Simple geometrical analysis for mechanizing the ankle joint stretching treatment procedure of a PT using a numerical calculation

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Abstract
In this paper, to mechanize a human ankle joint stretching treatment that is mainly performed by a PT (Physical Therapist), the geometrical relationships among the Ankle joint, Hip joint, Sole, and pushing device rotation center are analyzed using a simple numerical calculation model, and the effectiveness of the model was examined in an actual developed system. The stretching of the ankle joint is an important medical treatment that PTs perform to help their patients to recover their ability to walk and to prevent contracture. Because the ankle joint treatment requires a large amount of force (equal to the subject’s weight) and precise angle control at the same time, manual treatment by PTs has not been replaced by mechanical treatment systems. In a previous study, we developed a new mechanism of ankle joint stretching that involves fixing the length of the subject sitting chair and the device; the novel mechanism can realize comfortable stretching without pain. However, the optimum geometrical relationships among the Ankle joint, Hip joint, Sole, and pushing device rotation center have not been analyzed. In this paper, to develop the effective mechanism of the stretching treatment, the geometrical relationships were analyzed mathematically by using numerical calculation, and the effectiveness of the numerical calculation was confirmed by manufacturing a treatment device comprising two force sensors and two DC motors based on the calculation results. Numerical calculation results show that the PT’s key point of the ankle joint treatment was a position located between the Ankle joint and the pushing device rotation center. The analytical result will effectively promote the development of the mechanical systems used as ankle joint stretching treatment devices.

Keywords: Ankle joint contracture removal, Ankle joint pushing mechanism, Numerical calculation, Physical Therapist(PT), Rehabilitation system

1. Introduction
The ankle is an indispensable body part for carrying out daily activities, such as walking. The ankle has a strong anatomical design that is adequate to bear a heavy load in daily life. If the ankle joint cannot be moved for a long time because of a sickness or injury, then it will suffer an ankle joint contracting state. The PT performs treatment on the ankle joint stretching by a manual therapy (Fig. 1). The manual therapy has advantages of ankle joint stretching by a large force (equal to the body weight), and it can avoid the over-stretching of the patient. However, manual therapy requires approximately 20 minutes of exercise at one time, and daily treatment is necessary, making the performance of manual therapy difficult for the PT. Typical manual therapy involves the following steps: 1) the PT holds the patient’s heel with the PT’s palm and 2) the PT pushes the Sole of the patient’s foot via the PT’s forearm. This therapy can effectively stretch the relevant muscles and tendon, namely, the muscles of the calf and the thigh and the Achilles tendon. As shown in Fig. 2, the patient foot floats upward during the ankle joint stretching (Fukui, 2010; Kakurai, 1994). It is important to consider realization of the foot floating process when mechanizing the above-described ankle joint stretching process. The foot floating process involves the use of the pushing force of the PT’s sole to move the foot upward while stretching the muscles and tendon. It is important to ensure the mechanized foot stretching approach is not painful to the subject.
Fig. 1 An important medical treatment in which the physical therapist (PT) bends the ankle joint to help the patient recover her/his ability to walk and to prevent contracture.

Fig. 2 The foot is floating above the floor during the ankle joint stretching process performed by the PT.

Note that the treatment method/strategy of the PT cannot practically be analyzed using a mathematical approach because of the time required to perform the difficult mathematical analysis.

1.1. Previous study

Interest in medical rehabilitation equipment for persons requiring long-term care has increased rapidly in recent years. To prevent a person from being bedridden, daily rehabilitation of the ankle is necessary. Fukui et al. reported that if rehabilitation of the ankle is not conducted one day, then rehabilitation of the ankle for seven days is required; even worse, if this seven days of rehabilitation are not conducted, then rehabilitation of the ankle for 51 days is necessary (Fukui, 2010; Hagbarth, 1985; Nagasawa, 2011; Watanabe, 2013).

The tilt table (Nihon-Medix Corp.) is a typical rehabilitation system for the ankle joint. The tilt table requires the patient to be strapped to a bed with belts; the bed angle is tilted using an actuator inside the base of the bed. The weight of the patient is gradually transferred to the patient’s ankle while the tilt angle is changed. However, some problems related to forcibly changing the slope of the body were reported: 1) the patient may faint and 2) the force may not be correctly applied to the patient’s ankle. Because of these problems and the large required setup space of the tilt table, smaller ankle joint rehabilitation systems have been proposed (Hayashibara, 2003; Merlo, 1992; Nagase, 2010; Noda, 2006; Nomura, 2016; Onodera, 2013; Saga, 2010; Suzuki, 2005; Tanaka, 2012; Tsukamoto, 2008). These smaller systems are composed of a calf attachment system and a component to fix the foot via the use of belts. Because it is necessary to apply a large force to the ankle joint, a high-power torque generator that uses a complex gearbox or artificial muscles that use air pressure is required. Even though the system is small, a large force on the ankle joint (nearly equivalent to the body weight) is essential, and the conventional system does not have a mechanical system for managing such a large force (Hayashibara, 2003; Nagase, 2010; Noda, 2006; Saga, 2010; Tsukamoto, 2008), as discussed above. The conventional system did not sufficiently consider the center of the ankle joint’s rotational axis, which must not be moved during application of a large force.

1.2. Developed ankle joint stretching device

The basic structure of our proposed ankle joint stretching mechanism is shown in Fig. 3 and Fig. 4. The device is composed of the following: (a) base stainless steel (SUS303) stand, (b) bucket (foot sole pushing part), (c) two DC motors, and (d) foot rest (the subject’s Achilles tendon lies on it). The bucket denoted by (b) is rotated by the two DC motors (Sankaku Co., worm gear motor, GW600, 24V DC, 9 rpm/min) denoted by (c). Moreover, the base stand denoted
Fig. 3 Illustration of the developed ankle joint stretching device based on the previously proposed brace structure: (a) base plate, (b) bucket (foot sole pushing part), (c) DC worm gear motor, (d) foot rest made of sponge, and (e) stainless pipe that is adjusted to the subject foot length.

Fig. 4 Developed ankle joint stretching device. The definitions of the parts indicated by (a) to (e) are the same as those in Fig. 3.

by (a) is connected to the subject sitting chair by the stainless pipe denoted by (e). When the bucket (b) is rotated to the dorsal direction by the DC motors (c), the subject’s foot sole is pushed by (b), and the bucket (b) attempts to move along the ventral direction via the reaction force of the foot sole pushing force. In the timing, because the stainless pipe (e) that had been adjusted to the subject foot length before the experiment fixed the length between the foot rest (d) and the subject sitting chair, the base stand (a) cannot move along the ventral direction. By fixing the length between (d) and the chair base, the position of the DC motor’s axis does not move (5 mm) during the application of the high pushing force (100 N, normally). This mechanism is the basis of our proposed ankle joint stretching system. The concept of our proposed ankle joint stretching system is to fix the ankle joint positions to the center of the system rotational axis using the connection mechanism (referred to as a brace in architecture) between the subject’s chair and the system while the subject keeps her/his knee fixed (Matuura, 2012; Toda, 2012; Toda, 2014; Matsumoto, 2015; Toda, 2016; Toda, 2017) to realize stable ankle joint stretching for a wide range of subjects (from ages 20 to 70 deg). However, the optimal geometrical arrangement of the Ankle joint, Hip joint, Thenar, and pushing device rotation center remain unknown. In our previous study, a stable ankle joint stretching was realized when the subject foot was floating (more precisely, the subject’s Achilles tendon was floating above the foot rest part (d) by a few mm). This paper is focused on the mechanism of the foot floating process of the ankle joint stretch treatment and presents an analysis of the geometrical/force balance mechanisms based on a simple numerical calculation. In addition, the geometrical rotational axis layouts of the ankle joint stretching system were confirmed by the real developed system.

2. Method

2.1. Numerical calculation model of the ankle joint stretching process

Figure 5 shows a proposed two-dimensional numerical calculation of a simple model of the human ankle joint stretching process. In the simplification, the foot is described by a single link that is represented by three points - Toe, Ankle joint, and Hip joint. In addition, a device rotation center is defined to represent the stretching movement, and the link between the toe and the device rotation center is connected at the toe position. The basic concept of the mathematical model is that, assuming that the position of the toe does not move during the ankle joint stretching process, a simple link length-fixed four-link model can be used. In addition, the proposed simple model is based on the fact that, during the PT’s treatment of a patient, when the right hand of the PT holds the heel of the patient, the subject does not feel the holding force of the PT’s right hand because the right hand is only used to prevent the foot from falling during the stretching process.
Fig. 5 Proposed numerical calculation model of the ankle joint stretching process. The model is described as a four-link system, and there are four rotation axes: device rotation center, ankle joint, hip joint, and toe.

Fig. 6 Variable and coordinate definitions of the numerical calculation model of the ankle joint stretching process performed by the PT. The initial value \( l_2 = 70 \) and \( l_3 = 200 \) are fixed, and \( s_1, s_2 \) are firstly calculated by the initial position of A.

process.

Figure 6 shows the defined geometrical layout and the coordinates for the numerical calculation. There are four rotation axes in the model in two-dimensional space: Device rotation center (A), Hip joint (B), Toe (C), and Ankle joint (D). In the model, all geometrical points from (A) to (D) are rotated. The points (A) and (B) are fixed in space, and points (C) and (D) are not fixed. Origin (0, 0) is defined to be at the Ankle joint (D). First, bucket model (ankle joint pushing part from A to C) is described by length \( s_1 \) and \( s_2 \) links, and the two links are fixed at 90 degrees relative to each other. The length of \( s_1 \) and \( s_2 \) are first calculated according to the initial position of (A). The bucket angle is defined relative to the horizontal line as \( \theta_1 \). Next, the bucket is connected to ankle at (D), and an angle between the bucket and the ankle is defined as \( \theta_2 \). Length from (C) to (D) is defined as \( l_2 \), and an angle (C) (D) (B) is also defined as \( \theta_3 \). Last, length between (D) to (B) is defined as \( l_3 \).

If the angle \( \theta_1 \) is changed, the position of the (C) will be changed, and under the condition of constant length of \( s_1, s_2, l_2 \) and \( l_3 \), the \( \theta_2 \) and \( \theta_3 \) will be adjusted. Numerical calculation realizes the above processes. Evaluation function \( J \) is defined as follows:

\[
J = (l_2' - l_2)^2 + (l_3' - l_3)^2
\]

where \( l_2' \) and \( l_3' \) are calculated length (C) (D) and (D) (B) when \( \theta_2 = \theta_2' \) and \( \theta_3 = \theta_3' \). By adjusting the \( \theta_2 \) and \( \theta_3 \) simultaneously with small value \( \Delta = 0.0001 \) rad to minimize the \( J \), the best angle of \( \theta_2' \) and \( \theta_3' \) could be calculated. The constants \( l_2, l_3 \) are first calculated from the first position of (A) to (D) in the numerical calculation. In this calculation process, the Steepest descent method is used to finely adjust the remaining two angles \( \theta_2, \theta_3 \) when shifting the angle \( \theta_1 \) by the small value \( \Delta \) rad as geometric constraint is established.

With the initial values \( l_2 = 70 \) and \( l_3 = 200 \) fixed, and \( s_1, s_2 \) are first calculated by the initial position of A (which depends on the experimental conditions). Although the initial value does not correspond to the actual length of the foot...
and leg, the process of the floating foot during the stretching is not affected by the values of \( l_2 \) and \( l_3 \); thus the length \( l_2 \) and \( l_3 \) were defined to allow ease of viewing of the geometric link layout. If the actual size link movement result is required, \( l_2 \) and \( l_3 \) are defined as the actual foot and leg lengths simultaneously (e.g. \( l_2=0.2 \text{ m}, l_3=1 \text{ m} \) in young adult man). \( s_1 \) and \( s_2 \) are also calculated according to the initial position of A.

2.2. Developed experimental device

To perform an actual device experiment, a device shown in Fig. 7 was developed (top view and DC motor axis positions, side view was Fig. 3) with the bucket rotated by two DC worm gear motors. Figure 8 left shows the specifications of the device. The height of the device rotation center is 0.48 m and is located at the Hip position (subject is sitting a chair), and the Foot rest (d) is located 3 cm lower and 1 cm in the dorsal direction, and the distance from the device rotation center and the soft sponge pad touching to the toe is normally 7 or 9 cm (it was changed because of an experimental condition).

3. Experiment

3.1. Experiment 1: Numerical calculation of ankle joint stretching process

In experiment 1, the effect of the position during the ankle joint stretching process between the device rotation axis (A) and the ankle joint rotation axis (B) is confirmed by using the numerical calculation model (Fig. 6). Five positions are used in experiment 1. Three of the positions are (1) same, (2) up, and (3) down conditions of the point (A). For example, Fig. 6 shows the case of (3) down condition. In addition, the (4) left and (5) right conditions were also considered for comparison to the experiment 2 conditions. For initial position, \( s_1=100, s_2=100, l_2=70, l_3=200 \), the angles \( \theta_1, \theta_2, \theta_3 \) were defined such that the link \( l_3 \) is positioned on the foot rest horizontally. Next, the angle \( \theta_1 \) was rotated slightly (step was \( \Delta \theta=0.01 \) clockwise direction until the total iterative calculation cycle approached to \( t=50 \) (time step was \( \delta t = 0.0001 \), total cycle = \( \frac{50}{0.0001}=500,000 \)). The \( \theta_1 \) slight change process represents the ankle joint pushing process implemented by the device or the PT. By using this calculation, the movement of the foot link (B) (C) is analyzed.
3.2. Experiment 2: Real force output transition measurement during the ankle joint stretching process by the subject

For the setup of experiment 2, the center position of the bucket can change the position along the vertical direction 2 cm from patient’s ankle joint position (Fig. 7 right) in four conditions, and the experiment 2 performs the pushing or floating features by using two set of load cell sensors positioned at the Sole and the Achilles tendon. Figure 8 right shows the positions of the load cell force sensors FC-23 (Measurement Specialities Co., Maximum load of 8900 N), and each sensor outputs are denoted as $F_s$ (Sole) and $F_a$ (Achilles tendon). Each output was amplified by an operational amplifier of OP-07D via a bridge circuit. In the experiment, the positions of the device rotation axis are selected 0, -2, +2 cm from the subject’s ankle joint position during the period from the patient sitting to the end of one time of dorsiflexion stretching process of the ankle joint (the distance from the rotational center to the soft sponge pad touching the toe is 7 cm). Each condition corresponds to the following conditions of experiment 1: (1) same, (2) up, (3) down. Moreover, the Right condition (corresponding to Right condition (5) in experiment 1) was examined (the distance from the rotational center to the soft sponge pad touching the toe is 9 cm). The Left condition (corresponding to Left condition (4) in experiment 1) could not be examined because of mechanical interference between the bucket and the aluminum plate. One subject (age 21, adult man) is participated in the experiment. The operation of the device is as follows: after the placing the Achilles tendon on the (d) foot rest, the length of the part (e) is changed to the patient’s leg length, and the (b) bucket is rotated by the (c) motors and the subject’s toe is pushed by the (b) bucket. The stretching angle is used 10 deg from the ankle toe touching to the bucket to dorsal direction. All of the experiments in the present paper involve a simple ankle joint rotational stretching exercise with a low force (maximum of approximately 60 N) and one stretching cycle and does not represent a long time period rehabilitation or an ankle joint angle range of motion (ROM) experiment. The experiments are not experiments for which ethical review is required.

4. Result

Figure 9 shows the result of the numerical calculation of the ankle joint stretching model when the ankle joint is pushing the sole clockwise direction. In the Fig. 9, Same rotational axis condition (1) (A and D are at the same positions as those of Fig. 7), the A and B did not move from the original horizontal position during the pushing process of the bucket. In this simulation, $t$ is the internal cycle time of the numerical calculation. Next, in the Up condition (2) that the device rotation center (A) was positioned at the upper part, the link of (D) (B) was moved in the downward direction (the link was stuck at the foot rest (black filled circle)). In other words, the subject foot was pushed toward the foot rest direction and caused pain to the subject. In the Down condition (3), in which the device rotation center (A) was positioned at the lower part, the link of (D) (B) was moved in the upward direction during the pushing process of the bucket. This observation is the main result of the use of the proposed numerical calculation model. As mentioned in the introduction section, the PT’s ankle joint treatment technique involving the foot floating during the ankle joint stretching treatment could be realized by using the simple link model technique.

In addition, in Fig. 10, Left condition (4) shows almost same results as those of Up condition (2). Under the Left condition, the downward movement of the foot is generated, causing the subject to feel pain at the foot point. Alternatively, Right condition (5) shows a foot floating, which could be one of the desirable conditions.

4.1. Results of experiment 2

Figure 11 shows result of the $F_s$ (Sole) and $F_a$ (Achilles tendon) transition during 10 deg ankle joint pushing treatment (Same condition, 0 cm). These conditions correspond to Same condition (1) of experiment 1. During the period of (A), the subject set the foot on the foot rest. The period between (A) and (B) corresponds to simply placing the foot on the foot rest ($F_a$ is 20 N during the period and corresponds to the weight of the subject foot). The device rotation started at 5.4 deg/sec during the period of (B). After 10 sec stretching, the device rotation is reversed at the same speed during the period of (C). In this case, the force sensor $F_s$ is increased $\Delta F_s = 50.3$ N, and the foot rest force sensor output $F_a$ is decreased $\Delta F_a = -8.8$ N. In other words, the foot is slightly floating because the $\Delta F_a$ takes on a negative value. In the case of +2 cm case (Up condition, 2 cm, Fig. 12), the force sensor $F_s$ (Sole) is increased $\Delta F_s = 30.6$ N, and the foot rest force sensor output $F_a$ (Achilles tendon) is increased $\Delta F_a = 2.4$ N. It corresponds to (2) Up condition of experiment 1. In this case, the foot is not floating because the $\Delta F_a$ takes on a positive value. In the case of -2 cm case (Down condition, -2 cm, Fig. 13), the force sensor $F_s$ is increased $\Delta F_s = 57.4$ N, and the foot rest force sensor output $F_a$ is decreased $\Delta F_a = -19.9$ N. This case corresponds to Down condition (3) of experiment 1. In this case, the foot is floating substantially because $\Delta F_a$...
(1) Same
(2) Up
(3) Down
(4) Left
(5) Right

Fig. 9 Result of experiment 1: numerical calculation results in the case of (1) Same, (2) Up, and (3) Down position conditions of the device rotation center axis.

Fig. 10 Result of experiment 1: numerical calculation results in the case of (4) Left and (5) Right positions of the device rotation center axis.

takes on a negative value compared with the Same condition case (Fig. 11). Figure 14 shows the result of right condition, +2 cm, in which the force sensor $F_s$ is increased $\Delta F_s=50.3$ N, and the foot rest force sensor output $F_a$ is decreased $\Delta F_a=-8.8$ N. This case corresponds to case (5) of experiment 1. The effect of the device rotation center position was almost same as that of Same condition (1) of Fig. 11.

Figure 15 shows the summarization of the experiment 2. Sole pushing force $\Delta F_s$ takes on the maximum value (57.4 N) when the device rotation axis is the down position, and the Achilles tendon’s force sensor output $\Delta F_a$ also takes on a minimum value (-19.9 N). For three conditions (same, down, and right), the $\Delta F_a$ takes negative value, indicating that the foot is floating during the ankle joint stretching process. Only one “down” condition takes on a positive $\Delta F_a$ value, and the $\Delta F_s$ takes on a relatively small value compared with the other three conditions. The above four results demonstrate that the force sensor $F_a$ (Achilles tendon) is an important factor to use to examine the relationships between the device rotation axis and the subject’s ankle joint position. Moreover, if the device rotation center is positioned lower than the ankle joint position, then $F_a$ is negative, thereby realizing floating of the foot during the ankle joint stretching treatment.

5. Discussion

In experiment 1, if the ankle joint and device rotation center were matched (the case of (1) in the numerical calculation result), then the foot was not floating. In the Same condition of experiment 2 (Fig. 11), however, a relatively small floating process was observed during the ankle joint stretching treatment. In other words, the correct ankle joint rotation axis is not the position of the top of the talus of the ankle, and, although the device rotation axis and the ankle joint axis are matched in this case, the result is the foot floating condition. Anatomically, the correct ankle joint rotation center position is moved by the movement of the talus (ex. Figure 11-13 in page 312 of Mansfield, 2013), making it difficult to determine the correct position. Nevertheless, the correct ankle joint center position can be estimated to exist between the down (0, −2) and the up (0, 2) condition ranges. In the proposed system, even if there is no information regarding the correct ankle joint center position, it can realize foot floating during the ankle joint stretching under the same or down conditions of the device rotation axis.

The main difference between our proposed device ankle joint stretching mechanism and PT’s method would be the
point that PT is usually wrapping the heel with her/his palm for ankle joint stretching. On the contrary, our device holds the subject foot by Footrest (d) only and not the heel position. The Footrest is used primarily because, when the device stretches the ankle joint, it keeps the heel wrapped while the heel is softly pressurized. When the heel would be wrapped by a type of sponge or urethane, each subject received uncomfortable pressure on her/his heel, and the device could not correctly stretch the ankle joint.

In a case of applying the proposed device to a subject with highly contracted contracture of the ankle joint or late-stage elderly subject with decreased motor function, the proposed device structure could not be used under the proposed structure. In this situation, the effectiveness of the treatment mainly depends on the deformation of the contracted foot and limited ROM, making it necessary to observe the stretching treatment performed by PTs.

As shown in Fig. 1, the PT fixes the lower limb by pressing the left hand against the patient’s shin. Our proposed system does not prevent knee flexion during the ankle joint stretching if the ankle joint height is the same or higher than the height of the hip joint. This mechanism is not clearly analyzed to date, making it necessary to study this mechanism in future works.

6. Conclusion

In this paper, to mechanize a human ankle joint stretching treatment that is manually performed by a PT (Physi-cal Therapist), the geometrical relationships among the Ankle joint, Hip joint, Sole, and pushing device rotation center was analyzed using a simple numerical calculation model, and the effectiveness of the model was examined in a developed system based on the model calculation results. To analyze the PT’s manual therapy method for treating the ankle joint, a simple geometrical multi-link system designed via numerical calculation was proposed, and the relationships between the layout of the device rotation center and the ankle joint axis were confirmed. In addition, an ankle joint stretching
device was developed allow for the change of the position of the device rotation axis. The numerical calculation of the link system experiment indicated that the foot floating manual treatment process performed by the PT is related to the lower position of the device rotational axis compared to the subject ankle joint. In addition, the rotation axis position relationship was confirmed by the device developed using DC worm gear motors, and the lower position of the device rotation axis was found to be important to reduce the force sensor output of $F_a$. The proposed numerical calculation model can be used to effectively promote the development of ankle joint treatment system.

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