

Pneumatic-driven ankle stretching machine

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Abstract—Paralysis after a stroke typically causes equinovarus, for which ankle stretching is a major treatment to facilitate the recovery of the ankle’s range of motion. To provide patients with long-term stretching at home after discharge from the hospital, we have been developing a pneumatic-driven stretching machine that stretches the ankle plantar flexor muscles that cause equinovarus. Thus far, commercial products for this purpose have not been available. In the present study, we conducted experiments on healthy young people (22.3 ± 3.6 years of age) in order to test the effectiveness of our prototype. The participants’ ankle stiffness, which is an index used to assess the joint contracture, was significantly decreased ($F(1, 84) = 20.8$, $p < 0.001$) by their use of our prototype machine.

Index Terms—equinovarus, stretching machine, test of effectiveness

I. INTRODUCTION

Paralysis after a stroke typically causes equinovarus, a three-dimensional foot deformity, by increasing muscle hypertone of the ankle’s plantar flexor muscles. This deformity causes a deterioration in the walking ability of the patient, and increases their risk of falling. Physical therapists treating an equinovarus foot primarily stretch affected muscles to recover the ankle’s range of motion (ROM). Long-term extended stretching is essential since the muscle hypertonia continues after the patient is discharged from a hospital. Therefore, a stretching machine for home-use offers particular value to patients post-discharge.

A number of studies on the topic of ankle stretching machines have been reported in the literature. Waldman et al. developed a machine for ankle dorsiflexion (DF) using an electromagnetic motor and demonstrated the effects on stroke patients’ feet [1]. Yamada et al. prototyped a three-dimensional stretching machine by adopting a wire-driven mechanism [2], [3].

Toda et al. developed a machine for ankle DF [4]. Homma and Usuba developed a machine to move a foot in plantar flexion (PF) and DF direction for improvement of blood circulation [5]. Their machine also offers a degree of freedom of passive motion, allowing both inversion and eversion so as to facilitate physical therapy for a wider range of foot deformities than just those requiring PF and DF. Despite these studies, and the established value of the service that could be

Part of this study was supported by a MEXT KAKENHI grant (17K13108) and Aichi Medical College. We also acknowledge technical support from LAP Co., Ltd.

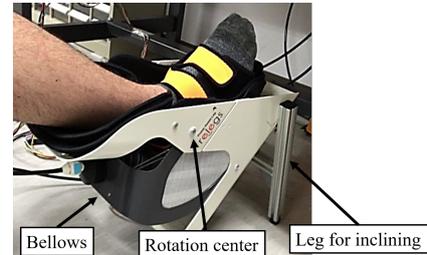


Fig. 1. Prototype of stretching machine for ankle dorsiflexion (DF).

provided with an ankle stretching machine, no such machines are currently commercially available.

In the present study, we develop a prototype ankle stretching machine for treating equinovarus. Further, we verify the effect of the machine’s stretching on the feet of healthy young people by investigating ankle stiffness. The experiments were conducted with the approval of the Institutional Review Board of the School of Engineering, Nagoya University (#18-2).

II. PROTOTYPE STRETCHING MACHINE

The prototype stretching machine shown in Fig. 1 was based on the commercial foot exerciser (Relegs, LAP Co., Ltd., Japan) that provides repeated PF and DF for the prevention of disuse syndrome. This movement is controlled by applying pressure to the bellows, which expands in the longitudinal direction, and then relieving this pressure. The expansion of the bellows pushes and rotates the machine’s moving part around the rotation center located to the outer-facing side of the ankle (Fig. 2). However, the Relegs is not intended for stretching equinovarus feet. To do this effectively, it needs to be remodeled, because it lacks the functionality to facilitate extended stretching of tense ankle plantar flexor muscles. Therefore, the present study remodeled the Relegs for use with equinovarus feet.

The prototype was driven and controlled using an air compressor (CP-12Si, Minato Electrical Co., Ltd., Japan) and an electro-magnetic regulator (ITV1030-312S, SMC Co., Ltd., Japan). The regulator controlled pressurization to the bellows and thereby the resultant DF of the foot. Details of the machine’s stretching operation are provided in the next section.

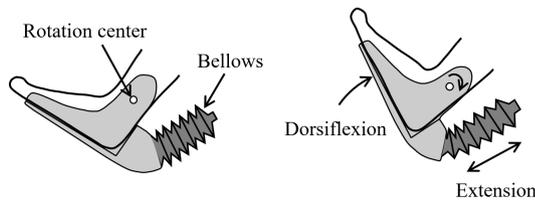


Fig. 2. Operational principles. Left: Initial stage. Right: Pressurization causes bellows to extend longitudinally, leading machine's moving part to rotate around rotation center.

III. EXPERIMENTS: TEST OF EFFECTIVENESS

Healthy young people (14 men and 2 women, 22.3 ± 3.6 years of age) provided informed consent and participated in the experiments to test the machine's effectiveness.

Stretching was performed as follows. The participants sat on a chair and were subjected to the stretching operation of the machine 5 times in a row on a particular foot, with the foot relaxed and with the knee in an extension position. The foot was first dorsiflexed and then maintained in the dorsiflexed posture, following the manual stretching procedure used by physical therapists [6]. The stretching duration was 5 minutes (25 minutes in total). The machine's operational speed slowed as the foot was dorsiflexed, the rate of movement becoming smaller than $2^\circ/\text{s}$ near the end of the ankle's ROM. For safety purposes, the machine was operated using a 3-positioned enabling switch (A4EG-BM2B041, OMRON Co., Ltd., Japan) and the operation continued only while the participants gripped the switch properly.

To respond to individual differences in the ankle's ROM and stiffness, the upper limit of pressure for ankle DF was set by the individual participants according to the following procedures. While the switch was gripped, the foot was dorsiflexed slowly. When a participant felt their calf muscle stretching, the switch was released and the pressure at that point was adopted as the upper limit for their specific flexion range. The upper limit was determined at the beginning of every 5 minutes period of stretching.

Ankle stiffness before and after stretching was measured using a hand-held dynamometer (MT-100, Sakai Medical Co., Ltd., Japan). The dynamometer was pushed against the thenar of participant's sole on the foot involved in the stretching experiments. The relaxed foot was passively moved up to DF angles of 0° , 5° , and 10° , and the passive resistance force at each angle was measured. Resistance was measured 5 times before and after stretching, respectively, and the mean values were calculated for each individual.

IV. RESULTS

The result of the ankle stiffness investigation at DF 10° is shown in Fig. 3. Passive resistance was normalized with each participant's value at DF angle 0° before stretching. Ankle stiffness at DF angle 0° , 5° and 10° decreased by 8.1%, 22.3% and 26.8%, respectively. A two-way ANOVA with pre- and post-stretching and the measurement angles (0° , 5° , and 10°) being factors showed that ankle stiffness significantly decreased

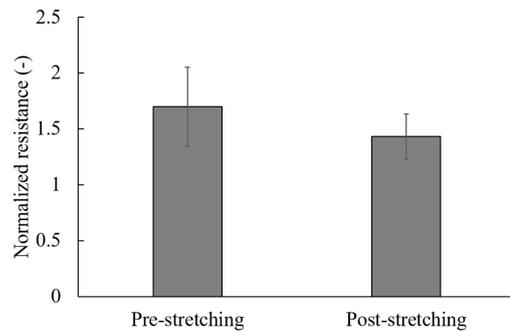


Fig. 3. Ankle stiffness (passive resistance) at dorsiflexion angle 10 degrees. Ankle stiffness of post-stretching decreased by 26.8%. The error bars represent standard errors.

after stretching ($F(1, 84)=21$, $p<0.001$) and interaction was not observed.

V. DISCUSSION AND CONCLUSIONS

A commercial pneumatic-driven foot exerciser was remodeled to develop a prototype ankle stretching machine for the treatment of equinovarus. To verify the effectiveness of the prototype, experiments were conducted on the feet of healthy young volunteers and ankle stiffness before and after stretching was investigated. The previous studies about static stretching reported that ankle stiffness decreased after stretching [7], [8]; our research supported this finding, as, ankle stiffness was decreased significantly. This result indicates that the stretching performed by the prototype machine is indeed effective in improving the ankle's ROM.

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