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Original Article

Machine-assisted foot stretching in the elderly: a comparison with self-stretching

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Abstract. [Purpose] Self-stretching is the traditional at-home stretching method of choice. We developed an automatic foot-stretching machine to perform effective dorsiflexion stretching safely and easily at home. The effects of automatic stretching using our machine and self-stretching were investigated and compared. [Participants and Methods] Twelve healthy elderly people participated in the study. Automatic dorsiflexion static stretching was performed with the right foot, and self-stretching using a towel was performed with the left foot. Before and after each stretching, passive range of motion in dorsiflexion, maximal voluntary contraction strength in plantarflexion, passive resistive torque during passive dorsiflexion, and displacement of the muscle-tendon junction of the medial gastrocnemius muscle were measured. [Results] The range of motion in dorsiflexion had a significantly greater increase after automatic stretching than after self-stretching. The maximum strength in plantarflexion tended to decrease after automatic stretching but did not decrease after self-stretching. The passive resistive torque in both types of stretches decreased in some of the participants but increased in others. The displacement of the muscle-tendon junction of the medial gastrocnemius tended to shorten during automatic stretching as compared with self-stretching. [Conclusion] Foot stretching using a machine is as effective as self-stretching and tends to affect the tendon rather than the muscle.

Key words: Stretching machine, Elderly, Foot stretching

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INTRODUCTION

Stretching is often performed clinically to improve the range of motion of the ankle joint. Stretching the calf muscles increases ankle dorsiflexion range of motion[1, 2]. In addition, static stretching has been shown to reduce muscle stiffness in healthy young and elderly[3] and is also considered effective for abnormal muscle tone caused by neural disorders[4, 5]. While there is an argument that short-term stretching is clinically ineffective[6], it is shown that constant stretching of the foot has a chronic effect[7]. Therefore, it is desirable to stretch continuously, not only in the hospital but also at home. To achieve this, the patient must perform proper stretching alone rather than by a therapist.

Some automatic rehabilitation devices to treat the foot have been studied. An automated foot-stretching device had been studied for use in the bed-side; it is suggested that robot-assisted passive stretching and active movement training effectively improve motor function and mobility for post-stroke patients and children with acute brain injury[8–13]. Toda et al. created a foot-stretching machine that simulates a therapist pulling the heel and dorsiflexing the foot in a sitting position[14, 15]. Their machine had one degree of freedom of motion for dorsi- and plantar flexion. On the other hand, Yamada et al. investigated physical therapists' manual stretching techniques and statistically revealed that the therapist stretched the foot in three dimen-

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sions[16, 17]. Their research group subsequently developed a three-dimensional control foot-stretching device that simulates this manual stretching technique[18, 19]. There are other studies about foot-stretching devices to maintain foot function[20–22], but none have been commercialized yet.

We developed an automatic stretching machine for the foot that can be used at home for continuous intervention[23–25]. This machine was developed by the authors' group, utilizing the mechanism of a commercial foot exerciser (Relegs, LAP Co. Ltd., Japan), which originally repeated dorsiflexion and plantar flexion, and was not designed for stretching. Since it is necessary to apply a large external force to the body to stretch, risk reduction of a stretching machine is very important. The stretching machine we have developed is driven by a pneumatic actuator, so it can return the foot to a resting position in an emergency by shutting off the supplied air. In our earlier study[23], the effect of this machine in dorsiflexion static stretching for healthy young people was verified. Owing to the foot stretching by this machine, the maximal voluntary contraction strength in plantar flexion decreased, and the passive resistance during passive dorsiflexion significantly decreased. This meant that the rigidity of the foot was reduced. However, in the earlier experiment, only the effect of stretching using the machine was investigated, and it was not compared with the effect of stretching by a therapist or self-stretching.

Yoo et al.[26] developed a robotic ankle stretching system called the Motorized Ankle Stretcher (MAS). The MAS stretches the foot by inclining the left and right footplates to dorsiflex and evert the foot, while the participant stands on the footplates and holds the safety bar. They compared the effect for stroke survivors of stretching using the MAS and self-stretching by standing on a board. They reported that stretching by the MAS significantly improved the range of motion of the ankle, walking speed, walking rate, and step length. However, there were no significant changes in self-stretching outcomes other than balance.

We aim to develop a stretching machine that is safe and easy to use at home and can be used while sitting instead of while standing. The effect of a stretching machine used at home should be equal to, or higher than, the effect of self-stretching; but no study has compared the effects of stretching machines with those of self-stretching in the sitting position. Therefore, in this study, we compared the stretching effect of our machine to self-stretching in a sitting position in elderly people who require self-stretching at home.

PARTICIPANTS AND METHODS

Twelve healthy elderly people (5 males and 7 females, 73.2 ± 3.8 years old [mean ± standard deviation]) participated in the experiment. Those with marked restriction of range of motion of the ankle joint, or pain in the foot, were excluded. The details of the study were explained in writing and orally in advance, and each participant signed an informed consent form. This study was conducted with the approval of the Ethics Committee of Aichi Medical College (approval number: 18016).

All participants performed static stretching under two conditions: automatic dorsiflexion stretching of the foot using the developed stretching machine and self-dorsiflexion stretching performed by the participant (Fig. 1). Ideally, the right and left foot should be random to investigate the effects of the stretching machine; however due to the structure of the stretching machine, automatic stretching was performed on the right foot and self-stretching was performed on the left foot.

In automatic stretching, the right foot was placed on the stretching machine, with the knee joint extended, while sitting on the chair. This stretching machine is driven by a pneumatic actuator. The bellows connected to the part on which the foot is placed expands according to the air pressure inflow. At this time, the center of rotation of the machine's foot part is set at a position close to the user's ankle joint. When the air flows in, the bellows expands, and the foot is dorsiflexed (Fig. 2). When the air flows continuously, the foot can maintain this dorsiflexed position to achieve static stretching. When the inflow of air stops, the bellows contract, and the foot returns to the initial position. Since the stretching machine uses a hold-to-run method, in which the pneumatic actuator drives only while the user is pressing the switch, all operations in the experiment were performed when the participant pressed the button.

The maximum dorsiflexion angle during stretching was adjusted to the foot condition of each participant. Before starting the stretch, while the machine passively dorsiflexed the participant's foot, the participant found the dorsiflexed angle at which he or she felt an extension of the muscle. This took about 20 seconds and determined the maximum dorsiflexion angle. After the foot was returned to the initial position, the machine was operated again up to the maximum dorsiflexion angle with the participant pressing the switch and stretching was performed by holding this position for 2 minutes. The setting of the maximum angle and the 2 minutes of stretching were repeated 5 times in succession.

Self-stretching was performed in the sitting position with the knee extended. In this study, self-dorsiflexion stretching was performed using a towel as this is easy to replicate at home. The center of the towel was placed under the foot, and the participant pulled the ends of the towel proximally to dorsiflex. This was done for 10 minutes, during which the participant was instructed to continuously pull the towel. Self-stretching on the left foot was performed after automatic stretching, because holding the towel for 10 minutes could increase fatigue in the upper limbs and affect the operation of the stretching machine.

Passive range of motion in dorsiflexion (DF-ROM), maximal voluntary contraction strength of plantarflexion (PF-MVC), passive resistive torque during passive dorsiflexion, and the displacement of the muscle-tendon junction (MTJ) of the medial gastrocnemius muscle were measured before and after automatic stretching, and before and after self-stretching. All measurements were performed supine with the knee in 30° of flexion. DF-ROM was measured using a goniometer. PF-MVC was measured 3 times by pressing a handheld dynamometer (Mobie, SAKAI Medical Co., Ltd.) in the plantar direction using the bottom of the foot, fixed to the frame at the height of the metatarsal head (Fig. 3A). Passive resistive torque and MTJ

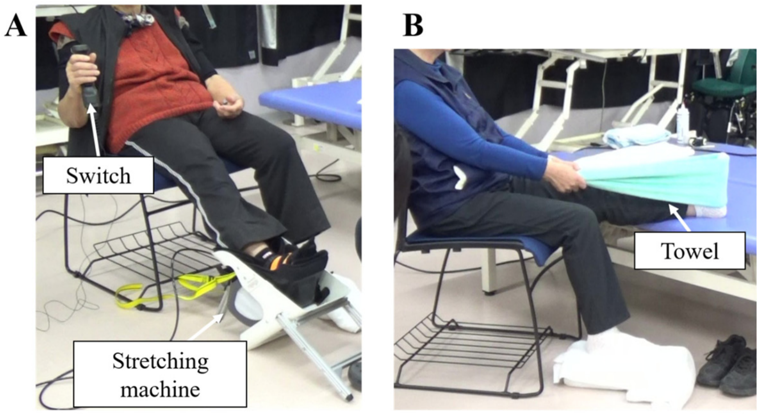

Fig. 1. (A) Automatic stretching, (B) Self-stretching.

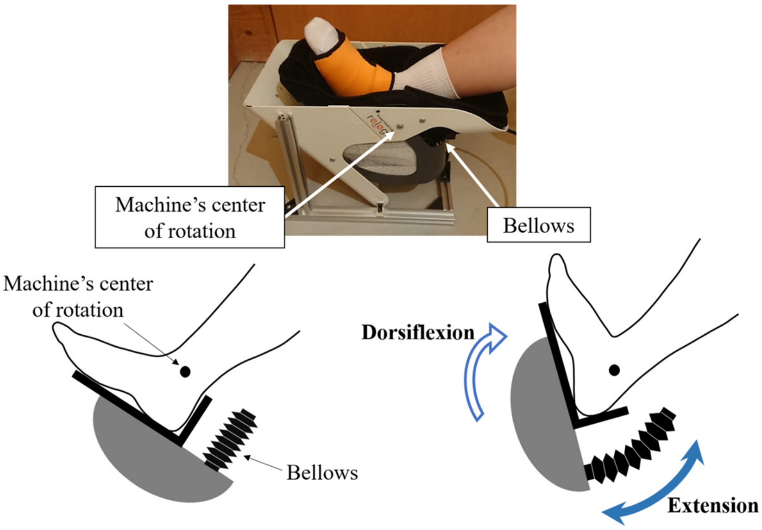

Fig 2. Operating principle of the stretching machine.
When the bellows expands, the foot is dorsiflexed.

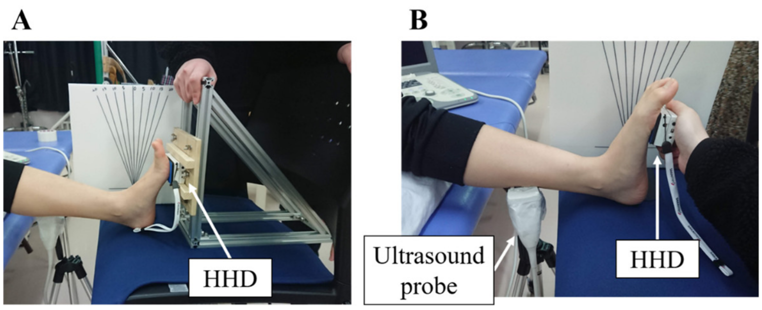

Fig. 3. (A) Measurement of PF-MVC, (B) Measurement of passive resistive torque and MTJ displacement.
PF-MVC: Maximal voluntary contraction strength of plantarflexion; MTJ: Muscle-tendon junction; HHD: Handheld dynamometer.

displacement were measured simultaneously (Fig. 3B). Bressel et al.[4] evaluated the stiffness of the foot which was calculated as the relationship between the passive torque and the dorsiflexion angle during passive foot dorsiflexion, to verify the effect of stretching. Using this as a reference, the examiner passively dorsiflexed the participant's foot by 5° from 0° to 15° by

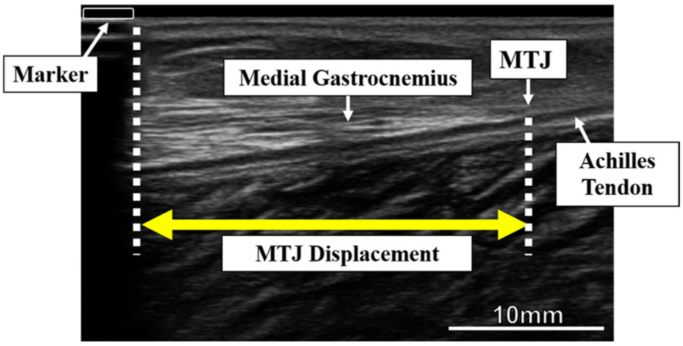

Fig. 4. Measurement of distance from the reflective marker to the MTJ in which using to evaluate MTJ displacement.
MTJ: Muscle-tendon junction.

touching the foot at the bottom of the base of the toe with the handheld dynamometer so that the resistive force was measured 3 times at each angle. During the measurement, the participant tried to relax in order to not exert any active force. By multiplying the measured resistive force and the distance from the outer malleolus to the base of the toes, the passive resistive torque during passive dorsiflexion was obtained. The examiner measuring the resistive force was the same in all experiments.

While performing the passive dorsiflexion movements to measure the resistive force, the movement of the MTJ of the medial gastrocnemius muscle was simultaneously photographed with an ultrasonic imaging device (ARIETTA Prologue, Hitachi, Ltd.). Using the method of Morse et al.[27] as a reference, the position of the MTJ was identified on the ultrasound image before measurement, and then an acoustic reflection marker was attached on the skin above the MTJ. The position of the marker was the same before and after stretching. An ultrasound probe was fixed to a tripod was set so that the marker and MTJ could be imaged within the same frame. The passive dorsiflexion angle was changed by 5° from 0° to 15°, and an ultrasound image was taken 3 times at each angle. Image J (National Institute of Health, Bethesda, MD, USA), software was used to calculate the distance from the reflective marker to the MTJ in each image; this distance was used to evaluate the MTJ displacement of the medial head of gastrocnemius (Fig. 4).

For statistical analysis, a three-way analysis of variance for three factors: individual, pre and post stretching, and stretching methods (automatic stretching and self-stretching) was applied for DF-ROM and PF-MVC. For passive resistive torque and MTJ displacement, a four-way analysis of variance was applied for four factors: individual, pre/post stretching, auto/self-stretching, and dorsiflexion angle (DF-angle) at each measurement. The significance level was $p<0.05$. Post-hoc tests were performed when an interaction appeared between the factors.

RESULTS

The means and standard error of DF-ROM and PF-MVC are shown in Table 1, and the results of the three-way analysis of variance are shown in Table 2. From these results, in DF-ROM, there were main effects of all factors: individual, pre/post stretching, and auto/self-stretching; therefore, DF-ROM increased significantly after stretching. Moreover, the interaction appeared only between the stretching method and the individual. According to each individual's result, seven out of the twelve participants had at least a 3° greater increase in DF-ROM with automatic stretching than by self-stretching and three participants had a greater increase by self-stretching than by automatic stretching. A post-hoc t-test was performed on the results of DF-ROM before stretching, and there was significant difference between the right (automatic stretching) and the left (self-stretching) feet ($p<0.01$). In PF-MVC, the main effect appeared with pre/post stretching and the individual, so PF-MVC significantly decreased after stretching. There were interactions between the individuals and auto/self-stretching, and between pre/post stretching and auto/self-stretching. Individual results showed that nine out of twelve had at least a 2.8% decrease in mean PF-MVC with automatic stretching, and six out of nine had at least a 12.6% greater decrease in mean PF-MVC with automatic stretching when compared to self-stretching. The self-stretching of the remaining three participants decreased mean PF-MVC to a greater extent (by at least 5%) compared to automatic stretching. Furthermore, a t-test was performed as a post-hoc analysis to the results of PF-MVC before and after stretching, which was divided into automatic stretching and self-stretching, respectively. As a result, PF-MVC tended to decrease after automatic stretching ($p=0.07$), while there was no significant difference before and after self-stretching ($p=0.49$). There was no significant difference between the right (automatic stretching) and the left (self-stretching) feet before stretching was performed ($p=0.62$, t-test).

The means and standard deviations of passive resistive torque and MTJ displacement are shown in Table 3 and the results of the four-way analysis of variance are shown in Table 4. Five participants out of all participants did not reach 15° of passive dorsiflexion during the measurement of passive torque and MTJ displacement, so they were excluded from the analysis. The remaining seven participants were included in the analysis of passive resistive torque and MTJ displacement. It was clear that

Table 1. Means and standard error of DF-ROM and PF-MVC

		DF-ROM (deg)	PF-MVC (Nm)
Auto	Pre	18.3 ± 1.5	196.0 ± 10.1
	Post	24.1 ± 1.7**	173.1 ± 11.7
Self	Pre	13.9 ± 1.4†	184.8 ± 8.8
	Post	18.7 ± 1.2**†	180.0 ± 9.4

**p<0.01; Pre vs. Post in Auto or Self stretching by t-test as post-hoc analysis. †p<0.05; Auto vs. Self in Pre or Post stretching by t-test as post-hoc analysis. In PF-MVC, no significant differences were observed after comparing all factors. DF-ROM: Passive range of motion in dorsiflexion; PF-MVC: Maximal voluntary contraction strength of plantarflexion.

Table 2. Results of three-way analysis of variance of DF-ROM and PF-MVC

		DF-ROM		PF-MVC	
		F	p-value	F	p-value
Main effect	Individual	15.5	< 0.01	46.8	<0.01
	Pre/Post	66.2	< 0.01	10.3	<0.01
	Auto/Self	58.0	< 0.01	0.3	=0.61
Interaction	Individual × Pre/Post	1.2	= 0.39	1.3	=0.24
	Individual × Auto/Self	3.0	< 0.05	10.7	<0.01
	Pre / Post × Auto/Self	0.6	= 0.45	4.4	<0.05

DF-ROM: Passive range of motion in dorsiflexion; PF-MVC: Maximal voluntary contraction strength of plantarflexion.

Table 3. Means and standard error of passive resistive torque and MTJ displacement

		Passive resistive torque (Nm)				MTJ displacement (mm)			
		0°	5°	10°	15°	0°	5°	10°	15°
Auto	Pre	17.6 ± 1.2	20.2 ± 1.6	22.3 ± 1.8	25.6 ± 2.1	25.3 ± 0.8	26.2 ± 1.3	25.8 ± 1.4	26.0 ± 1.4
	Post	17.7 ± 1.1	18.7 ± 1.7	21.1 ± 1.8	24.3 ± 2.5	22.9 ± 1.0	24.4 ± 1.0	24.5 ± 1.2	24.9 ± 1.2
Self	Pre	16.2 ± 1.5	20.8 ± 1.8	22.7 ± 2.3	26.0 ± 2.7	28.0 ± 1.5	27.6 ± 1.6	29.8 ± 0.7	30.4 ± 0.6
	Post	17.1 ± 1.6	18.2 ± 1.6	18.8 ± 1.8	23.5 ± 2.0	26.6 ± 1.3	26.8 ± 0.9	28.3 ± 0.7	28.2 ± 0.7

0°, 5°, 10°, and 15° are passive dorsiflexion angles (DF-angle) of participants' ankle joint when passive torque is measured. MTJ: Muscle-tendon junction.

Table 4. Results of four-way analysis of variance of passive resistive torque and MTJ displacement

		Passive resistive torque		MTJ displacement	
		F	p-value	F	p-value
Main effect	Individual	185.5	<0.01	101.8	<0.01
	Pre/Post	13.4	<0.01	29.0	<0.01
	Auto/Self	1.8	=0.18	120.4	<0.01
	DF-angle	64.0	<0.01	7.3	<0.01
Interaction	Individual × Pre/Post	16.7	<0.01	14.1	<0.01
	Individual × Auto/Self	2.7	<0.05	28.0	<0.01
	Individual × DF-angle	8.2	<0.01	2.7	<0.01
	Pre / Post × Auto/Self	1.7	=0.20	0.1	=0.73
	Pre / Post × DF-angle	2.8	<0.05	0.2	=0.89
	Auto / Self × DF-angle	0.5	=0.70	2.6	=0.05

MTJ: Muscle-tendon junction; DF-angle: Dorsiflexion angle.

the DF-angle had the main effect, so we focused on the results of the other three factors.

Passive resistive torque had main effects in pre/post stretching and the individual, and the torque decreased significantly after stretching; however the factor of the stretching method had no significant effect. Interactions only appeared between individuals and other factors, not between pre/post stretching and auto/self-stretching. Therefore, we performed a two-way analysis of variance as a post-hoc analysis for each individuals' results of automatic stretching and self-stretching, respectively, using two factors: pre/post stretching and DF-angle. As a result, in the automatic stretching, passive torque was significantly decreased in three out of seven participants and increased significantly in two out of seven participants. In self-stretching, passive torque decreased significantly in four of seven participants after stretching, while in two of them, it increased significantly.

As a result of the four-way analysis of variance for MTJ displacement, all factors had main effects and MTJ displacement became significantly shorter after stretching. There was also an interaction between the individual and other factors, but no interaction between pre/post stretching and auto/self-stretching. A two-way analysis of variance was performed as a post-hoc test using the same procedure as for passive resistive torque. As a result, in automatic stretching, MTJ displacement was significantly shortened in three out of seven participants after stretching, although in one participant it became significantly longer. In self-stretching, MTJ displacement was significantly shortened in three out of all the participants after stretching, while it was significantly increased in two participants.

DISCUSSION

To verify the effect of the foot-stretching machine DF-ROM, PF-MVC, passive resistive torque, and MTJ displacement before and after automatic stretching by the machine were evaluated for healthy elderly people. Additionally, the effect of self-stretching performed by the participants in the same sitting position as the automatic stretching was also evaluated to confirm the usefulness of using this stretching machine at home. DF-ROM increased significantly after stretching and there were significant differences between automatic stretching and self-stretching, although there was no interaction between the stretching methods. This indicated that automatic stretching was as effective as self-stretching in increasing the range of dorsiflexion. Konrad et al.[28] reported that stretching with constant torque increased the ankle dorsiflexion range of motion rather than stretching with a constant angle. In automatic stretching using our machine, the dorsiflexed stretching position was updated every 2 minutes of stretching. Hence, continuous stretching with an appropriate force could be applied to the foot, which gradually changed during stretching.

PF-MVC tended to decrease after automatic stretching, but did not decrease after self-stretching. Fowles et al.[29] reported that, in healthy participants, MVC decreased after stretching due to changes in neuromuscular feedback response. On the other hand, a study of stroke patients reported that MVC increased after stretching[30], so the effect of stretching on MVC is still under debate. A review of the effects of static stretching on muscle function revealed that stretching for 60 seconds or longer negatively affected performance such as muscle speed and power[31]. In the present study, the results of automatic stretching, which tended to decrease PF-MVC after stretching, indicate that stretching using the machine was able to be performed for an adequate period. On the other hand, in self-stretching which did not change PF-MVC, static stretching might not be performed constantly. While the participant pulled the towel to stretch the foot for 10 minutes, the pulling force on the towel might have gradually weakened. From the viewpoint of performing proper stretching for a long time, it is considered that automatic stretching using the machine is effective.

Although passive resistive torque decreased significantly as a main effect after stretching, in both automatic and self-stretching, some individuals had a decrease and other individuals had an increase. Similarly, although MTJ displacement was significantly shortened after stretching as a main effect, both types of stretching decreased the displacement in some individuals and increased it in others. Morse et al.[27] performed 1 minute of static stretching 5 times in healthy adults and measured passive plantar flexion torque and MTJ displacement, before and after stretching. The results showed that passive torque decreased and MTJ displacement increased after stretching. Hirata et al.[32] reported that, after performing static stretching for 5 minutes in healthy men, passive torque was significantly reduced compared to before. At the same time, the fascicle length of the medial gastrocnemius muscle was measured, but there was no significant difference between before and after stretching. Konrad et al.[28] reported that 30 seconds of foot stretching 4 times significantly reduced passive resistive torque and made no change in muscle or tendon stiffness. Furthermore, Kato et al.[33] performed static stretching for 20 minutes on the foot and measured the amount of extension of the gastrocnemius muscle and tendon. As a result, the amount of extension of the tendon increased after stretching, but the amount of muscle extension did not change. As described, many studies report that passive stretching reduces passive torque, but there is still no consensus on the effect on muscles and tendons[34]. In the present study, out of the three participants in which passive torque significantly decreased by the automatic stretching, two participants had a significantly decreased MTJ displacement and one participant had no significant change. This indicates that the muscle and tendon had the same effect, or the tendon had more influence than the muscle, in improving the flexibility of the foot by automatic stretching. On the other hand, in self-stretching, out of the four participants in which passive torque significantly reduced, one had significantly reduced MTJ displacement, and another did not have significant change; the remaining two participants had significantly increased MTJ displacement. In other words, sometimes the muscle affected the improvement in foot flexibility during self-stretching, and sometimes the tendon affected it equally. Thus, by both automatic stretching and self-stretching in this study, the muscle or tendon was occasionally stretched. However, the tendon rather than the muscles may have affected the flexibility of the foot by stretching using our machine; thus, a more detailed examination is necessary.

The limitation of this study was that automatic stretching was performed only on the right foot due to the machine's structure. Participants did not have any symptoms of the foot, but it is possible that the participant's history had an effect on their foot condition, in fact, there was significant difference in DF-ROM before stretching between the right and the left foot as shown in Table 1. A study comparing the functions of the dominant and non-dominant legs in healthy, middle-aged people, reported that there was a difference between legs in maximal voluntary isometric ankle joint torque and surface electromyography of the lower limb muscles[35)]. Furthermore, in terms of MTJ displacement, there was a significant difference between automatic stretching and self-stretching, but there was no interaction between before/after stretching and auto/self-stretching. This indicates that there could have been differences in the right and the left feet before stretching. In a previous study of healthy young people, the baseline of muscle-tendon unit stiffness was considered not to affect static stretching[36)]. However, in this study, it was targeted at the elderly, so the difference in baseline may have affected the results. It was difficult to control the conditions of the participants' foot and their individual differences; hence, future randomized experiments in which each foot performs each stretching method are required. Moreover, although previous studies report that static stretching decreased passive resistive torque[27, 28, 32)], there were some participants in this study whose passive resistive torque increased after automatic stretching and self-stretching. Our manual measurement might have been incomplete; therefore, more appropriate measurement methods must be chosen in future studies.

We developed the stretching machine to enable the user to perform effective dorsiflexion stretching easily and safely at home. A home-use stretching machine requires an effect equal to, or better than, self-stretching, which has been the main method for stretching at home. Since there are no studies that have examined the effect of self-stretching in sitting position in detail, we investigated the effect of automatic stretching by comparing the effect of self-stretching under the same conditions for elderly people who may require stretching at home. As a result, the range of motion of dorsiflexion increased, and muscle strength of planter flexion tended to be reduced after automatic stretching compared to self-stretching. Furthermore, passive resistive torque decreased in three out of seven participants with automatic stretching, and four out of seven participants in self-stretching. Furthermore, although the amount of MTJ displacement varied depending on the individual, it was suggested that the tendon rather than the muscle might have influenced the improvement in flexibility of the foot in automatic stretching. The results of this study show that the developed stretching machine is as effective as, or better than, self-stretching. This machine may be useful to increase rehabilitation opportunities at home and provide a continuous therapeutic approach to the foot. In the future, we will further verify the effectiveness of this stretching machine by investigating the effects of continuous use on participants with foot pathologies.

Presentation at a conference

Part of the data of this study was presented in 2020 IEEE Global Conference on Consumer Electronics in October 2020[37)].

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Conflict of interest

There are no conflicts of interest to declare.

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