Ankle joint pushing mechanism by stabilization of ankle position using a brace structure

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Received 15 September 2015

Abstract
In the present study, a human ankle joint pushing mechanism with a brace structure was developed, and the force balance relationship of the proposed system to avoid pain at sites other than the ankle joint was evaluated. The proposed system uses the brace structure to prevent the movement of the geometric arrangement of the ankle joint and the device rotational axis when pressure is applied to the foot. The results of experiments revealed that the proposed brace mechanism did not change the position of the ankle joint when a force was applied to the foot so that pain could be avoided. The proposed mechanism will be useful for developing a device for the purpose of applying large forces to the ankle joint.

Key words: Ankle joint contracture removal, Ankle joint pushing mechanism, Brace structure, Stabilization by hip, Footrest mechanism

1. Introduction
In the present study, a human ankle joint pushing mechanism with a brace structure was developed and the force balance relationship of the proposed system to avoid pain at other sites was evaluated. The ankle joint is critical in being able to walk by oneself without assistance (Kakurai, 1994; Kunihiro, 2010). The development of a mechanical device customized to rehabilitate the ankle is difficult because it is difficult to fix or control the center of the rotational axis between the system and the ankle joint. The concept of the proposed system is to fix the ankle joint positions to the center of the system rotational axis using a connection mechanism (referred to as a brace in architecture) between the subject’s chair and the system while the subject does not bend his knee (Fig. 1) (Matuura, 2012; Tanizaki, 2012; Toda, 2012; Toda, 2014; Matsumoto, 2015).

1.1. Importance of the human ankle joint
The number of elderly people who need care on a daily basis continues to grow. Since such care requires hard work, a number of approaches have been undertaken to prevent elderly people from becoming bedridden (Kakurai, 1994). In particular, interest in medical rehabilitation equipment for persons requiring long-term care has increased rapidly in recent years. In order to prevent a person from becoming bedridden, daily rehabilitation of the ankle is necessary. Fukui et al. reported that if rehabilitation of the ankle is missed for one day, rehabilitation of the ankle for seven days is necessary, and that if seven days of rehabilitation are missed, rehabilitation of the ankle for 51 days is necessary (Kuni, 2010; Watanabe, 2013; Hagbarth, 1985; Nagasawa, 2011).

1.2. Previous system
The tilt table (Nihon-Medix Co.) is a typical rehabilitation system for the ankle joint that requires extensive setup space. The tilt table requires a patient to be strapped to a bed with belts, and the bed angle is then tilted using an actuator in the base of the bed. The weight of the patient is gradually transferred to the patient’s ankle. However, some problems
related to forcibly changing the slope of the body were reported in that 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 required setup space, smaller ankle joint rehabilitation systems have been proposed (Mero, 1992; Kato, 2003; Suzuki, 2005; Nagase, 2010; Hayashihara, 2003; Noda, 2006; Tsukamoto, 2008). These smaller systems are composed of a calf attachment system and a component to fix the foot by belts. Since it is necessary to apply a large force to the ankle, these systems require a high-power torque generator that uses a complex gearbox or artificial muscles that use air pressure.

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 (Nagase, 2010; Hayashihara, 2003; Noda, 2006; Tsukamoto, 2008), as discussed above and shown in Fig. 2(b). The conventional system did not sufficiently consider the center of the ankle joint’s rotational axis, which must not be moved even by a large force.

### 1.3. Difficulty of developing a customized ankle joint pushing device

In order to construct an ankle joint pushing mechanism, two features are important: (1) a mechanism for applying large forces, and (2) a mechanism for generating a force to induce ankle joint rotation only. Fig. 2 shows the importance of fixing the center of the rotational axis of the system and the ankle joint. In Fig. 2(a), the center of the rotational axis of the ankle and that of the system are the same, and the subject feels no pain or pressure while the ankle joint is being pushed by the device (gray bent bar). As shown in Fig. 2(b), if the rotational axis of the device (yellow circle) is positioned incorrectly with respect to the center of the ankle joint (white circle), the foot received force $F$ from point (i) (sole of the foot). Force $F$ can be divided into $f_1$ and $f_2$, where $f_1$ is the rotational component that rotates the ankle joint around the white circle, and $f_2$ is the translation component that acts to bend or push the body parts of the subject. $f_2$ generally causes the subject’s pain or broken bones. For example, if force $f_1$ is 100 N (approximate treatment force for healthy subjects as reported by Kunihiko, 2010) and the distance between the centers of the two rotational axes is $d=100$...
mm (as in the conventional device design) and the distance between the pushing point (i) and the ankle joint is \( h = 250 \text{ mm} \) (approximately foot size), \( f_2 \) is calculated as 40 N. If \( d \) is not small, then \( f_2 \) is generated by the above geometrical reason. Since 40 N is not small, if the pushing force is increased, \( f_2 \) increases, which will bend or push the subject body part (such as the heel or places touched by belts) and cause pain. In contrast, if \( d = 0 \text{ mm} \) (there is no displacement between the bucket rotational axis and the subject’s ankle joint), then \( f_2 = 0 \text{ N} \). This means that the device generates no bending or pushing forces on the subject.

In order to avoid the generation of force \( f_2 \), the brace-structure-supported mechanism was considered, as shown in Fig. 1. When pushing the foot by (a) the bucket, the bucket received the force in the direction away from the body as the reaction force. Using (b), the brace structure (as shown on the right-hand side of Fig. 1), the reaction force is cancelled, and the position of the bucket is fixed by the brace. The part that pushes against the sole of the subject’s foot is connected to the chair in which the subject sits by the means of the brace. If the subject does not bend his knee, the length from the subject’s hip to his ankle is fixed because the length of the subject’s leg does not change. As a result, the center of the rotational axis of (a) the bracket and the ankle joint is fixed for any value of the pushing force.

Since the pushing force direction changes with the bucket angle, the stress on the sole of the subject’s foot can be divided to a compression stress and a shear stress if the bucket angle exceeds 45 [deg] or -45 [deg], where the perpendicular direction of the brace is 0 [deg] on the sagittal plane, and the shear stress would exceed the compression stress. The ankle joint ROM range should be from 45 [deg] (plantar flexion) to -20 [deg] (dorsiflexion) (Kunihiko, 2010). This means that the developed system could work within the ROM range necessary for physical therapy. In addition, since the proposed system has a pressure sensor system inside the footrest (Achilles tendon), uncomfortable shear stresses can be detected.

Moreover, in the proposed system, the influence of parallel factors along the brace direction of the \( f_1 \) would be reduced by the brace. Also, the influence of the perpendicular factor of \( f_2 \) (perhaps including small a \( f_2 \) factor in the real situation) would remain and is intended to absorb and fix the ankle position by the footrest part. In addition, during the sole pushing process, the calf muscles would pull the heel and rotate the ankle joint against the bucket pushing direction. This floats the Achilles tendon (which is easy to confirm by hand by pushing the fingers from the direction of the palm). The floating force reduces the pushing force on the Achilles tendon.

The objective of the present paper is to develop a mechanical system for ankle joint rehabilitation that can mechanically adapt to the misalignment of the subject’s ankle joint and to the rotational axis of the device during periods of large pushing force using the proposed brace structure. The device was developed in order to treat the ankle joint rehabilitation movement in the dorsiflexion direction, because this movement requires the largest force and it has been physical works for physical therapy long time. In addition, the force balance relationship of the proposed system required to avoid pain was evaluated for the case of a misalignment of the subject’s ankle joint and the rotational axis of the device.

1.4. Outline

Section 2 shows the developed human ankle joint pushing mechanism with a brace structure and the sensor system used to confirm the effectiveness of the proposed system. Sections 3 and 4 show the experimental setup used to evaluate the force balance relationship of the proposed system and the experimental results, respectively. Conclusions are described in Section 6.

2. Method
2.1. Developed system

Fig. 3 (left) shows the developed ankle joint pushing mechanism, which is constructed from (a) a bucket, (b) a brace, (c) a footrest, a chair, and a linear actuator (Dewert Co., MULTIMAT B32, 4000 N, 12.5 mm/s). (a) The bucket can be rotated by the linear actuator sliding via two rotation joints (red circles) around the rotational axis (yellow circle), as shown in Fig. 3 right. (b) The brace is made of stainless steel pipe (SUS303), and its length can be adjusted to fit the subject’s leg (from the hip to the ankle joint). (c) The footrest is made from hard sponge and touches the subject’s Achilles tendon. The footrest is mainly used to maintain the Achilles tendon height to be approximately the same as the ankle joint y-axis displacement. The brace structure acts to keep the x-axis of ankle joint displacement constant. Basically, the subject’s Achilles tendon is positioned on the footrest, and the center of the ankle is positioned at the rotational axis of the bucket.

The usage processes of the proposed device are shown below. First, the subject sits in the chair and places his Achilles tendon on the footrest. The subject must sit in the chair and straighten his knee joint as shown in Fig. 4(d). Next, the length of the brace is adjusted to be the same as the length of subject’s leg (from the hip to the ankle joint). By adjusting the brace length and straightening the knee joint, the position of the bucket rotational axis (yellow circle) and
the subject’s ankle joint is fixed to be approximately constant. It is the main features of the proposed device ankle position fixation stability. Basically, the subject sitting in the chair and placing his Achilles tendon on the footrest is the whole process of the device usage before the ankle joint pushing process.

The kinematic relationship between the device and the subject is shown in Fig. 4 (bottom). As shown in Figs. 1 and 2, if the system applies a large force to the sole of the foot, a reaction force is generated in the direction away from the body. A previous system used a system of belts to keep the position of the system from moving as a result of the reaction force (Nagase, 2010; Hayashibara, 2003; Noda, 2006; Tsukamoto, 2008). However, it was difficult to fix the original position using only belts because the pushing force is large and the subject felt pain. In most conventional devices, the forces other than for those associated with the rotating the ankle joint (such as $f_2$ in Fig. 2) were concentrated by the belts or at the heel of the subject, which was in contact with the base plate. The range of force is basically proportional to the pushing force. The proposed system can fix the ankle position using the brace structure with the subject straightening his knee joint. We have been developing and confirming the effectiveness of the above mechanism (Tanizaki, 2012; Nagase, 2010; Hayashibara, 2003; Noda, 2006; Tsukamoto, 2008).
2.2. Sensor system

Fig. 5 shows the developed embedded force sensing system. There are two load cells in this system. Sensor 1 is positioned between the sole of the subject’s foot and the bucket. Sensor 2 is positioned between the base stainless steel pipe of the footrest and the sponge. An FC-23 load cell (Max load: 2000 [Lbf], Measurement Specialties Co.) was used. The sensor output was generally measured as a voltage and was transformed to a pressure force N in all experiments.

3. Experiment

First, since the developed system would be designed to fix the distance between the rotational axis of the bucket and the subject’s ankle joint while a large force pushes against the sole of the foot, it is necessary to measure the movement of the ankle joint position at the sagittal plane in order to confirm the stability of the ankle joint position under a large pushing force (approximately 100 N) treatment. In experiment 1, the trajectory of the ankle joint while pushing the sole by the proposed system with or without the brace was examined. This experiment reveals the function of the proposed brace structure in the system.

In experiment 2, the pressure changes measured by sensors 1 and 2 (Fig. 5) were measured from the time of putting the foot on the footrest until the end of the pushing process. As shown in Fig. 1, the proposed system has only three contact points with the human body: (1) contact with the chair (hip), (2) contact with the bucket (sole of the foot, sensor 1), and (3) contact with the footrest (Achilles tendon, sensor 2). The basic idea of the experiment is that, if the subject feels pain, the pressure value would be measured either of or only from the three contact points. At the three contact points, the hip contact point was not used in this experiment because the pressure was almost always due to the weight of the subject’s body. If a subject feels pain, it would be supposed to increase the pressure value of sensor 2 (Achilles tendon) while the treatment. In this experiment, we checked whether the pressure value increased by extending the brace length 15 mm in the dorsal direction in order to shift the rotational axis of the device and the subject’s ankle joint position.
Finally, by inserting a rigid 10 mm insole, experiment 3 was designed to more precisely measure the pressure transition in sensor 2 while pushing against the sole of the foot. The insole was used to change the position of the bucket rotational axis and the subject’s ankle joint position. Here, the brace length was also extended in the direction of the insole thickness. As a result, the ankle joint position was unstable during the pushing experiment when only the length of the brace was changed.

All of the experiments in the present paper is simple ankle joint rotational stretching exercise and the maximum stretching cycles are 5 times, and it is not long time period rehabilitation or not ankle joint angle range of motion (ROM) experiment. The experiments are not the experiment like ethical review is required.

3.1. Experiment 1

Experiment 1 confirms the ankle joint movement trajectory during the pushing process using the proposed system with/without the proposed brace structure. One subject (age 21 years, N = 1) participated in this experiment. The subject sits down in the chair (Fig. 3) and places his Achilles tendon on the footrest while changing the length of the brace (Fig. 3(b)) in order to set the ankle position at the center of the rotational axis of the bucket. As shown in (Fig. 7), an OptiTrack V100R2 (640x480 pixels, 100 fps, positional resolution: 1.6 mm) was used as the measurement system, and the ankle joint position on the sagittal plane was continuously measured during five pushing processes under a force of 100 N. This force condition is based on the rehabilitation process used by physical therapists (Kunihiko, 2010). The position of the ankle joint was measured and calculated by two InfraRed reflection markers on the side of the fibula (indicated by (A) in Fig. 7). The position of the center of the rotational axis of the bucket and the bucket terminal were also measured at the same time. Generally, defining the center of the rotational axis of the ankle joint is difficult. In this experiment, we used the top of the medial malleolus of the tibia as the position of the ankle joint center.

As a pushing procedure, the angle of the bucket was changed from −25 [deg] to 45 [deg] over a period of 40 [s], and the bucket angle was defined as shown in Fig. 7. If the bucket was set in the vertical direction, the angle was 0 [deg]. The angle was increased (decreased) if the bucket was rotated in the dorsal (ventral) direction. The angular velocity was approximately 1.75 [deg/s]. The subject was instructed to push the controller button if he felt stretching in his calf or thigh. After pushing the button, the bucket was stopped in 20 [s] and reversed for 5 [s]. This procedure was performed five times. The experimental procedure is the same at the ROM exercises performed by physical therapists (Hamada, 2008). The total experimental time was approximately 40 × 5 = 200 [s].

3.2. Experiment 2

In experiment 2, the time series of the pressure change of sensors 1 and 2 were measured while pushing against the sole of the foot. One subject (age 21 years, N = 1) participated in this experiment. The experimental procedure was the same as that of experiment 1, but the ankle was shifted 15 mm in the dorsal direction from the bucket rotational axis by changing the brace length.
3.3. Experiment 3

The change of 15 mm in the brace length in the dorsal direction of experiment 2 revealed the existence of an important relationship between the ankle and the bucket rotational axis position in the proposed system. The relationship between the thickness of the sole of the foot, which was changed from 0 to 30 mm for the purpose of shifting the two rotational axis positions, was measured. At the same time, the brace length was also changed by the change in thickness of the sole of the foot. The rigid insole changed the thickness in the front of the pressure sensor (load cell), as shown by (A) in Fig. 6.

4. Result
4.1. Result of experiment 1

Figs. 8 and 9 show the ankle joint movement trajectories in the sagittal plane for pushing with the brace five times.
and for pushing without brace one time, respectively. With the brace, even though pushing procedures were performed five times, the ankle joint position was fixed at \((x,y) = (2.64 \pm 5.39, 3.99 \pm 5.37)\) mm. The displacement from the center of the rotational axis of the bucket (S.D. of the dorsal axis \(\sigma_x\) and S.D. of the cranial axis \(\sigma_y\)) was approximately 5.4 mm. From the viewpoint of the clinical side, the allowable displacement mm of the bucket rotational axis and the ankle joint position are thus far unknown. However, the sole of the subject’s foot always correctly touches the physical therapist’s forearm when holding the subject’s heel with his palm. Therefore, the physical therapist would be able to use only his forearm to rotate the subject’s ankle joint. From the perspective of kinematics, if the proposed system generates a 100 N pushing force on the sole of the subject’s foot, \(f_2 = d/h \cdot 100 \text{ N} = (d = \sigma_x = 5.4\text{mm})/250\text{mm} \cdot 100 \text{ N} = 2.16 \text{ N}\) (in Fig. 2) is calculated from this result. Compared to \(d = \text{approximately 100 mm and } f_2 = \text{approximately 40 N}\) for the conventional device, the \(f_2\) value of the proposed device is lower.

On the other hand, without the brace, the ankle joint drops as the heel moves over the footrest for only one pushing process. The bucket moved in the ventral direction as a result of the reaction force of the bucket pushing. The ankle joint trajectory is plotted in Fig. 9 for the case in which the center of the rotational axis of the bucket is set to \((0,0)\) mm. The results indicate the importance of the brace structure.

### 4.2. Results of experiment 2

Fig. 10 shows the outputs of force sensors 1 and 2 during the pushing process. Figs. 10a and 10b show the results for the condition in which the ankle joint and the center of the rotational axis of the system are the same and for the condition in which the ankle position are shifted from the center of the rotational axis to dorsal direction with 15 mm by changing the brace length, respectively. At point (A), the subject leg was positioned on the footrest, a weight increasing occurred by the reason of the subject leg weight \((22.5 \pm 2.25 \text{ and } 16.5 \pm 0.6 \text{ N in conditions (a) and (b)}, \text{ respectively, where } \pm \text{ is the standard deviation, S.D.}, \text{ of the 500 [ms] period})\). At point (B), the bucket angle was increased until the subject pushes the controller button. Sensor 1 (blue) revealed that the pressure increased from point (B). This increase was caused by the pushing of the bucket. The value of (i) shows the pressure on the sole of the foot under the two conditions. Differences of more than approximately 75 N were generated in each experiment. The differences of (ii) were the pressure force differences at the footrest, which were measured to be (a) \(10.1 \pm 1.3\) and (b) \(56.5 \pm 1.86\) N.

The difference of (ii) in (a) \((10.1 \text{ N})\) was clearly less than that in (b) \((56.5 \text{ N})\). This means that (a) if the rotation center of the system and the ankle joint are the same and the pushing force generated by the linear actuator is applied to the subject’s ankle (approximately 75 N), then a low pressure force is measured at the footrest \((10.1 \text{ N})\). On the other hand, (b) if two rotational positions are shifted by approximately 15 mm and a pushing force can be applied to the subject’s ankle, then a high pressure force acts from the footrest \((56.5 \text{ N})\).

In order to understand the lower pressure force, we assumed that during the sole pushing process, the calf muscles would pull the heel and rotate the ankle joint against the direction of bucket pushing. This enables the Achilles tendon to float. This floating force would reduce the pushing force on the Achilles tendon. This phenomenon can be confirmed by hand. By pushing the fingers from the direction of the palm, the wrist joint should result in dorsiflexion, which would stretch the flexor digitorum superficialis muscle. The muscle tension would result in anti-rotation of the wrist joint, which would generate a force at the finger position. As such, the wrist would float as a result of the force factor in the longitudinal direction.

Based on the results, a displacement of the bucket rotational axis of tens of millimeters would occur, and the position of the subject’s ankle joint would be greatly affected by the pressure on the Achilles tendon. Next, experiment 3 is designed to confirm the relationship between the displacement of the bucket rotational axis and the position of the subject’s ankle joint and the output of pressure sensor 2 (Achilles tendon).

### 4.3. Result of experiment 3

In order to examine the pressure force transition of sensor 2, the distance between the subject’s ankle and the rotational axis of the proposed mechanism was changed. Fig. 11 shows the pressure transition of sensor 2 for the case in which a rigid insole (width: 10 mm, not transform solid wood material) was added between the bucket and the subject sole from 0 to 30 mm. At (A) in Fig. 11, the bucket angle starts to change, and, after approximately 20 [s], the subject pushes the stop button of the controller when he feels his calf or thigh stretching. There were large pressure force differences on the footrest by changing the thickness of the rigid insoles (which corresponds to the change in displacement between the subject’s ankle and the bucket rotational axis).

The four lines on the right-hand side of the figure indicate the theoretical values of \(f_2\) calculated from Fig. 2. In this
case, \( h = 250 \text{ mm (foot size),} \ d = 10, 20, 30 \text{ mm, the pushing force,} \ f_1, \text{ is} \ 100 \text{ N, and the zero bias value of the pressure takes a value of} \ 0 \text{ mm after 30} [s]. \text{ Large differences were found between the theoretical and measurement values. This means that the displacement between the bucket rotational axis and the ankle joint position changes significantly as the thickness of the insole changes. Controlling the displacement of the bucket rotational axis and the ankle joint position are therefore important in order to develop ankle-joint-pushing treatment devices.}

In addition, experimental results suggest the importance of the footrest pressure sensor (sensor 2) and will be useful for realizing a safety system for ankle joint pushing mechanisms. The results of experiment 1 reveal that the brace structure plays an important role in fixing the center of the bucket rotational axis and the ankle joint. The results of experiments 2 and 3 reveal that the force transition of the footrest during the pushing process is directly related to the displacement between the center of the rotational axis and the ankle joint position.

5. Discussion

In Fig. 2, when pushing the sole by the brace, since the ankle joint is not a completely mechanical joint, there exists a force factor of \( f_1 \) that acts not only in the rotation direction but also in the longitudinal direction of the leg. As a result, the longitudinal factor of \( f_1 \) is added to \( f_2 \) and is measured as the pressure force on the footrest (Fig. 5). If the longitudinal factor of \( f_1 \) is large, the pressure force on the footrest can be measured (Fig. 8a), but this would be inhibited during the pushing process.

In addition, since \( f_2 \) generates a force factor because the ankle joint is not a completely mechanical joint, the force factor of \( f_2 \) acts as a frictional force between the bucket and the sole of the foot. However, the force may be small enough to be absorbed by a slight sliding of the sponge ((A) in Fig. 6). The above-described factor can be reduced if sliding or low-friction parts are used.
6. Conclusion

In the present study, a human ankle joint pushing mechanism with a brace structure was developed and the force balance relationship of the proposed system to avoid pain at sites other than the ankle joint was evaluated. The proposed system only touches the subject at three points: (1) at the buttock, (2) at the sole of the foot, and (3) at the Achilles tendon. Therefore, the proposed system could simplify the determination of the reaction/anti-reaction relationship of the linear actuator power. The proposed brace structure can fix the center of the bucket rotational axis and the ankle joint. In addition, in order to analyze the force balance of the proposed system, two force sensors were used, and the force transition of the footrest during the pushing process is directly related to the displacement between the center of the rotational axis and the ankle joint position. The proposed mechanism will be useful in developing a device for the purpose of applying a large force to the ankle.

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