Ankle stretching rehabilitation machine for equinovarus: Automation of eversion and flexion control

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Abstract—Equinovarus is a foot deformity characterized by the patient's foot being at rest in an abnormally supinated state. In a clinical setting, physical therapists manually stretch the foot to a pronated state to allow the patient to retain some degree of mobility. Currently, no automated ankle stretching machine is commercially available. To tackle this issue, we have developed an automated stretching machine that controls the eversion and flexion angles of a patient's deformed foot using two pneumatic actuators. We designed a proportional and integral (PI) controller to place the foot in the desired dorsiflexed position and performed a user test involving a healthy participant. Even when the initial foot position of the participant was in an equinovarus position, the foot was successfully everted and dorsiflexed to match the desired reference posture via the stretching machine. The average differences between the reference and measured foot angles at the final state were found to be within $2°$ for both the dorsiflexion and eversion angles. The machine replicated the reference angles with acceptable errors.

Fig. 1. Direction of foot joint motion. Left: Pronated and dorsiflexed position. Right: Equinovarus position. Dorsi/Plantar-flextion is the rotation on the sagittal plane. Eversion/inversion is the rotation on the frontal plane. Ad/abduction is the rotation on the horizontal plane.

I. INTRODUCTION

Brain trauma and cerebrovascular accidents, commonly known as strokes, often cause significant reduction or complete disconnection of neural signals to muscles. A deformity caused by an overactive passive tension of the muscles comprising the gastrocnemius-soleus complex and the tibialis posterior muscle is known as equinovarus. As shown in the right side of Fig. 1, equinovarus is a foot deformity in which the foot rests in an unnaturally supinated state, also known as a state of excessive adduction, inversion, and plantarflexion [1]. A varus deformity is inhibitory to gait since it severely hinders balance. Therefore, it is crucial for patients with equinovarus to regain regular foot posture to walk normally.

Consistent stretching is a non-operative remedy that may be sufficient for patients with a minor case of equinovarus. Therapy focused on stretching to maintain the range of motion for the joints, referred to as equinovarus rehabilitation, is a long-term commitment that requires daily attention. Without the proper technique or sufficient motivation to continue rehabilitation regularly, the likelihood and completeness of recovery is significantly reduced. If the muscles involved are an integral part of everyday life, such as the legs, one's quality of life becomes severely diminished. To combat this issue, we have developed an automated stretching machine that the patient can use from the comfort of his or her home, while
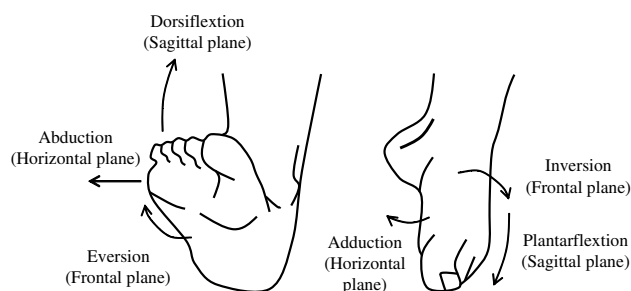
being assured that the machine can provide an effective and consistent stretch.

Current home rehabilitation tools for equinovarus include the slant board and physical therapy resistance bands. Although these devices provide adequate stretch when used properly, usage of the slant board poses a risk of fall for stroke patients who may have partial or complete paralysis in other parts of the body. Similarly, for the resistance bands, a stroke survivor may not be able to recruit the necessary strength in their arms to provide a satisfactory stretch to their leg.

An automated stretching machine could provide an adequate stretch without the need to worry about the loss of balance or arm strength. Devices introduced in the previous studies [2], [3], [4], [5] were able to apply a stretch only around dorsi/plantarflexion because the plantarflexion is the major deformity for the majority of patients. However, equinovarus is a result of the tightening of several muscle groups. The gastrocnemius and soleus complex are plantarflexion muscle groups with origins and insertions that come straight down [6], and thus their fibers are directed vertically. However, other muscles such as the tibialis posterior have fibers that run diagonally and are not fully stretched from an exclusively dorsiflexion movement. Therefore, since the rehabilitation stretch provided by physical therapists for equinovarus involves both eversion and dorsiflexion movements [7], the stretching device should have multiple degrees of freedom so as to stretch all muscles involved in equinovarus to the maximal degree, in other words, maximizing the opposite movements of inversion and plantarflexion that characterize equinovarus. There are some studies on automated machines for continuous passive motion of multiple degrees of freedom [8]. These studies

support the possibility to extend this type of technology for stretching purposes; however, none have demonstrated the technology applied to ankle stretching devices, specifically.

The purpose of the present research was to develop a machine to successfully automate ankle motion control across multiple degrees of freedom. Thus far, no automated ankle stretching machines that allow for multiple degrees of joint motion have been reported. The hardware was originally designed by the authors [9], where the device was manually controlled and the clinical effects were approved involving healthy subjects. In contrast, the present study focuses on the automation of the machine.

II. DESIGN AND CONFIGURATIONS OF STRETCHING MACHINE

A. Hardware of stretching machine

The ankle stretching machine prototype [9] developed by the authors was used. As shown in Fig. 2, the machine consisted of a metal frame housing two McKibben-type pneumatic actuators (Air Muscle, Kanda Tsushin Kogyo Co. Ltd., Japan), each of which was controlled by an electro-pneumatic regulator (ITV 1000 E/V, SMC Corp., Japan, maximum shortening: 100 mm) and a footplate made of hard rubber on which the foot was secured by using Velcro straps. Each pneumatic actuator pulled each of the two wires connected to the lateral and medial side of the footplate by way of a pulley. An analog three-axis accelerometer (MMA7361, Freescale Semiconductor, USA) was installed on the underside of the footplate to obtain the state of the foot based on the direction vector of gravity. It should be noted that the accelerometer measured the plantar/dorsiflexion and eversion/inversion angles, whereas it could not respond to the change in the ab/adduction angle that was the rotation around the gravity direction. The regulators were controlled by a microcomputer that also read the outputs from the accelerometer as well as the self-pressure monitor of each regulator at 100 Hz.

The user rested the lower thigh on the cloth supporter with the foot fastened to the plate. He or she was instructed to relax during the operation of the machine. The footplate was controlled by two wires connected to the pneumatic actuators and tilts the user's foot such that the shortened muscle systems were stretched. The principle of the wire system is described in the following Section.

Pneumatic actuators were selected for their relative safety over alternatives. Other similar ankle stretching machines use highly reduced electro-magnetic motors, which halt in the stopping position owing to the friction of the reduction gears. In other words, if one were to stop the motor while he or she is in pain, the machine would halt in that painful position. The pneumatic actuators relax when deactivated, reverting the foot to the original position. While the true safety factor of this feature has yet to be concluded, this allows for a safer stretching machine, in principle.
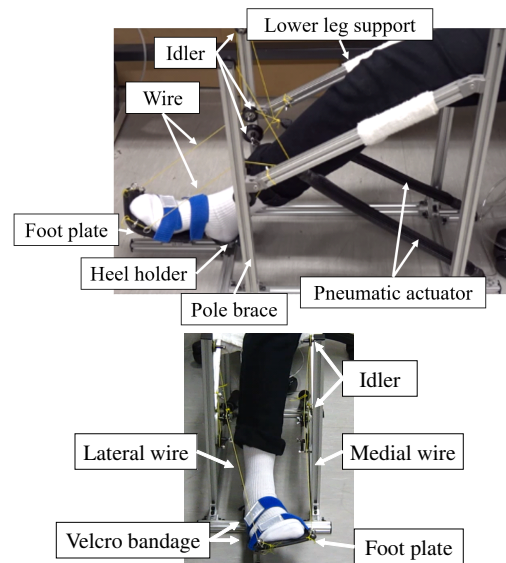

Fig. 2. Prototype of ankle stretching machine. Top: Side view and part names. Bottom: Top-frontal view.
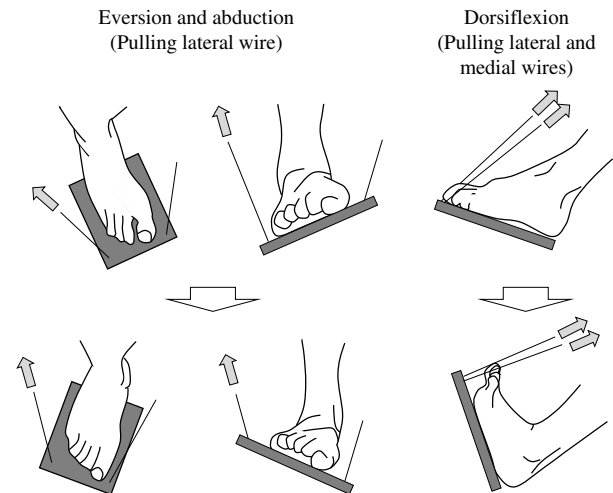

Fig. 3. Working principles of the ankle stretching machine. Left: The lateral wire mainly controls the eversion and abduction of the foot while these motions are weakly associated with the dorsiflexion. Right: The dorsiflexion is mainly controlled by simultaneously pulling the lateral and medial wires.
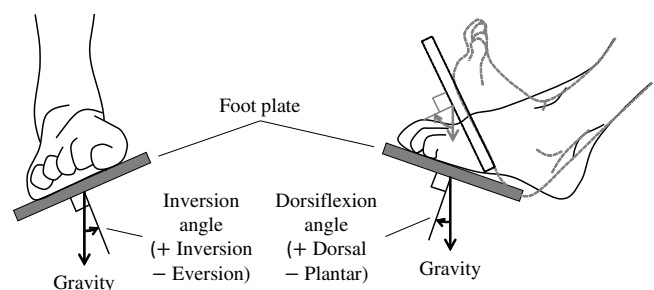

Fig. 4. Definition of foot angles. In/eversion and dorsi/plantarflexion angles were defined with respect to angles between the footplate and gravity. Note that dorsi/plantar-flexion angle was not defined between the foot and lower thigh.
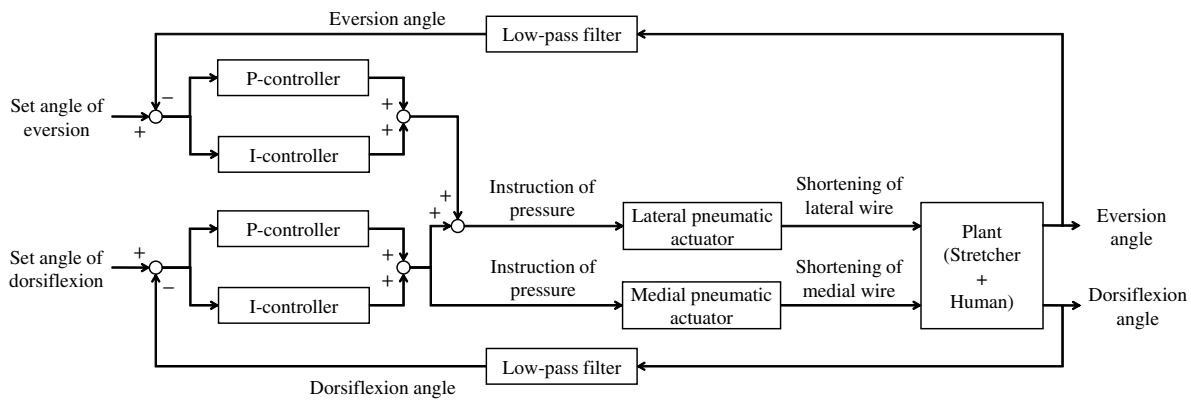
Fig. 5. Meta-scale control block of the ankle stretching machine. Two pneumatic actuators were PI-controlled with two inputs. The lateral actuator was controlled such that both the set eversion and dorsiflexion angles were achieved. The medial actuator was controlled to achieve the set dorsiflexion angle.

B. Working principles of wire-footplate system

As shown in Fig. 1, equinovarus is a deformity that affects the foot across three degrees of freedom: inversion, adduction, and plantarflexion. The wire-footplate system allows for three-dimensional control to stretch against these movements. The working principles of the stretching machine are shown in Fig. 3. When the lateral wire alone is pulled, the foot will abduct and evert, since the two movements are coupled owing to the characteristics of ankle joint [10]. When both wires are pulled simultaneously, a dorsiflexion movement occurs, thus allowing for three degrees of freedom of movement.

In this manner, the wire-footplate system realizes three-dimensional stretching for treatment of equinovarus, though it does not intend to control the motions around the three axes independently. The two wires were mechanically coupled. Further, as previously mentioned, inversion and adduction of the human foot are anatomically coupled. Thus, the underactuated system, with two actuators, can rectify the supinated and plantarflexed foot.

C. Controller

We used two types of foot angles for the controller, as defined in Fig. 4. They were in/eversion (roll) and dorsi/plantarflexion (pitch) angles; the foot angles were defined referring to gravity. The eversion and dorsal directions were positive.

As shown in Fig. 5, the stretching machine was controlled by proportional and integral (PI) controllers on both the lateral and medial actuators with the eversion and dorsiflexion angles being the controlled values. The PI controller for the lateral actuator controlled the eversion angle, since only the lateral actuator was required to evert the foot. In contrast, the medial and lateral actuators were controlled by another PI controller for the dorsiflexion angle, which was influenced by both actuators. Hence, the output of the lateral actuator was determined by summing the pressure instructions from the two controllers. The PI controller was expected to converge the foot angles to the desired values. The control gains were

determined such that the foot angles would move slowly for safety purposes.

This controller does not ensure that the set values are achieved mainly because of the trade-off between the dorsiflexion and eversion of the foot. Both actuators need to shrink to impose the foot into the dorsiflexed position; however, the shrink of the lateral actuator also everts the foot. In order to ensure that shrink of the lateral actuator does not overly evert the foot, the maximal output of the medial actuator needs to be large enough to cancel or pull back the everted foot. Unfortunately, the outputs of the two actuators are finite and the system may converge to an undesired foot position where both the eversion and dorsiflexion of the foot are imperfect.

III. EXPERIMENTAL PROCEDURE

An experiment was conducted to evaluate the functionality of the automated ankle stretching device. The foot of a healthy subject, who provided informed consent, was strapped to the footplate, and the lower thigh was placed on the cloth hung from the rigid frame. During the operation, the lower thigh hardly moved on the leg support cloth.

Before the stretching machine was activated, we determined the set angles of the foot. A physical therapist displaced the subject's foot to an everted and dorsiflexed position at which the ankle muscles were stretched. The final angles measured at this position were recorded by the software as the set eversion and dorsiflexion angles. After the therapist released the subject's foot, the stretching portion of the program was activated in an attempt to bring the foot to the set position. The subject relaxed and did not intend to resist the force exerted from the actuators.

Ten trials were conducted in the abovementioned manner. The set position designated by the therapist naturally varied among the trials. For each trial, the errors between the measured and set angles were calculated when the stretching machine reached a steady state.
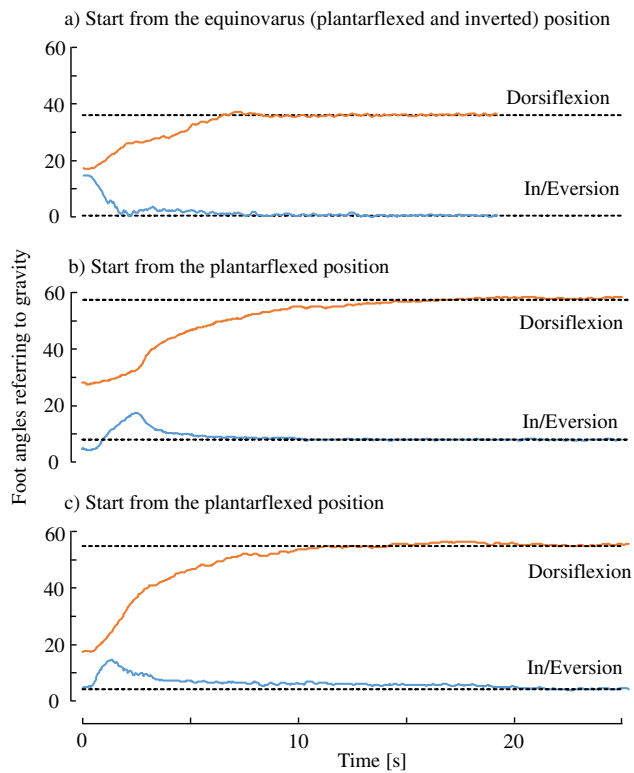
Fig. 6. Three examples of time-series foot-angles. The dotted lines are the set values. a) Initial posture of the foot was in an equinovarus position. b), c) Initial posture of the foot was plantarflexed, and the initial eversion was nearly zero. The dorsiflexion angle referred to the floor. The angle was zero when the sole was parallel to gravity.

IV. RESULTS AND ANALYSIS

Changes in the foot angles for three representative trials are shown in Fig. 6.

In one case, shown in the top figure, the initial posture of the subject's foot was in an equinovarus position with the foot being plantarflexed and inverted. This operation is also shown in Fig. 7. As the operation was initiated at $t = 0$, both angles started approaching the set values (dotted lines), and they approximately reached the final values in 7 s. In terms of the inversion, the foot was mostly corrected within 4 s. This was because supi/pronation was mechanically leveraged, and slight shortening of the wire resulted in relatively large rotation.

In other cases shown in the bottom two figures, the subject's foot was initially in a plantar position with little inversion. The set eversion angle was $8°$, which is a slightly inverted position (Fig. 6b)). The set angle of the dorsiflexion was deep at $58°$. A notable observation is that the eversion angle increased before decreasing to the steady state angle. This is a demonstration of the PI controller: when the medial actuator activated, the eversion angle increased slightly owing to the extra pull. This is not preferable and will be resolved by carefully tuning the PI gain parameters. Nonetheless, the PI controller sets the eversion angle back to the desired angle. Such an overshoot of
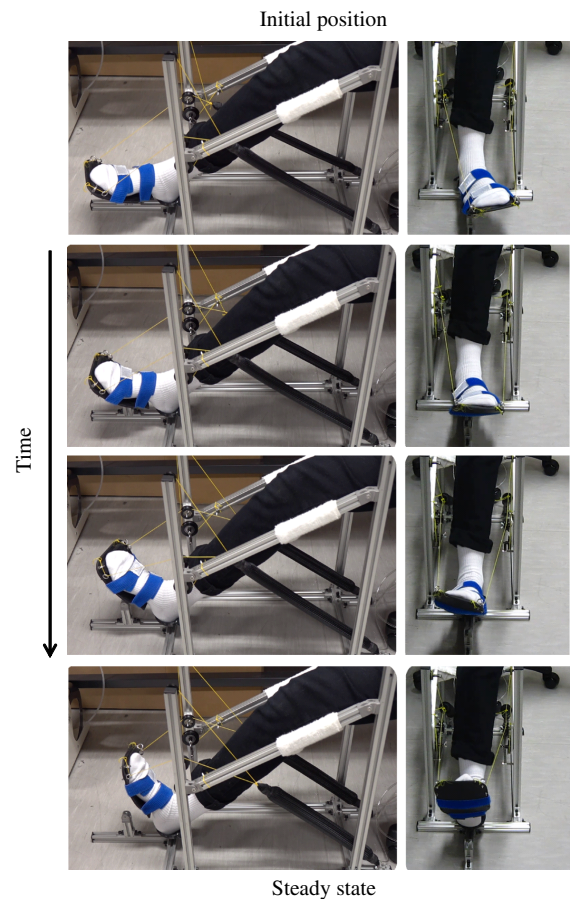

Fig. 7. Scenes during the operation. Top) At the initial stage, the foot rests at an equinovarus position. Middle) The inversion is mostly rectified, and the dorsiflexion is to be started. Bottom) At the steady state of the operation, the foot remains at the dorsiflexed position. The left and right parts are the sagittal and frontal views, respectively.

eversion is undesirable in some cases and should be resolved in the future.

Fig. 8 shows the means and standard deviations of the steady state errors of flexion and eversion angles among the ten trials. The mean and standard deviation of the flexion error were $0.38° \pm 0.57°$. Those of the eversion were $-0.18° \pm 0.42°$. It should be noted that we adopted different set angles across the trials because a physical therapist manually determined the set position. Further, the initial foot posture of the subject naturally varied among the trials with no specific instructions provided. The stretching machine could finalize the posture control with fairly small errors for ten trials with the distinct initial and final states.

The average absolute error between the reference and steady state eversion angle was $0.57°$ with a standard deviation of $0.47°$. The average absolute error between the reference and steady state dorsiflexion angle was $1.68°$ with a standard deviation of $1.18°$. Since there currently is no standard for the accuracy of stretching machines, it is difficult to determine whether these results indicate complete efficacy of
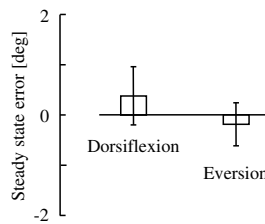
Fig. 8. Steady state error of the dorsiflexion and eversion angles. Means and standard deviations among ten trials. They are not statistically different from zero at a significance level of 0.05.

the automated stretching machine. However, 4–6° of error have been noted for visual confirmation among numerous studies [11], [12], [13]. According to the standards of these previous studies, it is reasonable that the average errors for both eversion and dorsiflexion angles were at an acceptable level.

V. CONCLUSION

With the ultimate goal of developing a stretching machine for foot deformity, which is one of the major aftereffects of stroke, we implemented an automation control to evert and dorsiflex the foot in patients with equinovarus. As shown by the results of the experiment, the automated ankle stretcher was capable of controlling the position of the subject's foot across three degrees of freedom. There are still several steps to be carried out to refine the stretching device. Mainly, the clinical effectiveness of the resulting stretch needs to be evaluated. When a physical therapist applies a stretch, there is an increase in force after the reference position is reached to apply a proper stretch, which implies that force control may be needed in addition to the position control that was implemented in the present study. Nonetheless, the present study demonstrated that our wire-driven mechanism could place the foot that was in a deformed position into the position at which the foot is stretched, which leads to automated ankle stretching machines for in-home use in the future.

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