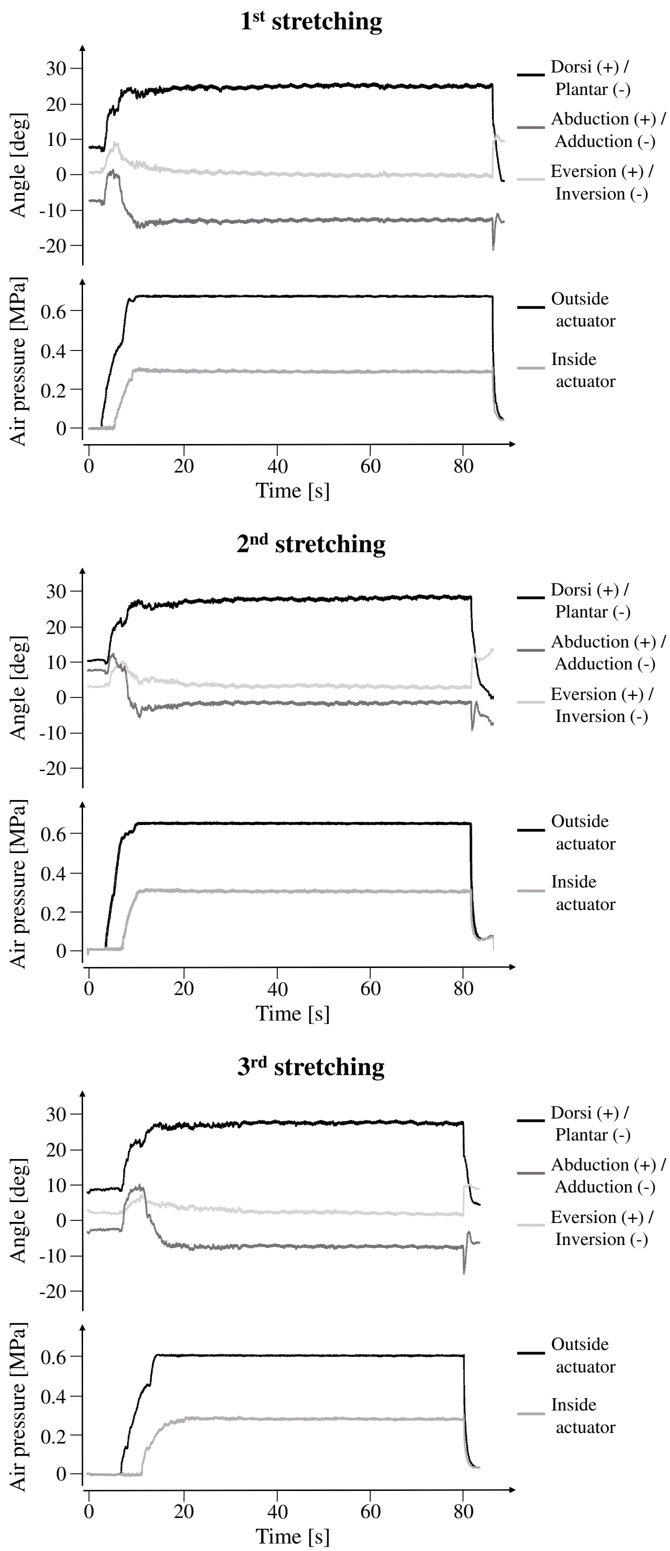

Fig. 7. Foot angles (upper) and air pressure (lower) during operation. Top: the results of the 1st experiment, Middle: the results of the 2nd experiment, Bottom: the results of the 3rd experiment.

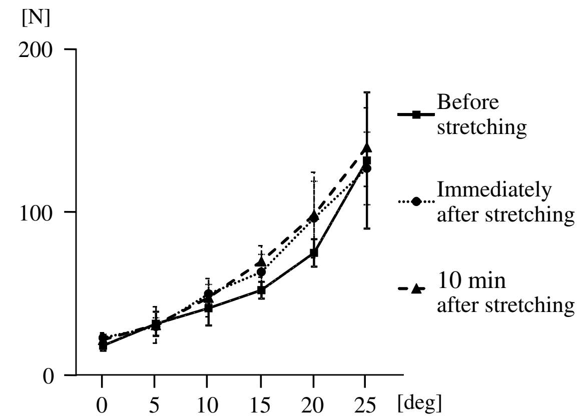

Fig. 8. Measured ankle stiffness before and after stretching.

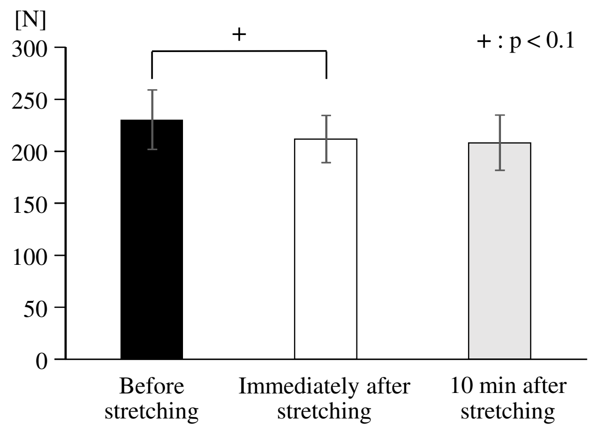

Fig. 9. Maximum voluntary contraction of the plantar flexors.

In previous research, stretching is often performed using a torque sensor, and the relationship between the angle and the torque measured by the torque sensor is often used to evaluate the stiffness. In the future, we will implement a method to evaluate the stiffness in a way that is not affected by examiners.

3) Maximum voluntary contraction : The results for the MVC are shown in Fig. 9. The MVC just before stretching was 230 ± 29 N (mean $\pm$ SD); however, immediately after stretching, it was 211 ± 23 N, and after 10 min, it was 208 ± 26 N. That is, the MVC decreased after stretching. A statistical analysis using a t-test was performed to compare the MVC before and immediately after stretching ($p = 0.07$) and before and 10 min after stretching ($p = 0.11$).

It has already been shown that the MVC decreases by sustained stretching [16], and our results indicated the same findings. This experiment only focused on the plantar flexor MVC, but the MVC of the posterior tibialis and flexor pollicis/digitorum longus muscles, which are the targets of three-dimensional stretching, should be evaluated in the next step. Since the pull sensor of the handheld dynamometer used in this experiment cannot measure the muscle force at the inversion and adduction foot positions, in order to evaluate the effects of stretching by three-dimensional control in more detail, it is necessary to consider a method capable of measuring the maximum muscle force during three-dimensional foot motion.

VI. Conclusion

In order to develop an effective stretching machine for a three-dimensionally deformed foot, i.e., equinovarus, a design for a stretching machine capable of three-dimensional control was proposed in this study, and its effects were examined from a clinical viewpoint.

The three-dimensional foot control mechanism using two wires actuated by pneumatic actuators is instrumented in the prototype. This mechanism makes it possible to stretch the ankle with an anatomically efficient method while reducing the burden on the human joint. Dorsiflexion foot movement after adduction and inversion was performed during stretching by this prototype.

Although the stiffness after stretching slightly increased, the MVC decreased. We do not have conclusive results regarding the stiffness because the ankle stiffness was measured in a simplified manner. As in previous research, the plantar flexor MVC decreased after stretching by the developed prototype machine; thus, the efficacy of this machine was demonstrated.

Acknowledgment

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