

Effect of the relative rotation axis position of the stretching machine and ankle

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Abstract: At the onset of a stroke, paralysis of the lower leg typically causes a foot deformity called the foot drop. Stretching is an effective technique for physical therapy. An automated stretching machine provides the option to incorporate long-term stretching at home. We have remodeled a commercial foot exerciser to function as a stretching machine for ankle dorsiflexion [1]. It is believed that the rotation axis of such machines should be aligned with the biomechanical axis of the human body, which is the design principle our prototype is based on. However, there have been no studies that have investigated the best position of the axis required to achieve effective stretching. In this study, we evaluated several positions of the machine's rotation axis in the sagittal plane with respect to the stretching effect and physical burden (safety). The force applied on the foot and ankle dorsiflexion angle were measured during the stretching experiments. We computed the work involved in ankle dorsiflexion and the force not contributing to the dorsiflexion movement, which served as indicators for the stretching effect and potential physical burden, respectively. It was found that the best position of the machine's rotation axis can be above the ankle.

Keywords: Foot deformity, Stretching machine, Rotation axis

1. INTRODUCTION

The paralysis of the lower leg after a stroke increases the tone of the ankle's plantar flexors, and causes a foot deformity called the foot drop [2] (Fig. 1). The contact area of the foot sole is decreased in the stance phase of the gait, adversely affecting stability. Additionally, a trip is induced in the swing phase of the gait with an increased risk of having a fall [3], [4].

Stretching the affected muscles is an effective treatment for the foot drop [5], [6]. This causes a decrease in the muscle and tendon stiffness, and increases the ankle range of motion [7], [8], resulting in improved walking ability. It has been reported that more than 40% of all paralyzed patients exhibit the above mentioned symptoms even after three months after the onset of a stroke [9]. Thus, this indicates that long-term stretching is essential. However, it is difficult for patients to engage the services of a physical therapist to help with stretching over an extended time period. There are also additional restrictions that have been introduced by medical insurance companies. Stretching machines can be useful for solving the above problem. The availability of at-home rehabilitation devices such as therapy bands and stretching boards may still prove insufficient as some patients may have paralyzed body parts in addition to the lower limbs, which makes the use of these devices difficult.

Few studies on ankle stretching machines have been reported to date. Zhang et al. developed a machine that facilitates ankle dorsiflexion for stretching using an electromagnetic motor [8], [10]. Yamada et al. developed a machine for the three dimensional control of the foot using wire-driven mechanisms [11], [12]. This machine

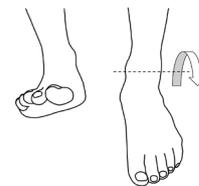


Fig. 1 Foot drop: Foot deformation of the plantar flexion due to hypertonia of the plantar flexor muscles.

achieves three-dimensional foot movement by independently pulling the lateral and medial wires using two McKibben-type pneumatic actuators.

However, despite various research studies, there is no commercially available stretching machine due to problems such as effectiveness, safety, and usability. We have previously proposed safety concepts that should be incorporated when developing stretching machines. The safety measures and stretching function were implemented in a commercial foot exerciser. Further, we verified and demonstrated the effect of our prototype stretching machine in healthy young volunteers prior to tests in foot drop patients [1].

In this study, we discuss the position of the rotation axis of the machine that achieves improvement in the stretching effect. In studies on ankle rehabilitation machines, the axis aligns along the ankle [8], [10], [13], [14]. However, to date this conclusion has not been quantitatively established. In the present study, we identify parameters that represent the indices of the effect and investigate the position of the machine's rotation axis based on the defined parameters. The results of our investigation are reported for the sagittal plane.

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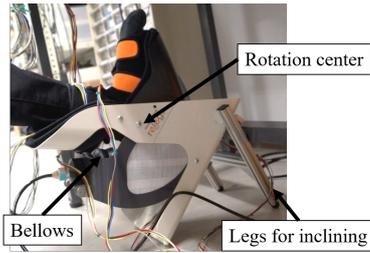


Fig. 2 A prototype stretching machine for ankle dorsiflexion. Developed in [1].

2. PROTOTYPE MACHINE

The machine used in our study is based on a commercial foot exerciser (Relegs, LAP Co., Ltd., Japan) that is originally not used for stretching. Fig. 2 shows the stretching machine that was used, which contains a remodeled chassis of the Relegs [1]. An air compressor (CP-12Si, Minato Electrical Co., Ltd., Japan) and an electro-pneumatic regulator (ITV1030-312S, SMC Co., Ltd., Japan) were used to drive and control the machine. The regulator was controlled by a micro-computer (mbed LPC1768, Arm Holdings plc, UK). The pneumatic actuator (bellows) expanded along the longitudinal direction when pressurized, causing the machine's moving part to rotate around the axis near the ankle. This movement caused the dorsiflexion of the foot. The operation of the machine was controlled by the user via an industrial enabling switch (A4EG-BM2B041, OMRON Co., Ltd., Japan). The machine continued to operate and dorsiflex the foot while the switch was constantly pushed. The operation stopped when the switch was released, and the foot was returned to the initial relaxed position. The operational speed of the machine reduced as the foot was dorsiflexed, with the rate of movement dropping to less than $2^\circ/s$. Other measures were also implemented to enable safe use of the machine in addition to the above detailed stretching functions.

3. EXPERIMENT

3.1 Objectives

Experiments were conducted to measure the ankle joint angle and force applied on the forefoot and to also investigate the appropriate position of the machine's rotation axis.

3.2 Participants

Five healthy volunteers participated in the experiments. They had no foot or leg injuries prior to commencing the experiments.

3.3 Procedures

Participants sat in a chair and experienced the stretching of the machine. The knee joint was fully extended by changing its position relative to the stretching machine. Fig. 3 shows that the position of the machine's rotation axis relative to the ankle was changed by placing a few cushions (7 mm in thickness) below the heel. No cush-

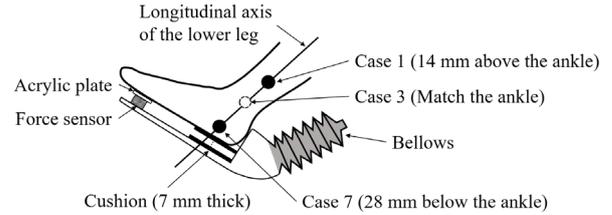


Fig. 3 The experimental setup. The force sensor was mounted on the moving part of the machine where the sensor and acrylic plate pushed the thenar and the hypothenar. The height of the heel was changed in the sagittal and frontal planes as follows. The machine's rotation axes in cases 1 and 2 were 14 mm and 7 mm above the ankle, respectively. The machine's rotation axis in case 3 was aligned along the ankle while in cases 4-7, it was 7, 14, 21, and 28 mm below the ankle, respectively.

ions were used in case 1. Cases 2 and 3 had one and two cushions, respectively. The experimental conditions up to case 7 were prepared in a similar manner. The machine's rotation axis aligned with the ankle in cases 2 or 3 for all the participants.

The participants operated the machine to dorsiflex their feet using the enabling switch. They then released the switch when they felt that the plantar flexors had stretched to the desired extent. This trial was conducted twice in a succession. Once the measurements were performed in the order of the cases 1-7, the reverse order of the cases 7-1 was executed. The above procedures reduced the effect of the measurement order on the results. A total of four trials were conducted in each case.

3.4 Angle and Force Measurement

The ankle joint angle was measured by monitoring the direction of gravity using two three-axis accelerometers attached to the foot and tibia. The sensors were attached in the regions where there was no significant deformation in the skin surface due to ankle movement. The angle in an upright position was 0° along with a positive dorsiflexion angle.

The force applied on the forefoot was measured using a three-axis force sensor (USL08-H18-1KN-AP, TEC GIHAN Co., Ltd., Japan). Fig. 3 shows that the sensor maintained contact with the thenar and hypothenar of the foot sole via an acrylic plate (7 mm \times 25 mm \times 3 mm). The measured forces $\mathbf{f}_0 = [f_{y0} \ f_{z0}]^T$ were transformed into a force that was tangential and perpendicular to the foot sole. $\mathbf{f}_1 = [f_{y1} \ f_{z1}]^T$ shown in Fig. 4 (a) can be computed using the following equation:

$$\mathbf{f}_1 = \mathbf{R}_x(\phi)\mathbf{f}_0 \quad (1)$$

where, $\mathbf{R}_x(\phi)$ is the coordinate transformation matrix around the x axis, and ϕ is the angle between the foot sole and the upper surface of the machine's moving component (the acrylic board). The x axial forces f_{x0} and f_{x1} were not used as this study only focused on the movement

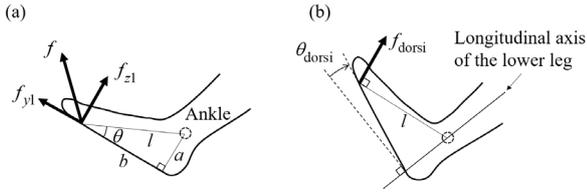


Fig. 4 Force applied on the forefoot. (a) f_{y1} and f_{z1} are the forces that are tangential and perpendicular to the foot sole, respectively. l is the length between the ankle and the point of force application. a and b are the lengths of the sides of the triangle with hypotenuse l . (b) f_{dorsi} is the force that contributes to ankle dorsiflexion and θ_{dorsi} is the ankle joint angle.

in the sagittal plane. Thus, the resultant force on the forefoot can be expressed as:

$$f = \sqrt{f_{y1}^2 + f_{z1}^2}. \quad (2)$$

3.5 Force and Work for Ankle dorsiflexion Calculations

The force contributing to and work associated with dorsiflexion were calculated from the measured ankle joint angle and forces.

The force contributing to dorsiflexion is the component that is perpendicular to the line segment of length l , as shown in Fig. 4 (b). This force can be calculated as:

$$f_{dorsi} = f_{y1} \sin \theta + f_{z1} \cos \theta \quad (3)$$

where, θ is the angle shown in Fig. 4 (a) that was calculated as:

$$\theta = \arctan \frac{a}{b} \quad (4)$$

using the measured lengths a and b .

The work in the dorsiflexion angle θ_{dorsi} range of 10° – 20° was calculated as:

$$W = \int_{10}^{20} f_{dorsi} \cdot l d\theta_{dorsi}. \quad (5)$$

4. RESULTS

Fig. 5 shows an example of the changes in the ankle dorsiflexion angle, and the y and z axial forces during an operation. The illustrated results are from one participant in case 4. The foot was dorsiflexed and reached the end of the range of ankle motion approximately 15 s after operating the machine. The dorsiflexion angle was subsequently approximately stable, while the z axial force continued to increase during machine operation. These trends did not depend on the position of the machine's rotation axis and the individuals. The changes in the y axial force were different in each of the cases under consideration. In the case shown in Fig. 5, the y axial force increased with an increase in the dorsiflexion angle, whereas it decreased after reaching its maximum value in a few cases. The maximum values in all cases were different for each individual or position of the machine's rotation axis.

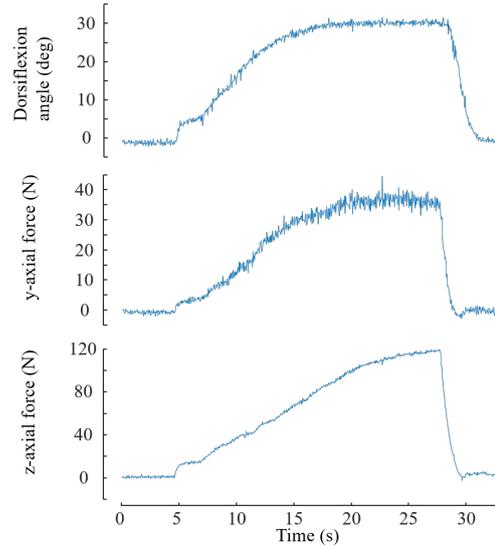


Fig. 5 An example of the dorsiflexion angle, and the y - and z -axial forces applied on the foot. Top: The dorsiflexion angle continued to increase till the foot reached the end of the ankle motion range in all the cases. Middle: The changes in the y -axial force were different for different positions of the rotation axis. The force increased with changes in the dorsiflexion angle in the depicted case. Bottom: The z -axial force kept increasing during operation in all the cases and amongst all participants.

Fig. 6 shows the maximum values of the dorsiflexion angle, the resultant force applied on the foot and force contributing to dorsiflexion, and the work for ankle dorsiflexion seen in all the cases. The values corresponding to all the participants were normalized to the mean values in case 3, wherein the machine's rotation axis approximately aligned with the ankle. The outliers in each dataset were eliminated by Smirnov–Grubbs test for each case. The number of the of data outliers corresponding to the dorsiflexion angle, resultant force, force contributing to dorsiflexion, and work equaled 8, 4, 5 and 8 samples, respectively, when a total of 140 samples from all the participants was considered.

Fig. 6 (a) shows that the maximum dorsiflexion angles did not significantly vary between the different position levels of the machine's rotational axis ($p = 0.39$). Fig. 6 (b) shows that the maximum resultant force had no dependency on the position of the machine's rotation axis ($p = 0.09$). Fig. 6 (c) shows that the force contributing to dorsiflexion decreased significantly ($p < 0.05$) with an increase in the case number. On the other hand, the work increased significantly with an increase in the case number ($p < 0.001$) as shown in Fig. 6 (d).

5. DISCUSSION

The maximum dorsiflexion angle was expected to increase when the misalignment between the machine's rotation axis and ankle reduced. However, the results in

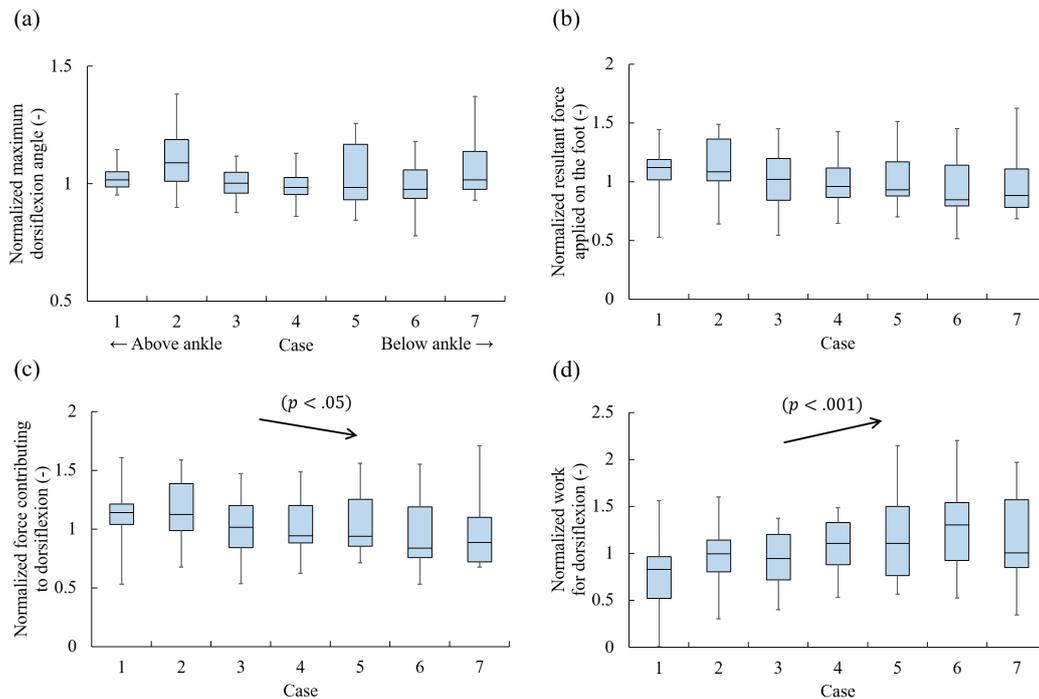


Fig. 6 Experimental results. The data values corresponding to each participant were normalized to that in case 3. (a) Maximum dorsiflexion angle. There was no dependence on the position of the machine's rotation axis. (b) Resultant force applied on the foot. There was no dependence on the position of the machine's rotation axis. (c) Force contributing to ankle dorsiflexion. This decreased as the machine's rotation axis was moved below the ankle. (d) Work for ankle dorsiflexion. This increased as the machine's rotation axis was moved below the ankle.

Fig. 6 (a) show that the position of the machine's rotation axis had a smaller effect on the stretching effect in terms of the maximum dorsiflexion angle. Stretching is generally performed to improve the range of joint motion. However, in our study, the maximum dorsiflexion angle was not used as an indicator of the stretching effect.

Figs. 6 (b) and (c) show that the resultant force applied on the forefoot remained constant, while the force contributing to dorsiflexion reduced when the machine's rotation axis was above the ankle (case 1). The force not contributing to dorsiflexion is perpendicular to that making a contribution, which was greater towards case 1. Further, the work for dorsiflexion was larger when the machine's rotation axis was positioned above the ankle.

The force that did not contribute to dorsiflexion was large in cases where the work was also large. This can be related to the efficiency of dorsiflexion as follows. The internal pressure in the talocrural joint rose and increased the ankle stiffness when the force not contributing to dorsiflexion increased towards the ankle. An increase in the ankle stiffness caused reduced efficiency and increased the work.

Here, we describe the techniques adopted by the physical therapists. The foot is dorsiflexed by stretching the ankle plantar flexors. Simultaneously, the heel is held and pulled by some therapists along the downward direction of the lower leg's longitudinal axis [15] (Fig. 7). These techniques are performed to separate the talocrural joint and improve the efficiency of ankle movement. Additionally, such methods are used to directly stretch the muscles



Fig. 7 An illustration of manual stretching. Physical therapists hold the heel and push the sole when stretching the muscles. Some therapists tend to pull the heel in the distal direction.

along the running direction, which terminate at the heel. This ensures that the therapists not only dorsiflex the foot but also simultaneously incorporate techniques to reduce the ankle stiffness. It is reasonable to speculate while the above factors into consideration that the force not contributing to dorsiflexion increased the work for dorsiflexion in our experiments.

There is to date a belief that the alignment of the machine's rotation axis with the ankle is safe and efficient. However, our study found that a misalignment between them is not significant in terms of the maximum dorsiflexion angle. Rather, there is an increase in the efficiency and the force not contributing to dorsiflexion can be prevented from being generated when the machine's rotation axis is positioned above the ankle.

6. CONCLUSIONS

In this study, we investigated the rotation axis position of the stretching machine in the sagittal plane to improve the stretching effect. The force applied on the forefoot and ankle joint angles were measured to evaluate the effect caused by the changes in the position of the machine's rotation axis. There was an increase in the force and work when the machine's rotation axis was located below the ankle. The force can raise the internal pressure in the talocrural joint and increase ankle stiffness, thus, increasing the work. The results obtained in this study are reasonable when taking the techniques used by physical therapists into consideration. It can thus be suggested that placing the machine's rotation axis above the ankle can increase the machine's stretching efficiency.

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