Effective position of the rotation axis of an ankle stretching machine and the effect of misalignment

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Abstract
The mechanical rotation axes of joint exercisers are believed to operate better when they match the biomechanical axes of human joints. However, there are few studies regarding ankle stretching machines. Further, the effects of rotation axis misalignments are not well known. Hence, we investigate the effective positions of rotation axes for ankle stretching machines and the effects of misalignments using a pneumatic-driven stretching machine developed in our previous study (Shiraishi et al., 2020). Eight healthy young males (ages 23.3 ± 1.4 years) participated in stretching exercises while the relative positions of the rotation axes between the machine and ankle were changed via plates installed under the heel. The stretching machine dorsiflexed the feet of the participants, and the dorsiflexion angles and three-axial forces applied to the forefeet were recorded. The measured values at the maximum dorsiflexion angle were evaluated by two-way analysis of variance and/or regression analysis. We determined that the rotation axis of the machine must be placed 7 mm above the lateral ankle because the normal force applied to the forefoot and maximum dorsiflexion angle were large, whereas the friction force was moderate. Further, the relationships among the dorsiflexion angle and contact forces were investigated via covariance selection. The three-axial forces significantly decreased as the axis of the machine was lowered below the ankle. Additionally, the force normal to the sole had large positive effects on the dorsiflexion angle and friction force of the sole, which could damage the skin. The misalignment of the rotation axis increased the contact force at the sole when the axis of the machine was above the ankle or decreased the efficiency of force transmission from the stretching machine to the user’s foot when the machine’s axis was below the ankle.

Keywords: Ankle contracture, Stretching, Ankle stretching machine, Rotation axis, At-home rehabilitation

1. Introduction

Ankle plantarflexion contracture is a common aftereffect of ankle fractures, stroke, and cerebral palsy, and it reduces the elasticity of the soft tissues comprising the muscles and tendons around the ankle, thereby limiting the range of motion (ROM) of the ankle. Reports have estimated that 77% of ankle-fracture patients generally suffer from ankle contractures immediately after cast removal (Pun et al., 1991), and approximately 84% of craniocerebral palsy patients (Yarkony and Sahgal, 1987) and 50% of stroke patients (O’Dwyer et al., 1996) are also prone to these effects. Stretching is the primary physical therapy for treating ankle contractures and is effective in improving the ROM of the ankle and reducing ankle stiffness (Bressel and McNair, 2002; Medeiros and Martini, 2018; Harvey et al., 2017; Radford et al., 2006; Mizuno et al., 2013). Ankle contractures typically continue to progress after the patient is discharged from the hospital, so long-term stretching is essential. However, medical insurance policies restrict the opportunities for rehabilitation after discharge, and patients encounter difficulties in receiving long-term care from physical therapists in some countries. Therefore, stretching machines developed for domestic usage are expected to address these problems.
Thus far, a few ankle stretching machines have been developed for treating or preventing ankle plantarflexion contractures. Machines for ankle dorsiflexion were developed using electromagnetic or linear motors (Waldman et al., 2013; Ren et al., 2017; Toda et al., 2016, 2019; Zhou et al., 2016). Yamada et al. developed a machine for 3D foot motion for dorsiflexion, abduction, and eversion using McKibben-type pneumatic actuators and wire-driven mechanisms (Yamada et al., 2017; Kimura et al., 2017). The authors of the present study have also developed an ankle stretching machine by modifying a commercial foot exerciser with a pneumatic actuator (Shiraishi et al., 2020) and demonstrated its effectiveness in decreasing the passive dorsiflexion resistance in young healthy subjects. In the present study, we use this developed machine. In addition, ankle rehabilitation machines for non-stretching purposes have been developed to prevent disuse syndrome or thrombus. Homma et al. developed a machine for ankle plantar/dorsiflexion using an electromagnetic motor to ameliorate blood circulation (Homma et al., 2011). Other studies have developed ankle exercise machines using pneumatic actuators (Sasanuma et al., 2018; Saga and Saito, 2008).

In this study, we focus on the rotation-axis position of an ankle stretching machine. It is believed that the rotation axes of ankle rehabilitation machines should be aligned with the ankle joints of the users. However, accurate localization of the biological rotation axis is visually impossible from external appearance, and the inclination may change during ankle plantar/dorsiflexion (Hicks, 1953; Barnett and Napier, 1952). In other words, misalignments may necessarily occur when using stretching machines. Studies on the effects of misalignments of the rotation axes of the machine and biological joints of the elbows, shoulders, and knees (Akiyama et al., 2012, 2015a, 2015b; Schiele and Van der Helm, 2006, Jarrasse and Morel, 2012; Zanotto et al., 2015) indicate that the contact forces increase in an undesirable manner. However, studies using ankle stretching machines and those regarding the effects of misalignments on stretching have not been conducted. Although some believe that the effects of misalignments are geometrically inferred because of the complex biomechanical systems, experimental measurements are necessary.

A study on the rotation axes of ankle stretching machines (Toda et al., 2019) investigated the position of the rotation axis of the machine using a machine that involves substantially different mechanisms from the one used in this study. Toda et al. reported that the rotation axis (of the machine) positioned at the back of the ankle was the optimal position considering that the stretching of the machine was similar to the techniques utilized by physical therapists. In this study, however, we investigate the rotation axis of the ankle stretching machine from the perspective of the stretching effect.

We previously investigated the effects of the relative positions of the rotation axes between the ankle stretching machine and ankle in the sagittal plane using our pneumatic-driven ankle stretching machine. The results suggested that the force that did not contribute to ankle dorsiflexion diminished the stretching effect (Shiraishi et al., 2019a). However, the relationship between the dorsiflexion angle and force applied to the foot was not investigated. This study, therefore, investigates the relationships between the three-axial forces applied on the foot and the dorsiflexion angle while changing the relative positions of the axes. We then discuss the rotation axis positions of the ankle stretching machine for ensuring effective stretching and lowering the risk of skin damage, as well as the effects of misalignments of the rotation axes.

The experiments were conducted with the approval of the Institutional Review Board of the School of Engineering, Nagoya University (#18-2).

2. Ankle stretching machine

The stretching machine (Fig. 1) was based on the chassis of a commercial foot exercise machine for ankle dorsiplantarflexion (Shiraishi et al., 2020). When the bellows (i.e., pneumatic actuator) were pressurized, it expanded in the longitudinal direction, and the foot was dorsiflexed with rotation of the moving part of the machine (Fig. 2). The machine repetitively moved the foot in the dorsiplantarflexion direction within the ROM of the ankle. The air pressure was output from an air compressor (CP-12Si, Minato Electrical Co., Ltd., Japan), and controlled using an electro-pneumatic regulator (ITV1030-312S, SMC Co., Ltd., Japan) and a microcomputer (mbed LPC1768, Arm Holdings plc, UK).

In the present study, the moving part of the machine lifted the forefoot using a foot contactor plate (7 × 2.5 cm) attached to the eminence. This enabled measuring the contact force between the foot and machine, as will be described later in Section 3.3. Without this contactor, the force from the moving part would be applied to the entire forefoot. The heel weakly contacted with the machine’s moving part. Hence, the force from the machine was primarily transmitted to the forefoot and secondarily to the heel. The reaction force was largely concentrated on the posterior part of the calf.

The safety functions of the machine, although not the focus of this study, are briefly mentioned here: To prevent the application of excessive forces on the foot, the output was restricted using a valve (JR-08, Astroproducts, Japan) and an electro-pneumatic regulator. Additionally, the ROM of the ankle was restricted using mechanical limiters, thereby
Fig. 1 Prototype of stretching machine for ankle dorsiflexion. The foot dorsiflexed slowly and maintained the dorsiflexed posture. Adapted from (Shiraishi et al., 2019b).

Fig. 2 Operational principles. Left: Initial stage. Right: Pressurization causes the bellows to expand longitudinally, causing the moving part of the machine to rotate around the rotation center. Adapted from (Shiraishi et al., 2019b).

preventing the ankle from moving out of the natural ROM by the excessive loads applied on the foot. The above-mentioned upper limits of air pressure and the ROM of the ankle were determined based on the individual ankle stiffness and the ROM. The machine was operated using an industrial three-position enabling switch (A4EG-BM2B041, OMRON Co., Ltd., Japan). While the user gripped the switch, the bellows continued to be pressurized and the foot was dorsiflexed. When the user released or strongly gripped the switch, the air pressure in the bellows was released and the foot slowly returned to the relaxed foot posture. Thus, stretching was continued only if the user intended so. The safety measures are detailed in (Shiraishi et al., 2020).

3. Experiments

Stretching was performed using our stretching machine under different conditions of relative rotation axis positions of the machine and the ankle in the longitudinal axis of the lower leg. During stretching, the ankle dorsiflexion angle and three-axial contact forces were measured, and the details are presented subsequently.

3.1. Participants

Eight healthy male participants in their twenties, with no injuries in their lower legs and feet, participated in the experiments. The data of five participants among the eight were used in our previous study (Shiraishi et al., 2019a).

3.2. Experimental setup

The relative rotation axis positions between the stretching machine and the lateral ankle were changed by installing plates of 7 mm thickness (Fig. 3). In Case 1 and 2, the rotation axis of the machine was 14 and 7 mm above the lateral ankle, respectively; in Case 3, it was aligned with the lateral ankle; in Case 4–7, it was 7–28 mm below the lateral ankle. A potential problem caused by this method is discussed in Section 4.4. The relative rotation axis position was determined at 5° of the ankle plantarflexion angle. To adjust to individual differences, the experimenter carefully selected the thickness of the base plate beneath the sole; the 7 mm-thickness plates were placed upon this base plate. By changing the position of the machine’s rotation axis relative to the human ankle, the direction of force received by the forefoot was also changed. This change in contact force is considered to be attributable to the change in the maximum dorsiflexion angle as the
Fig. 3 Rotation axis position of the machine relative to the ankle. Modification from (Shiraishi et al., 2019b).

Fig. 4 Coordinate system of the contact force. x-axis is from medial to lateral; y-axis is from the heel to the forefoot; z-axis is from bottom to top.

Fig. 5 Angle ($\phi$) between the upper surface of the force sensor and the sole. Left: $\phi$ is 0\(^\circ\). Right: upper surface of the force sensor is inclined from the sole at $\phi$ deg. This is because the relative positions of the rotation axes between the stretching machine and the ankle was changed by installing plates under the heel in our study. Note that neither of these figures represent any case numbers.

Direction of the applied force is a primary parameter of manual stretching (Yamada et al., 2014). Further, the dorsiflexion angle and contact force may interact with each other.

### 3.3. Measurement of ankle dorsiflexion angle and forces

The ankle dorsiflexion angle was measured using two three-axial accelerometers (MMA7361, Freescale Semiconductor, USA). Each sensor was attached on the instep of the foot and the tibia, where the skin does not deform largely during ankle movement. The variations in the inclination angles of the two sensors were measured, and a 0\(^\circ\) dorsiflexion angle was determined in the standing posture. The forces applied on the forefoot were measured using a three-axial force sensor with a built-in amplifier (USL08-H18-1KN-AP, TEC Gihan Co., Ltd., Japan) (Fig. 3). The sensor was in contact with the sole through an acrylic plate (70 \(\times\) 25 \(\times\) 3 mm). The positive directions of the forces were defined as shown in Fig. 4: x-axis is from the medial to the lateral side of the foot, y-axis is from the heel to the forefoot, and z-axis is from the sole to the instep of the foot. The relative position between the rotation axis of the machine and the lateral ankle was changed by placing plates beneath the heel, thereby introducing differences in the inclination angles of the sole and upper surface of the force sensor (acrylic plate) (Fig. 5). To calculate $\phi$, a three-axial accelerometer was attached on the moving part of the machine and the differences in angle between the moving part of the machine and the sole were calculated. The contact force $f$ (\(= [f_x, f_y, f_z]^T\)) was obtained by computing the rotation of the output of the force sensor $f_0$ (\(= [f_{x0}, f_{y0}, f_{z0}]^T\)):

$$f = R_x(\phi)f_0,$$

where $R_x(\phi)$ is a rotation coordinate transformation matrix around x-axis. The contact force at the dorsiflexion angle of 5$^\circ$ was the base: $f = [0 0 0]^T$. For example, the contact force components at the maximum dorsiflexion angle for Case 1
were $f_x = -4.9 \pm 0.5$, $f_y = 16.0 \pm 1.5$, and $f_z = 68.2 \pm 3.6$ (N) (mean ± standard error).

According to Mao et al. (2017b), an inherently safe threshold of tangential traction for skin abrasion caused by repeated rubbing motion is 40 kPa for the continuous stimulation of 300 s, which was the duration adopted in our previous study (Shiraishi et al., 2020). Considering the surface area of the forefoot plate ($1.75 \times 10^{-3}$ m$^2$), this threshold value corresponds to $f_y = 70$ (N), which is substantially greater than the value observed in the experiment. When using the setup in the present study, none of the participants claimed any skin problems after the experiments.

3.4. Tasks

The participants sat on a chair in a relaxed state and wore the ankle stretching machine with their knees fully extended. They wore a sock to prevent skin damage, and the foot was secured to the moving part of the machine with cloth bands to the extent of non-excessive pressure applied on the foot. The calf was supported by the cushion attached to the machine, as shown in Fig. 1.

The participants controlled the three-position enabling switch, and the foot was dorsiflexed. The initial foot posture was slight plantar flexion. The operational speed was less than $4^\circ$/s during ankle dorsiflexion. The participants released the switch when they felt the calf muscle had stretched. One operation typically spent 30 s. Each participant conducted four trials for each case. Considering the effects of measurement order, two trials were first conducted from Cases 1–7, and two trials were then conducted from Cases 7–1.

3.5. Results

An example of the ankle dorsiflexion angle and three-axial forces applied on the foot is shown in Fig. 6. As the foot was dorsiflexed, the dorsiflexion angle increased slowly (Fig. 6 (a)) and the magnitude of each force increased (Fig. 6 (b)–(d)). Similar trends were observed in most cases and participants. For the following analysis, the dorsiflexion angle $\theta$ and the forces $-f_x$, $f_y$, and $f_z$, which were all measured in the maximum dorsiflexed posture, were used; $-f_x$ was used because $f_x$ was measured as negative. Fig. 7 shows $\theta$, $-f_x$, $f_y$, and $f_z$ for each case after normalization with the mean value among all trials for individuals, such that the individual mean was 1. Fig. 8 shows the mean contact forces for each case.

To investigate the variation of $\theta$, $-f_x$, $f_y$, or $f_z$ between the cases, a two-way analysis of variance was performed.
Fig. 7 Means and standard errors of the dorsiflexion angles ($\theta$) and forces applied to the foot ($-f_x, f_y, f_z$) in the maximum dorsiflexion position. $\theta$ in Case 2 was significantly larger than that in other cases and exhibited interaction with individuals. Three-axial forces significantly decreased with the case number. *, **, and *** represent $p < 0.001$, 0.05, and 0.001, respectively.

Fig. 8 Means and standard errors of contact forces for each case.

using all cases and individuals as factors. In this analysis, the measured values before being normalized were used. The $F$-values and $p$-values are listed in Table 1. The results of all quantities exhibited the effects of cases, individuals, and interaction.

Post-hoc tests were performed as follows:

As shown in Fig. 7 (a), the maximum dorsiflexion angle $\theta$ in Case 2 was markedly larger than that in other cases. Therefore, Case 2 and other cases were compared via a two-way analysis of variance with no adjustment of $p$-values using the cases (Case 2 and other cases) and individuals as the factors. The $F$-values and $p$-values are listed in Table 2. The results exhibited the effects of cases, individuals, and interaction for all the comparisons.

As shown in Fig. 7 (b)–(d), the forces $-f_x, f_y$, and $f_z$ decreased with the case number. The significance of these trends was investigated via a single regression analysis as a post-hoc test. In this analysis, normalized force values were used to cancel the baseline differences between the participants. The results exhibited significant trends of $f_x$ ($t(223) = 6.4$, $p = 1.1 \times 10^{-9}$), $f_y$ ($t(223) = 3.1$, $p = 2.5 \times 10^{-3}$), and $f_z$ ($t(223) = 4.9$, $p = 2.0 \times 10^{-6}$).

4. Discussion

4.1. Causalities between dorsiflexion angle and forces

As noted in Section 3, it was found that the contact forces ($f_x, f_y$, and $f_z$) and $\theta$ varied with the position of the machine’s rotation axis. A reasonable speculation for this is that the change in the rotation axis position varies the
Still damage the skin.

Stretching posture, −f_x, −f_y, and f_z exhibit a positive partial correlation.

During stretching for ankle dorsiflexion, the triceps surae mainly stretched, and so did the tibialis posterior. Tibialis posterior is the main muscle of ankle inversion, as well as a collaborative muscle of plantarflexion, because it runs diagonally around the ankle (Fig. 11). Therefore, when tibialis posterior stretches during ankle dorsiflexion, the tension of the muscle works for both inversion and plantarflexion. In our experiments, the force in the inversion direction was measured as −f_x. Therefore, from an anatomical perspective, it is reasonable that f_y and f_z exhibited negative and positive effects on θ, respectively. These causalities were interpreted as follows:

The measured forces could mainly be the reaction forces of ankle plantar flexors and tendons. When the foot is dorsiflexed, the plantar flexors generate a resistance in the plantarflexion direction. In other words, passive ankle dorsiflexion applies a reaction force in the plantarflexion direction at the forefoot (red arrow in Fig. 10). At this time, the forces in the positive direction of f_y and f_z are applied on the foot as the reaction force. Therefore, it is reasonable that f_y and f_z exhibited a positive partial correlation.

During stretching for ankle dorsiflexion, the triceps surae mainly stretched, and so did the tibialis posterior. Tibialis posterior is the main muscle of ankle inversion, as well as a collaborative muscle of plantarflexion, because it runs diagonally around the ankle (Fig. 11). Therefore, when tibialis posterior stretches during ankle dorsiflexion, the tension of the muscle works for both inversion and plantarflexion. In our experiments, the force in the inversion direction was measured as −f_x. Therefore, from an anatomical perspective, it is reasonable that f_y and f_z exhibited negative and positive effects on −f_x.

It is clear that f_z exhibits a positive effect on θ because of the large contribution of f_z to ankle dorsiflexion. In the stretching posture, f_z mainly increases θ in the sagittal plane. However, f_z could indirectly affect θ through f_y and could still damage the skin.

### Table 1: Results of two-way analysis of variance: maximum dorsiflexion angle θ and applied forces f_x, f_y, and f_z

<table>
<thead>
<tr>
<th>Factor</th>
<th>θ</th>
<th>p-value</th>
<th>−f_x</th>
<th>p-value</th>
<th>−f_y</th>
<th>p-value</th>
<th>f_z</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individuals</td>
<td>31.9</td>
<td>7.0×10^{-14}</td>
<td>92.7</td>
<td>2.4×10^{-14}</td>
<td>54.8</td>
<td>3.8×10^{-10}</td>
<td>147.0</td>
<td>3.3×10^{-8}</td>
</tr>
<tr>
<td>Cases</td>
<td>3.2</td>
<td>5.9×10^{-3}</td>
<td>15.2</td>
<td>7.6×10^{-14}</td>
<td>9.0</td>
<td>1.6×10^{-4}</td>
<td>11.2</td>
<td>1.7×10^{-10}</td>
</tr>
<tr>
<td>Interaction</td>
<td>4.4</td>
<td>3.7×10^{-12}</td>
<td>2.5</td>
<td>1.7×10^{-5}</td>
<td>2.4</td>
<td>3.0×10^{-5}</td>
<td>3.5</td>
<td>5.6×10^{-9}</td>
</tr>
</tbody>
</table>

### Table 2: Results of two-way analysis of variance: post-hoc test for maximum dorsiflexion angle θ compared with Case 2

<table>
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<th>Case 2–3</th>
<th>Case 2–4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individuals</td>
<td>11.3</td>
<td>2.4×10^{-3}</td>
<td>12.4</td>
</tr>
<tr>
<td>Cases</td>
<td>5.6</td>
<td>2.2×10^{-2}</td>
<td>13.0</td>
</tr>
<tr>
<td>Interaction</td>
<td>3.3</td>
<td>6.2×10^{-3}</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Fig. 9 Causalities of dorsiflexion angle and three-axial forces applied on the foot at the maximum dorsiflexion position. The values are partial correlation coefficients. Red and blue arrows represent positive and negative effects, respectively. Black arrow represents partial correlation.
Fig. 10  Force generated by plantar flexors in the sagittal plane. Red arrow represents the reactive force of the plantar flexors, and black arrow represents the force applied on the foot in the positive direction of $f_y$ and $f_z$.

Fig. 11  Tibialis posterior of right foot. Left: side view from medial side. Right: view from the heel. The picture shows the part of the muscle whose originating location is actually at the crural interosseous membrane and the adjacent face of the tibia and fibula.

Fig. 12  Coupling motion of ankle. Abduction and eversion are coupled with dorsiflexion, thereby increasing the maximum dorsiflexion angle.

The negative effect of $-f_x$ on $\theta$ could be because of the disturbance of $-f_x$ for dorsiflexion. Ankle dorsiflexion occurs coupled with eversion and abduction (Fig. 12), whereas plantarflexion occurs coupled with inversion and adduction. $-f_x$ represents the force in the inversion direction, and disturbs eversion, which prevents ankle coupling motion and decreases the maximum dorsiflexion angle. Therefore, it is understandable that $-f_x$ negatively affects $\theta$.

From the above analysis, $f_z$ largely determines $\theta$. In this sense, the higher position of the machine’s rotation axis is favored because $f_z$ increases with decrease in the case number. However, $-f_x$ and $f_y$, which directly or indirectly disturb the increase in $\theta$, also increase with the case number. Hence, Case 2 where these force components are balanced well might have resulted in maximum $\theta$.

4.2. Effective position of the rotation axis of the machine

First, we focus on the stretching effect. The causalities in Fig. 9 indicate that $f_z$ increases $\theta$. Case 2, in which both $f_z$ and $\theta$ are large, is determined the best for effective stretching (Fig. 7 (a), (d)). Note that the effective position has individual differences because of the interactions between cases and individuals. Next, we focus on the shear force $f_y$ during stretching as an index of risk of skin damage. $f_y$ exhibited a positive partial correlation with $f_z$ and significantly decreased with the case number (Fig. 7 (c)). Comparing the safe thresholds of tangential traction (Mao et al., 2017b), i.e., 40 kPa, the mean $f_y$ values of all the cases were observed to be low. For example, the mean maximum $f_y$ was 16.0 N for
Case 1 (Fig. 8), and this corresponded to a traction of 9.14 kPa by considering the area of the forefoot contactor used in the study. The maximum force in one trial for Case 1 reached 44.0 N, leading to a traction of 28.6 kPa, which was still below the safe threshold. Hence, we may determine the best case on the basis of $\theta$, and Case 2 is suggested to be the most effective position.

The abovementioned discussion did not consider $-f_x$. The causalities showed that $-f_x$ decreases $\theta$. Following this trend, $\theta$ should have increased with the case number because $-f_x$ significantly decreased with the case number. However, the partial correlation coefficient between $-f_x$ and $\theta$ was as small as $-0.08$ and $-f_x$ had only an insignificant effect on $\theta$.

Further, we consider the anatomical validity of Case 2—in which the rotation axis of the machine was positioned 7 mm above the lateral ankle—which was determined as the most effective position. Studies on anatomical ankle rotation axis have shown that its position changes with ankle motion, and it is inclined in the dorsiflexed posture to pass through the medial and lateral tip of the ankle (Hicks, 1953, Barnett and Napier, 1952). Additionally, it has been reported that the rotation center of the ankle is at the midpoint of the medial and lateral tip of the ankle or slightly lateral side (Lundberg et al., 1989) (Fig. 13). In other words, the rotation center of the ankle is positioned a little above the lateral ankle, and the 3D ankle motion occurs around this rotation center. In our study, the heights of the medial and lateral tip of the ankle were measured at the standing position, and their midpoint was defined as the rotation center. Consequently, the rotation center is estimated to be positioned 6.8 ± 2.2 mm (mean ± standard deviation) above the lateral ankle. This height approximately matches the rotation axis position in Case 2. Therefore, in Case 2, the rotation axis of the machine can pass through the near position of the rotation center of the ankle. This is consistent with the existing belief that the rotation axis of the machine should match that of the ankle.

### 4.3. Effect of misalignment of the rotation axes

As shown in Fig. 7, when the rotation axis of the machine was positioned above the lateral ankle, the shear force $f_y$ was large and risk of skin damage was high. However, in the present study, we did not observe a tangential traction greater than the safe threshold estimated by (Mao et al., 2017b). When the rotation axis of the machine was positioned below the lateral ankle, the contact force applied on the foot was relatively small. Although the small shear force ($f_y$) decreases the risk of skin damage, the small normal force $f_z$ decreases the stretching effect.

Because of misalignment of the axes, the force from the machine might have not been effectively transmitted to achieve foot dorsiflexion. For example, it was observed that the leg was lifted slightly during operation in cases with higher numbers. The phenomenon of floating leg has been previously reported in a study on ankle stretching machines (Toda et al., 2019), where the authors showed that the relative positions of the rotation centers of the machine and ankle result in floating of the Achilles tendon, i.e., leg. In our experimental setup, as shown in Fig. 8, the resultant forces at the forefoot were smaller for the large case numbers than those for the small case numbers. This indicates that a part of the generative force of the machine exerted to parts other than the forefoot, i.e., heel, when the case number was large.

The machine’s force was partly used to push the sole near the heel toward the frontal direction. Although we did not measure the force at the heel, this change could be subjectively felt. Such forces near the heel contributed only slightly to the dorsiflexion of the foot because of the small moment arm. In other words, when the misalignment was significant, the generative force was not effectively utilized for foot dorsiflexion. Studies regarding wearable physical assistant robots have similarly reported that misalignments increase the unnecessary contact forces (Akiyama et al., 2012, 2015a, 2015b; Schiele and Van der Helm, 2006; Schiele, 2008).
Fig. 14 Geometrical relationship between the forces applied to the foot and the relative position of ankle and rotation axis of the stretching machine. Rotation axis of the machine (a) matches the ankle, (b) is below the ankle: $f_y$ is smaller and $f_z$ is larger, and (c) is above the ankle: $f_y$ is larger and $f_z$ is smaller. Note that the resultant force applied to the foot is assumed to be the same for all conditions.

Finally, we consider the effect of misalignment from the perspective of geometrical relationship. As shown in Fig. 14 (b), when the rotation axis of the machine is below the ankle, the direction of the force at the forefoot is slightly towards the back compared with that for the matched case in (a). Contrarily, as shown in Fig. 14 (c), when the rotation axis of the machine is above the ankle, the direction of the force at the forefoot is slightly towards the front compared with that for the matched case. This trend was mostly true for our experiments, as indicated by Fig. 8.

4.4. Limitations of the study

As described in Section 3.2, we inserted plates beneath the heel to change the relative positions between the ankle and machine’s rotation centers. This manipulation also changed the relative positions between the machine and the participants’ lower legs that received the force reactions to stretch the ankles. We cannot decouple these two types of changes and specify the effects of the latter changes on the contact forces at the forefoot and ankle dorsiflexion angles. The human calf area is not cylindrical but complex, and the changes in the contact between the calf and machine might have influenced the results of our experiment.

Further, our discussion and conclusions were based on the contact forces and foot angles at the maximum dorsiflexion position, and we do not have the data during the motions. Such data may tell us how the foot is dorsiflexed and help us specify effective stretching measures with low power consumption.

5. Conclusions

We investigated the effects of the rotation axis positions of a previously developed ankle stretching machine on the dorsiflexion angles and contact forces at the forefoot. The effective rotation axis of the machine is suggested to be positioned 7 mm above the lateral ankle as in Case 2 for relatively small shear forces and large dorsiflexion angles. This position can be close to the anatomical rotation center of the ankle, which corroborates the existing belief that the rotation axis of the machine should be aligned with that of the ankle. Further, when the rotation axis of the machine was positioned above the lateral ankle in Case 1, the contact force at the forefoot was large. This is a common effect of misalignment of the rotation axis, known from studies on wearable physical assistant robots. On the other hand, when the rotation axis of the machine was positioned below the ankle in Case 3–7, the forces applied on the forefoot were small. In this case, the misalignment decreases the efficacy of both force transmission and stretching effect. In a future study, this suggested position of the machine’s rotation axis should be tested in clinical scenarios.

References

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