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Abstract. The intelligent material, so-called magnetorheological (MR) fluid, is used in the design of an ankle foot orthosis. This paper presents the configuration of a multifunctional ankle foot orthosis that is equipped with a novel MR actuator. At first, the structure of the orthosis is introduced. Then, according to the mounting position of the actuator, the MR actuator is conceived by designing the structure and magnetic circuit. The actuator has three working modes, assistant, resistant and free modes. Finally, the manual power consumptions of two conditions, gait with and without the orthosis, are investigated; electricity consumptions of two cases, orthosis with and without the MR actuator, are compared.

1. Introduction

Given the global issue of aging, in recent decades, orthotic treatment has become a popular method to rectify abnormal gait styles, due to the portability, relative low cost and ease of use. In particular, the ankle foot orthosis (AFO) is one of the most commonly used orthotic devices.

In the early stage, AFOs were passive and a certain AFO was only suitable to a certain subject. In recent years, owing to the advance in smart materials and intelligent control technologies, active and multifunctional AFOs have been developed. Generally, an AFO is equipped with an actuator, which transmits the controllable energy from the power source to the ankle joint or dissipates energy of the shank. These actuators include pneumatic rotary actuator [1], hydraulic cylinder [2], series elastic actuator (SEA) [3], shape memory alloy [4] and electrorheological (ER) fluid [5]. However, it is found that pneumatic and hydraulic actuators have the problems of portability; ER fluids should be provided with high voltage.

Some researchers shifted the attention to development of orthosis that is equipped with MR fluid. MR fluid has the inherent advantage of quick response, low energy consumption and long life period. Kikuchi et al. [6] designed an AFO with an MR brake; this brake generates resistant torque of 10 Nm and can prevent foot drop effectively. Chen and Liao [7] presented an MR actuator that can transmit unidirectional assistant or resistant torque of 30 Nm. The switch between assistant and resistant torque modes is realized by setting a locking mechanism manually. Ma [8] conducted optimal design of an MR brake, which is used to generate resistant torque at the knee joint.

During a normal gait cycle, both changeable resistant and assistant torques are required at the ankle joint. To the best of our knowledge, few existing MR-based orthotic devices are able to transmit both changeable assistant and resistant torques. Therefore, in this study, a multifunctional MR actuator that can transmit changeable assistant and resistant torques is investigated. This paper is organized as follows. Firstly, the configuration of the ankle foot orthosis is presented. The following section is the

design of the MR actuator, both in structure and magnetic circuit. Last section investigates power consumption.

2. Configuration of Orthosis

2.1. Structure
The configuration of ankle foot orthosis is illustrated in figure 1. It is mainly composed of motor, gear box, bevel gear pair, MR actuator, main frame, fixing belt and insole. Force sensitive resistors are placed on the bottom plate; they are used to measure the ground reaction force and further detect the gait events. Furthermore, fixing belt is designed at the main frame and the bottom plate to attach the orthosis to the shank and the foot firmly.
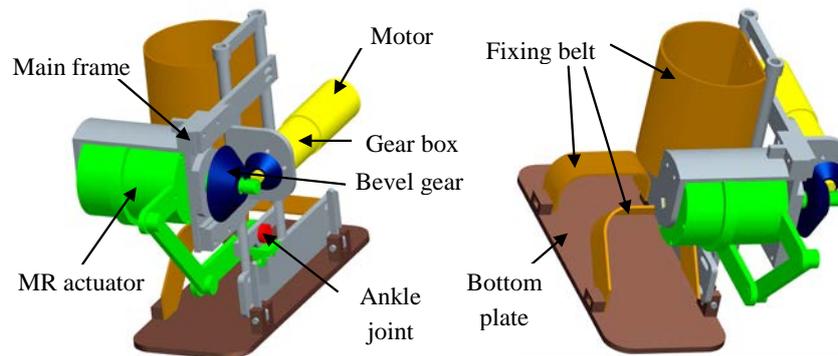

Figure 1. Configuration of the orthosis.

2.2. Function
The orthosis has three functions. Firstly, it can provide the changeable assistant torque. Subjects with weak muscle or motor control disorder can obtain the assistive torque and achieve the normal gait. Secondly, it generates the changeable resistant torque, which helps to overcome symptoms such as foot drop and get normal gait. Thirdly, it works in free mode. Subjects can walk almost freely and without the effect of the orthosis.

3. MR actuator

3.1. Structure
Figure 2 is the assembly of the actuator. It can be divided into three parts: part 1, 2 and 3; they are in the color of blue, green and yellow respectively. Part 1 is connected with the motor; while part 3 is fixed on the main frame of the orthosis. Part 1 and 2 can rotate independently relative to the main frame of the orthosis.

Each gap between inner polar plate and exterior polar plate is filled with MR fluids. The MR fluid is an intelligent material. Under the effect of magnetic field, its rheologic property will change steeply. Normally, the shear stress yield of MR fluids can be illustrated by Bingham Model:

$$\begin{aligned}
\tau &= \tau_0(H)\,\mathrm{sgn}(\dot{\gamma}) + \eta\dot{\gamma} \quad &|\tau| > |\tau_0| \\
\dot{\gamma} &= 0 \quad &|\tau| < |\tau_0|
\end{aligned} \tag{1}$$

where τ is shear stress yield; $\dot{\gamma}$ is shear strain rate; η is viscosity; τ_0 is mangneto-shear stress yield; H is magnetic field intensity.
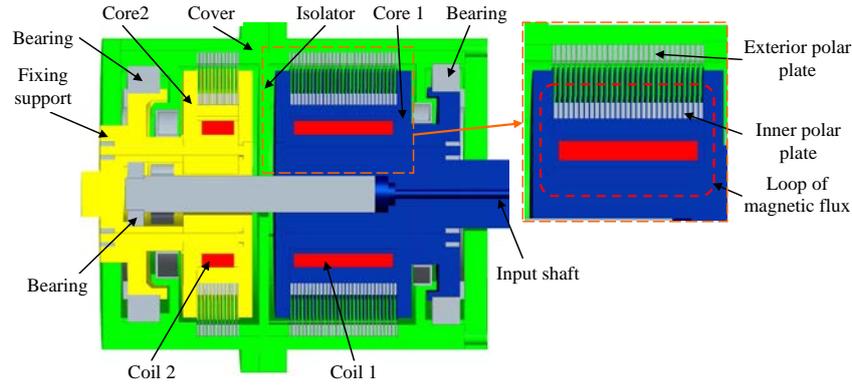
Figure 2. Magnetorheological actuator.

Based on the configuration of the actuator, the MR fluids is in shear working mode, shear strain rate $\dot{\gamma}$ can be expressed as

$$\dot{\gamma} = \frac{\omega r}{w} \tag{2}$$

where ω is the relative rotating speed of approaching polar plates; r is the radius; w is the gap between approaching external and internal polar plates.

3.2. Working modes
The MR actuator has three working modes: assistant, resistant and free modes. The details of each working modes are described in table 1:

Table 1. Working modes of the actuator.

Working mode	Output torque	Coil 1	Coil 2
Assistant	Assistant torque	Switch on	Switch off
Resistant	Resistant torque	Switch off	Switch on
Free	Zero-field torque	Switch off	Switch off

In assistant mode, coil 1 is switched on and the MR fluids between part 1 and 2 undergoes rheology. Accordingly, the assistant torque generated by the actuator under post-yield state is:

$$T_{ass} = 2N_{p1}\int_{r_1}^{r_2} 2\tau_2 \pi r^2 dr - 2N_{p2}\int_{r_1}^{r_2} 2\tau_1 \pi r^2 dr \tag{3}$$

where N_{p1} and N_{p2} are the number of inner polar plate 1 and 2 respectively; r_2 is the external radius of inner polar plate 2; r_1 is internal radius of exterior polar plate 2; τ_1 is the zero-field shear stress of fluids between part 2 and 3, that is $\tau_1 = \eta\dot{\gamma}_1$; τ_2 is the shear stress of fluids between part 1 and 2 of the actuator, that is $\tau_2 = \tau_{02} + \eta\dot{\gamma}_2$, where $\dot{\gamma}_1$ and $\dot{\gamma}_2$ are shear strain rates of fluids between part 1 and 2, and part 2 and 3 of the actuator respectively.

Using equation (1)-(3), assistant torque becomes

$$T_{ass} = \frac{4N_{p1}\pi\tau_{02}(r_2^3 - r_1^3)}{3} + \frac{\pi\eta(N_{p1}\omega_1 - N_{p2}\omega_2)(r_2^4 - r_1^4)}{w} \tag{4}$$

where ω_1 and ω_2 are relative rotating speeds between part 1 and 2, and part 2 and 3 respectively.

Similarly, resistant and free-mode torques can be calculated as follows:

$$T_{res} = \frac{4N_{p2}\pi\tau_{01}(r_2^3 - r_1^3)}{3} + \frac{\pi\eta(N_{p1}\omega_1 + N_{p2}\omega_2)(r_2^4 - r_1^4)}{w} \tag{5}$$

$$T_{free} = \frac{\pi\eta(N_{p1}\omega_1 + N_{p2}\omega_2)(r_2^4 - r_1^4)}{w} \tag{6}$$

where τ_{01} is mangneto-shear stress yield of fluids between part 2 and 3.

3.3. Magnetic Circuit

3.3.1. Materials of components. The electrical pure iron is chosen as the material of iron core due to its high relative magnetic permeability. Similarly, silicon-steel sheet is used to produce inner and exterior polar plates. Since magnetic flux leakage of the circuit should be prevented, cover is fabricated of aluminum because it has extremely high magnetic resistance.

3.3.2. Simulations. Simulation of magnetic circuit is conducted using ANSYS. Firstly, a geometrical mode is set up. Then, the geometrical model is meshed using element PLANE53 and each coil is applied with current of 1.5 A. The following graphs present some simulation results.
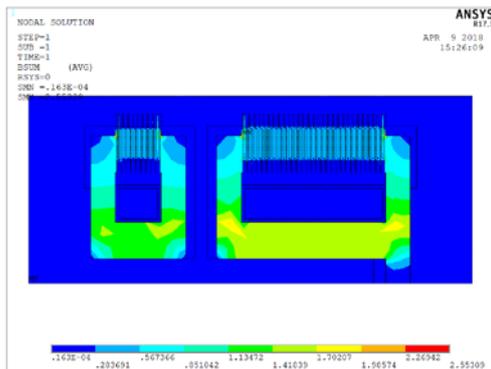

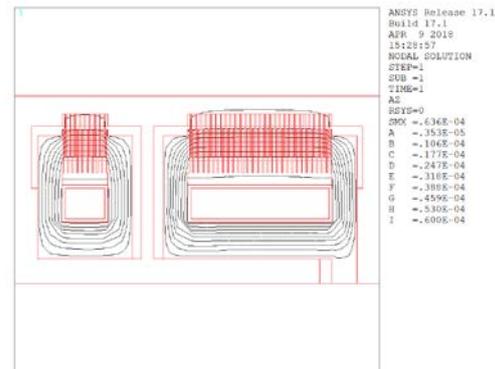**Figure 3.** Magnetic flux density.   **Figure 4.** Magnetic flux lines.

According to figure 3, the maximum magnetic flux density in most regions is less than 2 T and the average magnetic flux densities in damping gap (areas between inner and exterior polar plates) of part 1 and 3 are 0.408 T and 0.396 T respectively, which are in the normal scope. In figure 4, there is almost no magnetic flux line that traverses across part 1 and part 3. It means the actuator's assistant or resistant working mode can be realized independently.

4. Power Consumption

4.1. Save of manual power
Relying on simulations, this part explores the comparison of manual power consumption in two conditions, walking with and without orthosis. Suppose gait parameters, such as walking speed and joint velocities, are identical in two conditions, the difference between energy consumption of orthosis-based gait $W_{\mathrm{man,orth}}$ and nature gait $W_{\mathrm{man,natu}}$ can be described as follows:

$$\Delta W = W_{\mathrm{man,orth}} - W_{\mathrm{man,natu}} = W_{\mathrm{orth,tq}} - W_{\mathrm{orth,wt}} \tag{7}$$

where $W_{orth,tq}$ is the work of the input torque from the orthosis; $W_{orth,wt}$ is the work of subject to overcome the weight of the orthosis. They can be calculated as:

$$W_{orth,tq} = \int_T P_{orth,tq}(t)dt = \int_T T_{actu}(t)\omega_{ak}(t)dt. \tag{8}$$

$$W_{orth,wt} \approx \int_T P_{orth,wt}(t)dt = \int_T T_{orth,ak,st}(t)\omega_{sh,st}(t)dt + \int_T T_{orth,kn,sw}(t)\omega_{sh,sw}(t)dt + \int_T T_{orth,hi,sw}(t)\omega_{th,sw}(t)dt. \tag{9}$$

where $P_{orth,tq}(t)$ and $T_{actu}(t)$ are power and assistant torque provided by the orthosis respectively; $\omega_{ak}(t)$ is normal ankle rotation speed; $P_{orth,wt}(t)$ is power caused by the weight of orthosis; $T_{orth,ak,st}(t)$ and $\omega_{sh,st}(t)$ are torque of orthosis at the ankle joint and normal shank rotation speed at stance stage; $T_{orth,kn,sw}(t)$ and $T_{orth,hi,sw}(t)$ are torques of orthosis at knee and hip joints at swing stage respectively; $\omega_{sh,sw}(t)$ and $\omega_{th,sw}(t)$ are normal shank and thigh rotation speeds at swing stage respectively.

Some parameters are chosen as follows: shank length 0.396 m, weight of orthosis 2.5 kg and $T_{actu}(t)$ is set as half of the normal ankle torque; figure 5 shows the results, $P_{orth,tq}$ and $P_{orth,wt}$. Further, during a normal gait cycle, $W_{orth,tq}$ and $W_{orth,wt}$ are 15.3 J and 5.36 J respectively; it means that positive function of the orthosis outweighs its negative function.

4.2. Electricity consumption

Electricity consumption is mainly caused by motor and MR actuator. Here, two cases of electricity consumption are considered. Specifically, case 1 is the orthosis that is equipped with a motor and MR actuator; case 2 is the orthosis that is equipped with a motor only.

Further, the assistant torque is set as half of the normal torque when the normal torque is not larger than 40 Nm; otherwise, the assistant torque is defined as 20 Nm. Figure 6 presents the simulation results. It shows that the electricity power of case 1 is slightly larger than that of case 2. Therefore, addition of MR actuator will not exert burden of energy consumption.
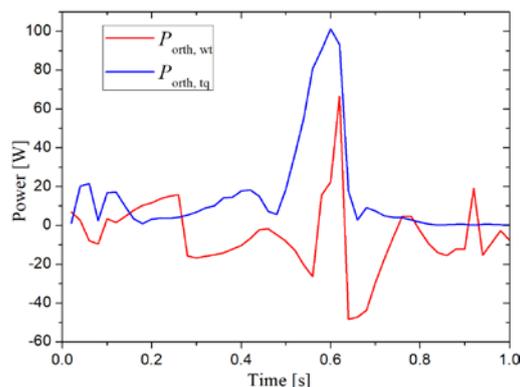

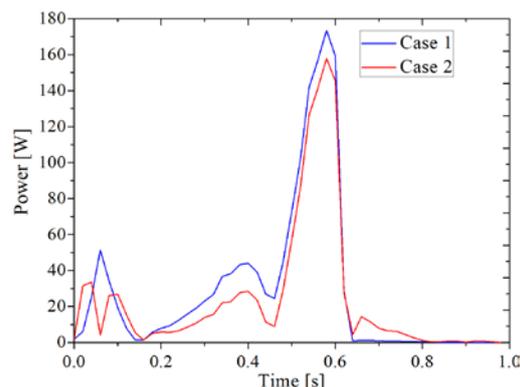**Figure 5.** Powers of output torque and weight of the orthosis.

Figure 6. Electricity power consumption of two cases.

5. Conclusions

In this work, the configuration of a multifunctional ankle foot orthosis was presented. The key component of the orthosis, a novel MR actuator, was developed by designing the structure and magnetic circuit. The actuator can transmit both bidirectional changeable assistant and resistant torques. Further, the magnetic circuit of the actuator was simulated using ANSYS.

Then, advantages of the MR-based orthosis were analyzed. Specifically, the manual power consumptions of two conditions, gait with and without the orthosis, were studied; electricity consumptions of two cases, orthosis with and without the MR actuator, were compared. Results indicated that the orthosis can relieve the manual power of subjects; difference of electricity consumptions of two cases is not significant. In the future, design factors including the weight and orientation of the ankle joint's axis will be considered to improve the feasibility of the device.

6. References

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