Proceedings of the 2021 IEEE International
Conference on Intelligence and Safety for Robotics
Nagoya, Japan, March 4-6, 2021

Effect of 4 Weeks of Foot Stretching with an Automatic Stretching Machine: A Case Report*

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Abstract— **We developed a stretching machine that automatically performed dorsiflexion foot stretching, and subsequently verified its long-term effect. One participant, with a history of cervical spine injury, underwent stretching of her left foot for 10 mins, twice a week, for 4 weeks. Before and after the experimental period, the ankle dorsiflexion range of motion (ROM), passive resistive torque during passive dorsiflexion, maximum voluntary contraction (MVC) of the ankle plantarflexors, 5-m walking parameters (time, steps, and cadence), and time up-and-go (TUG) test time were evaluated. We found that after 4 weeks of stretching, the ankle ROM was increased, and the passive torque at 10° dorsiflexion and MVC had slightly decreased. Although the 5-m walking time did not change significantly, the TUG test time was 1.2 sec faster. These results indicate that the rigidity of the foot decreased slightly and the stability during the turning motion increased owing to foot stretching using the stretching machine.**

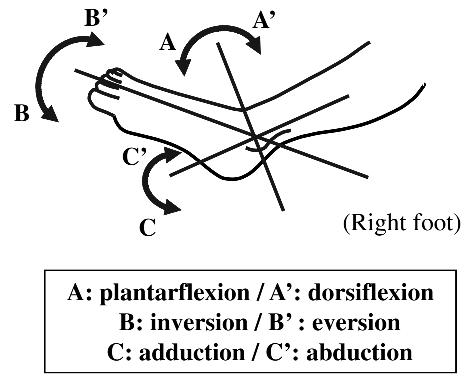

Fig. 1. The three degrees of freedom of the foot movement.

I. INTRODUCTION

Static stretching has the effect of improving range of motion and reducing muscle tone. In clinical practice, stretching is often performed to treat impairments of the foot. Several stretching equipment have been studied with the aim of automating foot stretching. One research group at Northwestern University previously developed a stretching machine for use in bed-side care, and suggested its effects for stroke patients [1], [2]. The foot has the three degrees of freedom as shown in Fig. 1, so that Yoo, et al. developed the three-dimensional foot stretching device for use while standing. They reported that stretching using this device improved the locomotion ability in stroke survivors [3]. In addition, Toda, et al. produced a stretching machine which simulated the therapists' manual stretching technique, which involves pulling the heel towards the bottom side during stretching [4]. However, the clinical effect of this machine has never been examined. Furthermore, Yamada, et al. had developed a three-dimensional foot stretching machine for use with sitting [5], [6]. This machine can automatically stretch the foot, facilitating eversion, abduction, and dorsiflexion and is under improvement to achieve a sufficient effect.

The dorsiflex movement is major procedure in clinical manual foot stretching [7]. Therefore, in the present study, we developed a dorsiflex stretching machine that can be used at home. A commercialized automatic foot exerciser that is pneumatically driven was modified with a function to allow static stretching over a long period [8]. Foot stretching using this machine in young healthy subjects increased the ankle joint range of motion and reduced the resistive torque during passive dorsiflexion. Furthermore, in healthy elderly people, 10 mins of foot stretching using this stretching machine increased the ankle joint range of motion, and potentially decreased the stiffness of the Achilles tendon [9]. These results verified the immediate effect of our stretching machine; however, the effect of long-term use remains unclear.

Although several previous studies have investigated the immediate effects of foot stretching devices, the effects of long-term interventions have not yet been fully demonstrated. Zhou et al. reported the effect of using an automatic stretching device three times a week for three months in stroke patients [10]. In their study, stretching was performed using the proprioceptive neuromuscular facilitation (PNF) method, in which 15-sec stretching was repeatedly performed, followed non-static stretching, which involves continuous stretches over a long period. A systematic review of a study of chronic foot stretching, including several types of stretching (i.e., static, dynamic, and PNF), suggested that more than 8-12 weeks of long-term intervention or more volume and intensity of each stretching was needed to change the structure of the muscles and tendons [11]. The stretching machine we developed is capable of static stretching for a long period, and long-term use of the device is expected to improve foot function. Therefore, using our stretching machine, we examined the effect of stretching when long-term intervention was performed in elderly people with a smaller foot ROM. In this paper, we present the data of one participant.

*This work was supported by JSPS KAKENHI Grant Nos. 17K13108 and 20K19403 and Grants-in-Aid for individual research in Aichi Medical College. We also acknowledge technical support from LAP Co., Ltd.

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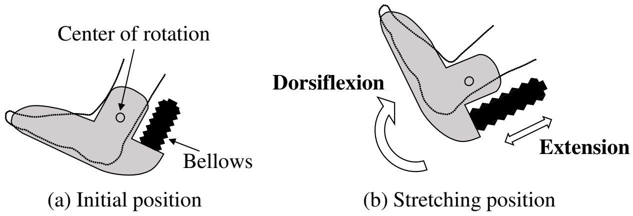

Fig. 2. The mechanism of the stretching machine. First, the foot is placed at the initial position (a). By air inflow, the bellows are extended and the foot is dorsiflexed (b).

II. Methods

A. Participant

The subject is a 68-year-old woman who attended an adult day care center. She had a history of cervical spine injury caused by an accident 3 years prior. Although she could walk independently, she presented with a mildly increased muscle tone in both lower limbs and mild restriction of the range of motion of the ankle joint on both sides. She usually visited the day care center 5 days a week for individual rehabilitation. She had no cognitive function problems. We explained to the patient the purpose and procedure of this study, both verbally and in writing, in advance and obtained informed consent before the experiment. This study was conducted with the approval of the ethics committee of Aichi Medical College (#19204).

B. Stretching method

The stretching machine we developed is pneumatically driven, and the mechanism is shown in Fig. 2. When air flows into the bellows, the foot is dorsiflexed. As the machine is driven with the hold-to-run method, air continues to flow while the user holds the switch.

To stretch the foot, a certain dorsiflexion angle must be maintained. Before stretching, the foot was passively dorsiflexed by the stretching machine, and the air pressure when the user experienced stretching in the lower limbs was recorded. The stretching intensity was thus determined by setting this value as the upper limit of the air inflow during stretching,. After this, to perform foot stretching, the user held the switch to allow upward air inflow until they decided that the stretching intensity had been reached, and the foot was kept in the dorsiflexion position. The machine was programmed to automatically block the inflow of air when the specified stretching time was reached.

The patient's left foot was stretched in the experiment because it had more movement restrictions than the right foot. The left foot was placed on the stretching machine while the patient sat in a chair. Her knee joint was extended, and she operated the switch with her dominant right hand (Fig. 3). Static dorsiflexion stretching using the stretching machine was performed twice a week for 4 weeks. Each session was performed for 10 min by repeating 5 sets of 2-min static stretching. The stretching intensity was set each time before the 2 min of stretching.

Fig. 3. Stretching situation. The participant sat in a chair and the foot was placed on the machine.

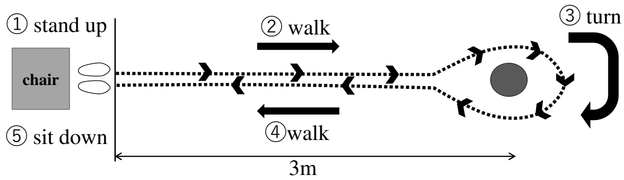

Fig. 4. Outline of time up and go test. The time taken from standing up, walking to a target placed 3-m away, turning around it, walking to the return point, and sitting in the chair is measured.

C. Biomechanical and functional measurements

Biomechanical and functional measurements were performed before and after the 4 week experiment. For biomechanical measurements, passive foot dorsiflexion angle, passive resistance torque during passive dorsiflexion, and maximum voluntary contraction (MVC) of active plantarflexion were evaluated. The dorsiflexion angle was manually measured using a goniometer. The passive resistive torque was evaluated using a handheld dynamometer by measuring the reaction force from the bottom of the foot when passively dorsiflexed to 0°, 5°, and 10°. MVC was measured as the participant was pushing the handheld dynamometer fixed to the frame with the bottom of the foot in the plantar flexion direction. Passive torque and MVC were measured three times each, and the average was used as the representative value.

As functional measurements, the time, number of steps, and cadence during normal 5-m walking and time up and go test (TUG) results were evaluated. Cadence was calculated as the number of steps per second. In the TUG, the time taken from standing up, walking to a target placed 3 m away, turning around it, walking to the starting point, and sitting in the chair (Fig. 4) is measured. The result of the TUG test is usually used to evaluate balance ability. For 5-m walking and TUG, each measurement was taken twice, and the faster times were used as the representative values for each test.

III. Results

The results are shown in Table I. As a result of stretching with the device for 4 weeks, the range of motion of the ankle

TABLE I

RESULTS OF BIOMECHANICAL AND FUNCTIONAL MEASUREMENTS PRE AND POST 4 WEEKS STRETCHING

		Pre	Post
ROM (°)		10	15
Passive torque (Nm)	at 0°	5.0±0.9	4.3±0.6
	at 5°	4.7±0.4	5.1±1.1
	at 10°	6.0±0.6	5.6±0.4
MVC (Nm)		4.5±0.9	3.5±0.2
5m walk	time (sec)	4.4	4.5
	steps (step)	11	11
	cadence (step/sec)	2.5	2.4
TUG (sec)		8.9	7.7

mean±standard deviation
ROM: range of motion in passive dorsiflexion
MVC: maximum voluntary contraction in planterflexion
TUG: time up and go test
0°, 5°, 10°: passive foot dorsiflexion angle during measurement

dorsiflexion increased by 5°. The passive torque decreased slightly at 0° and 10° dorsiflexed and increased at 5° dorsiflexed. The MVC in plantarflexion decreased by 1.0 Nm. In the 5m walk, the number of steps did not change, and the time and cadence showed minimal changes. The TUG time was 1.2 sec faster after 4 weeks.

IV. DISCUSSION

In this study, we investigated the effect of long-term use of the stretching machine we developed, in addition to normal rehabilitation. The participant performed 10-min foot dorsiflexion stretching using the machine twice a week for 4 weeks. After the experimental period, the dorsiflexion range of motion of the ankle increased by 5° and the passive torque at 10° dorsiflexed foot decreased, indicating decreased foot rigidity. We hypothesized that foot stretching using the machine mitigated the muscle tone, thereby increasing the ankle range of motion for a participant who had slight hypertonia of the lower limb because of the cervical spine injury. Moreover, it is possible that the ankle plantar flexion muscle strength also decreased due to the reduction in lower limb muscle tone. Additionally, although the results of 5-m walking did not change significantly, the TUG time was shortened. TUG measures both straight walking and turning; accordingly, the time could be reduced because the turning became smoother. Thus, it was predicted that the subject ' s balance ability had improved.

The limitation of this study is that the experimental period was only 4 weeks. Previous studies have suggested that continuous foot stretching for 8-12 weeks or longer is desirable to assess long-term effects [11], and verification over a longer period is required. In addition, this study reports the effects of machine use in only one participant; further studies with healthy participants and a larger sample size are required to verify our results.

REFERENCES

[1] G. Waldman, C.-Y. Yang, Y. Ren, L. Liu, X. Guo, R. L. Harvey, E. J. Roth, and L.-Q. Zhang, "Effects of robot-guided passive stretching and active movement training of ankle and mobility impairments in stroke," *NeuroRehabilitation*, vol. 32, no. 3, pp. 625–634, 2013.

[2] Y. Ren, Y.-N. Wu, C.-Y. Yang, T. Xu, R. L. Harvey, and L.-Q. Zhang, "Developing a wearable ankle rehabilitation robotic device for in-bed acute stroke rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 6, pp. 589–596, 2017.

[3] D. Yoo, Y. Son, D.-H. Kim, K.-H. Seo, and B.-C. Lee, "Technology-assisted ankle rehabilitation improves balance and gait performance in stroke survivors: A randomized controlled study with 1-month follow-up," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 12, pp. 2315–2323, 2018.

[4] H. Toda, T. Matsumoto, and S. Sugihara, "Simple geometrical analysis for mechanizing the ankle joint stretching treatment procedure of a PT using a numerical calculation," *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, vol. 13, no. 2, p. JAMDSM0034, 2019.

[5] N. Yamada, S. Okamoto, Y. Akiyama, K. Isogai, and Y. Yamada, "Ankle stretching rehabilitation machine for equinovarus: Design and evaluation from clinical aspects," in *IEEE International Conference on Systems, Man, and Cybernetics*. IEEE, 2017, pp. 1687–1692.

[6] T. Kimura, S. Okamoto, N. Yamada, Y. Akiyama, K. Isogai, and Y. Yamada, "Ankle stretching rehabilitation machine for equinovarus: Automation of eversion and flexion control," in *IEEE International Conference on Systems, Man, and Cybernetics*. IEEE, 2017, pp. 2696–2700.

[7] N. Yamada, S. Okamoto, Y. Akiyama, and Y. Yoji, "Principal motion analysis of manual stretching techniques for the ankle joints," *Journal of Physical Therapy Science*, vol. 32, no. 9, pp. 584–590, 2020.

[8] Y. Shiraishi, S. Okamoto, N. Yamada, K. Inoue, Y. Akiyama, and Y. Yamada, "Pneumatically-driven stretching machine for ankle dorsiflexion: safety concepts and effectiveness test involving healthy young subjects," *Robomech Journal*, vol. 7, no. 1, pp. 1–10, 2020.

[9] S. Hashimoto, N. Yamada, S. Okamoto, Y. Shiraishi, Y. Akiyama, and Y. Yamada, "Effect of static stretching using foot stretching device in the elderly: An interim report," in *2020 IEEE 9th Global Conference on Consumer Electronics*. IEEE, 2020, pp. 651–653.

[10] Z. Zhou, Y. Sun, N. Wang, F. Gao, K. Wei, and Q. Wang, "Robot-assisted rehabilitation of ankle plantar flexors spasticity: a 3-month study with proprioceptive neuromuscular facilitation," *Frontiers in Neurorobotics*, vol. 10, p. 16, 2016.

[11] D. M. Medeiros and T. F. Martini, "Chronic effect of different types of stretching on ankle dorsiflexion range of motion: Systematic review and meta-analysis," *Foot*, vol. 34, pp. 28–35, 2018.