Abstract—A brake in which the magnetorheologic fluid (MRF) is used has a simple structure and good responsibility. Therefore, MR brake is expected to perform a good adaptability for human-coexistence system. Being applied in an ankle-foot orthosis, however, conventional MR brake is too large to fit. Then, in this study we developed a shear-type MR brake with multi layer disks and minute gaps (50 micrometers) to realize compactness and high performance. This paper describes the development of a shear type compact MR brake and a new controllable ankle-foot orthosis with this brake. Furthermore, we design algorithm to control an ankle. We assist gait of a patient by changing a brake force.

I. INTRODUCTION

Recently, the change of lifestyles causes to increase the number of patients who get stroke. It is said that the half of them take hemiplegia after stroke. Stroke patients have different level of disorders, depending on the degree of their recovery. Therefore, proper rehabilitative activities by therapists are needed for their good recovery of motor skills. Lower limb orthosis, for example Ankle-Foot orthosis (AFO) is used for the walk rehabilitation. Selection of orthosis properly is important for patients, but difficult because their walk-characteristics have wide-rang.

In a normal walk, a gait consists of the stance phase and swing phase. Stance phase is defined as a period from heel contact to toe-off. The swing phase is defined as a period from toe-off to heel contact. The stance phase and the swing phase are repeated in turn. Figure 1 shows comparing a walk of a hemiplegic patient with a normal person.

In an ankle angle, plantar flexion is defined that tiptoe falls down, dorsal flexion is defined that tiptoe rises up. Because the hemiplegic patients cannot control their ankle of the paralysis side, swinging action is enlarged to avoid stumbling on a ground in the swing phase, and inclination of a body is enlarged to forward than normal gait as shown in fig 1. It causes much energy-loss for patients to walk.

Walking with bad gait needs much more energy than a normal gait, and this causes to get off the balance of the center of gravity. In that case, a tiptoe may hit the ground, lose the balance and damage in other parts.

Ankle-Foot Orthosis is a kind of orthoses attached to an ankle. There are a plastic type, a metal type, and so on. Orthoses are divided into static orthosis and dynamic orthosis depending on a function.

In order to improve the gait of the patients with paraplegia or hemiplegia, plantar flexion restricted ankle-foot orthoses (AFOs) is often in use. If stiffness characteristics of AFOs joint can be controlled depending on the gait ability of patients in both plantar flexion and dorsal flexion direction, the gait of the patients can be improved.

In this study, we propose to install a MR brake at the ankle joint of AFO to improve the gait with AFOs. A brake force (resistance) can be controlled by changing intensity of magnetic field applied. The information of the timing to control the MR brake are detected by a compressive force sensor and a bending moment sensor installed at the shoe sole part and shank of the AFO respectively.

By keeping dorsal flexion of the ankle joint with this brake during swing phase, the ground clearance is achieved and shock at heel-strike can be absorbed by the MR brake and the movement from heel-contact to foot-flat can be lead smoothly. In this paper, we describe about development of
the MR brakes and controllable AFO with it. Additionally, we describe about a control of this AFO. Subject and goal of the control are as follows.

Subject:
- Brunnstrom's Stage is 5 or 6.
- Patient can walk on own, but can not prevent drop foot in swing phase.

Goal of Control:
- To prevent drop foot in swing phase.
- To prevent slap foot at heel strike.

II. DEVELOPMENT OF SHEAR TYPE MR BRAKE

A. MR fluid (Magneto-Rheological fluid)

In late years, a study of functional fluids has advanced, and the MR fluid that can control big power that has been developed. A MR fluid is the non-colloidal solution that mixed a magnetism metal particle with a solvent of oil system. A diameter of metal particle is millimeters order. MR fluid changes viscosity very fast (about a few [ms]) by a change of a magnetic field very fast. The MR fluid used in this study is MRF-140CG developed by LORD Co., USA. Figure 2 shows a specific feature of an MR fluid. Figure 3 shows yield stress vs. magnetic flux density of MR fluid used in this study.

As MR fluid generates big shear stress with a magnetic field, it enables device uses it to become smaller and lighter. There are some operation modes to generate a yield stress with a functional fluid. There are shear mode, flow mode, and square mode.

We use a shear mode in this study. An MR fluid is picked up with a shear mode between two relative exercising walls. Shear stress occurs in a fluid by this relative exercise. Figure 4 shows shear mode.

B. A Shear-Type Compact MR Brake (SCMRB)

Making use of shear stress of an MR fluid effectively, we have to impress magnetic flux of about 1 [Tesla] on MR fluid parts. However, magnetic permeability of a MR fluid in itself is very small. In order to get a large total reluctance, we need big gap of a fluid part and large current source. In other words it cause the whole system to become big size. We suggest shear-type compact MR brake in this study. We adopt multi-layered disk structure to increase of braking torque, furthermore, to prevent increase of reluctance by the MR fluid layer increasing.

A coil rolled round a shaft apply an MR fluid to a magnetic field. Turning number of coils and spindle diameter are decided by magnetic field analysis. A rotor and stator are discal shape mainly on a shaft (an ankle axis), rotors are united with a shaft, stators are united with a housing. A housing is fixed to the orthosis. When an electric current is supplied to a coil, a magnetic field is impressed on the MR fluid layer. As result, shear stress occurs. (Cf. figure 5)

III. A CONTROLLABLE AFO (1ST PROTOTYPE)

A. User of the Orthosis and the Maximum Torque Needed to control

The controllable AFO developed in this research can be used for the patients who have following conditions.
1) The patients with a paralysis accompanying spasticity by a central nerve disease, however, not a severe level case.

2) There is no abnormality in the range of motion of ankle joint.

In order to keep a dorsal flexion smoothly during swing phase, setting up of the essential brake torque is indispensable to design the brake. According to the opinion of the therapist, the essential torque to control ankle during swing phase in a patient of above object is about 2[Nm]. In addition, according to the reference, the essential torque value that to control an ankle joint for keeping dorsal flexion during swing phase is about 2[Nm], which is obtained by experiments. So the targeted value of essential torque is decided as 2[Nm] when the first prototype of SCMR brake is to be developed.

B. Shear Type Compact MR Brake (1st prototype) and the AFO using this MR Brake

Thickness of rotor and stator disks that is magnetic pole is 0.2[mm]. Thickness of MR fluid layer is 50[μm]. We designed it to get big shear stress in thinner and smaller size.

About materials of each part, magnetism materials are used in a magnetic circuit part. In addition, a housing is made of a nonmagnetic body to avoid leaking of magnetic flux.

On the basis of the magnetic field analysis, when the turning number of coils is designed to 40[turn] and an electric current flow to a coil is 1[A], the magnetic induction to occur in the MR fluid layer was 0.3[Tesla]. Then, shear stress of an MR fluid is 10[kpa].

A theoretical value of the torque is 2.2[Nm]. However, when we flow 1[A] electric current to MRB, the torque is 0.71[Nm]. We cannot get a theoretical torque.

Figure 6 shows ankle-foot orthosis (1st prototype), figure 7 shows MRB (1st prototype). In addition, table 1 shows specification of MRB (1st prototype). MRB is installed in the ankle of orthosis.

<table>
<thead>
<tr>
<th>Table 1: Specification of MRB (1st prototype)</th>
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<tbody>
<tr>
<td>Total thickness</td>
</tr>
<tr>
<td>Outer diameter</td>
</tr>
<tr>
<td>Number of rotor disks</td>
</tr>
<tr>
<td>Number of stator disks</td>
</tr>
<tr>
<td>Number of MR fluid layer</td>
</tr>
<tr>
<td>Shaft diameter</td>
</tr>
<tr>
<td>Scroll number of coils</td>
</tr>
<tr>
<td>Idling torque</td>
</tr>
<tr>
<td>Maximum torque</td>
</tr>
</tbody>
</table>

Some causes are regarded for a gap between the theory value and the experimental value. For a cause, it is thought an analysis error in magnetic field analysis, Non-filling of a fluid, and so on.

IV. A CONTROLLABLE AFO (2ND PROTOTYPE)

A. Shear Type Compact MR Brake (2nd prototype) and the AFO using this MR Brake

Therefore, for a result in a first prototype, we designed new one. We describe changed points as follows.

1) To achieve a magnetic flux density value more than 0.5[T], the scrolled numbers of coil was added in SCMRB-2.
2) To make it easier of confirming the filled state of MRF in the gaps among laminated disks, changes of the position of the MRF infusion hole is needed.
3) To increase the design torque, outer diameter and number of the disks were enlarged. In addition, the control torque of ankle joint was designed as 15[Nm] to be capable of correspond to patients of various symptoms.
4) To achieve the compactness of the brake, reduction of the number and thickness of the bearings was done.
5) To reduce the upload-torque, the oil seal was changed.
6) To prevent fluid leakage, a piston mechanism was set up in the area where MRF is filled in by matching the property of thermal expansion and cold shrinkage of the MRF.

Figure 8 shows ankle-foot orthosis (2nd prototype), figure 9 shows MRB (2nd prototype).
Table 2. Specification of MRB (2nd prototype)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total thickness</td>
<td>29 [mm]</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>69 [mm]</td>
</tr>
<tr>
<td>Number of rotor disks</td>
<td>7 (thickness: 0.2 [mm])</td>
</tr>
<tr>
<td>Number of stator disks</td>
<td>6 (thickness: 0.2 [mm])</td>
</tr>
<tr>
<td>Number of MR fluid layer</td>
<td>12 (thickness: 50 [μm])</td>
</tr>
<tr>
<td>Shaft diameter</td>
<td>25 [mm]</td>
</tr>
<tr>
<td>Scroll number of coils</td>
<td>100 [turn]</td>
</tr>
<tr>
<td>Idling torque</td>
<td>0.1 [Nm]</td>
</tr>
<tr>
<td>Maximum output torque</td>
<td>11.8 [Nm]</td>
</tr>
</tbody>
</table>

Figure 8 shows ankle-foot orthosis (2nd prototype), Figure 9 shows MRB (2nd prototype). In addition, table 2 shows specification of MRB (2nd prototype).

As a result, we are able to get maximum torque of 11.8 [Nm] that aim for in a second prototype. In addition, idling torque keeps low level (0.1 [Nm]).

B. A Linkage Mechanism

2nd prototype of the controllable AFO with SCMRB-2 is shown in Fig.8. As mentioned in the previous section, the goal of the maximum torque is 15 [Nm]. Therefore, we decided to use a linkage mechanism as torque amplification (Cf. figure 10). The ratio of length is 17/30 (link 1/link2) as shown in Fig.10. Neutral position of the ankle joint is defined, when link 2 becomes parallel to link 1. At that time brake torque act on the axis of the ankle joint is 1.76 (30/17) times as the brake torque that occurred on the brake itself. In addition, a ratio of more than 2 can be achieved at the position maximum dorsal flexion and plantar flexion position. From the above, the torque acting on ankle joint in the 2nd prototype is capable to achieve 24 [Nm], therefore the 2nd prototype is considered possibly to be used for a clinical testing. In addition, an installation position of a brake is the ankle upper part; an ankle gets possible to install potentiometer to measure an ankle angle.

![Linkage Mechanism](image)

The potentiometer works to measure an ankle angle. Six-axis force-torque sensor works to measure ground reaction force (GRF). And we calculate a bending moment around an ankle from data of six-axis force-torque sensor and a bending moment sensor. Sampling frequency is 1 [kHz]. Braking torque is controlled with the change of an electric current on a coil and a magnetic field on it.

Each sensor is lead to PXI devices (National Instrument inc.), and PXI carries out a program that is downloaded from a PC. PXI measures a signal from the sensors, and outputs the order voltage for amplifier. A signal from a sensor is indicated in PC. The order voltage converts an electric current in amplifier.

In addition, we use real time three dimensions coordinate measurement device. We measure inclination of body, shake angle, and so on. The information of real time three dimensions coordinate measurement device is sent to another PC, after that to PXI from another PC.

B. Control Algorithm

As a characteristic of walking of hemiplegic patient, because they cannot reach the ground from heel, there is lack of dorsal flexion moment in early stance phase.

As above, roles of control (Cf. figure 12) are as follows;
1) To prevent drop foot in swing phase
2) To prevent slap foot at heel strike

1) As the foot entire surface arrived suddenly at heel contact, a shock is big. Therefore, they cannot move the weight forward and perform a fluent walk. In order to be able to perform weight movement to smooth front, torque of
a brake enlarges torque. So that the foot reaches the ground slowly, absorbs shock.

2) Enlarges torque in the case of maximum dorsal flexion angle. It can prevent a fall of a tiptoe in the swing phase. And brakes weaken it for reaching the ground of a heel slowly.

1) To prevent slip foot
2) To prevent deep foot

![Figure 12. Roles of control](image)

Figure 12. Roles of control

![Figure 13. Dividing into four states](image)

Figure 13. Dividing into four states

Gait motions are divided into four states defined as follows. Figure 13 shows them.

1) State 1 is to foot flat from heel strike.
2) State 2 is to maximum dorsal flexion from foot flat.
3) State 3 is to toe-off from maximum dorsal flexion.
4) State 4 is to heel strike from toe-off.

Each state has characteristics and control algorithm as follows. We define dorsal flexion is minus, and plantar flexion is plus.

1) State 1: GRF increases, a bending moment decreases and becomes minus. In addition, in tiptoe reaching the ground, a bending moment is minimum. So that if a bending moment is above threshold, or GRF is above threshold, state 1 shifts to state 2.

Braking torque is controlled in proportion of the absolute value of an ankle angular velocity.

2) State 2: An ankle angle changes to dorsal flexion, a bending moment increases. An ankle angle becomes maximum dorsal flexion angle, and a bending moment becomes max. If an ankle angle is below threshold and does not update maximum dorsal ankle angle for 30 counts, or maximum moment of bending is above threshold and does not increase for 30 counts, state 2 shifts to state 3.

Because we do not disturb weight movement forward, size of torque is 0.

3) State 3: As a foot leaves the ground, GRF and a bending moment decrease. In toe-off, GRF and a bending moment become 0. If GRF is below threshold and a bending moment is below threshold, state 3 shifts to state 4.

To maintain maximum dorsal flexion angle, give a torque. Size of torque is constant.

4) State 4: As a foot leaves the ground, GRF and a bending moment become 0. If GRF is above threshold and a bending moment is below threshold, state 4 shifts to state 1.

In swing phase, to avoid that a tiptoe falls down, we give brake torque. Torque turn down to possess heel contact.

Figure 14 shows a figure of distinction of a state.

In addition, we update the threshold to divide a state from a state of a gait. We demand largest reaction force, largest dorsal flexion angle every each step and change the each threshold based on them. The threshold that became basic was decided by data of a walk and an experiment.

Safe mode is first state. In safe mode, size of torque is 0. When there is abnormal gait to cancel a walk during a walk, any state shifts to safe mode. An opening of a walk is safe mode. In the case of a normal walk, it repeats itself with a turn of 1→2→3→4→1→2→3→4.

Figure 14. Distinction of states

VI. EXPERIMENT RESULT AND DISCUSSION

Table 3. Data of subject

<table>
<thead>
<tr>
<th>Sex</th>
<th>Man (age: 59)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>Infantility paralysis (polio)</td>
</tr>
<tr>
<td>Right ankle flaccid paralysis, sensory paralysis</td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>157 [cm]</td>
</tr>
<tr>
<td>Weight</td>
<td>44 [kg]</td>
</tr>
</tbody>
</table>

We perform clinical test by experimental system shown in Fig. 11. Table 3 shows data of subject. Subject is infantility
paralysis, and case is right ankle flaccid paralysis.

We make orthosis that fit the subject, and install MRB at ankle joint. The weight of experimental orthosis is 1.6[kg]. The subject walks interval of about 5[m]. At first, Subject stand erect. The subject starts to walk as the same time as we start measurement.

Figure 15 shows experimental result without control, figure 16 shows experimental result without control. Figure 15 and 16 shows an ankle angle, reaction force, and a bending moment.

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2) With control

- In swing phase, the subject can maintain the dorsal flexion, and prevent the drop foot.
- The subject can contact ground at heel.
- At contact ground, GRF doesn’t lack smoothness.
- Maximal value of a bending moment with control is larger than one without control. Therefore, subject can be weight shift to forward.
- Walking cycle is shorter than one without control.

As above, we prevent drop foot in swing phase and slap foot at heel strike. Consequently, we can think that gait is improved by control.

VII. CONCLUSION

In this study, a compact, and high-torque shear type MR brake was developed which is intended to be applied as a controllable AFO for paraplegic and hemiplegic patients, and a prototype of AFO with MR brake has also been developed. Furthermore, linkage mechanism is used as amplification system. Consequently, we were able to get maximum torque of about 24 [Nm]. Additionally, we built control algorithm not only dorsal flexion maintenance in the swing phase but also to give an effective brake for shock absorption at heel strike.

We carried out experiment by using developed MRB and built control algorithm. Consequently, we could prevent drop foot in swing phase, and slap foot at heel strike. The experimental result shows gait of the subject was improved.

In the future, the evaluation on the effectiveness of the prototype based on clinical testing is on schedule. Furthermore, we aim small and lightweight of MRB.

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