Prototype of haptic device for sole of foot using magnetic field sensitive elastomer

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Abstract. Walking is one of the most popular activities and a healthy aerobic exercise for the elderly. However, if they have physical and / or cognitive disabilities, sometimes it is challenging to go somewhere they don’t know well. The final goal of this study is to develop a virtual reality walking system that allows users to walk in virtual worlds fabricated with computer graphics. We focus on a haptic device that can perform various plantar pressures on users' soles of feet as an additional sense in the virtual reality walking. In this study, we discuss a use of a magnetic field sensitive elastomer (MSE) as a working material for the haptic interface on the sole. The first prototype with MSE was developed and evaluated in this work. According to the measurement of planter pressures, it was found that this device can perform different pressures on the sole of a light-weight user by applying magnetic field on the MSE. The result also implied necessities of the improvement of the magnetic circuit and the basic structure of the mechanism of the device.

1. Introduction
In Japan, people aged 65 or over account for more than 23% in 2012. This situation is called the super-aging society. Their qualities of life (QOL) are big issues nowadays. Maintenance of health for their mentalities and bodies is an important factor when we consider their QOL. According to the survey on favorite activities of the elderly in Japan [1], the most favorite activity of the elderly is traveling (see Table 1). Actually traveling around the world stimulates their mentality and body. However, a lot number of traveling need a lot of money. Then they love walking around their neighborhood as the second favorite activity. Because the traveling also includes much amount of walking activity, this survey indicates that the walking activity is a favorite physical activity of the elderly. From a viewpoint of their health, walking is a healthy aerobic exercise. Aerobic exercises have a statistically significant positive effect for the elderly with dementia and cognitive impairments [2]. During mild exercises we have increases of blood volume in our brains and these effects are considered to work well to prevent or slow dementia [3]. However, for people suffering from physical and / or cognitive disabilities and who really need the mild aerobic exercises, sometimes it is challenging to go somewhere they don’t know well. This is a reason why we are focusing on a virtual walking system which allows them to travel anywhere and anytime they want.

As a system that allows users to do a mild aerobic exercise, we propose a virtual walking system using a haptic device on soles of feet (Figure 1). This system consists of a visual system including a 3D projector and a shutter glass, a sound system, a force plate (Wii Balance Board, Nintendo) as an

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input device, and a desktop computer as a controller. When a user steps on the plate, the visual information and sounds work with the user’s motion. A computer graphics of a virtual city was made with computer graphics software and linked with these devices. The users can watch the 3D vision with the shutter glass that switches individual visions on left and right eye. Instead of the 3D glasses, we can use a head mount display for more compact system. The users can travel any places on the earth with staying in their rooms.

Table 1. Favorite activities of the elderly in Japan*.

|       | Male (%) | Female (%) |
|-------|----------|------------|
| 1st   | Traveling | 56.2       | Traveling | 53.1 |
| 2nd   | Walking  | 53.7       | Walking  | 37.6 |
| 3rd   | PC       | 37.1       | TV       | 27.5 |
| 4th   | TV       | 29.7       | Art      | 26.0 |
| 5th   | Golf     | 28.3       | Music    | 23.3 |

*Modified from [1]

Figure 1. VR Walking System.

In this study, we propose to use a magnetic field sensitive elastomer (MSE) [4], as an interface material of the haptic device on the soles of feet. The MSE is one of functional materials, which have been newly developed in recent years. This material is a composite of a polymer elastomer and magnetic fluids or magnetic particles. Its elastic modulus can be controlled with application of an external magnetic field. There are some mechanical platforms that can display haptic information on users’ feet during walking in virtual worlds. For example, Perreault et al. [5] developed a cable-driven parallel mechanism to perform reaction force on users’ feet and legs. As another example on the virtual walking system, Schmidt developed a large-scale linkage mechanism [6], and Iwata developed a 2 dimensional treadmill system [7]. In any case, they used very large scale system to perform the reaction force on users’ feet and legs. However, a compact haptic device on foot with a functional material is a new challenge.

This paper describes the first trial to develop a haptic interface using the MSE. We designed an electromagnet as a magnetic field generator for the MSE. The evaluation of this prototype was also discussed.

2. The first prototype of haptic interface with MSE
We have used a MSE that is a composite material of the magnetic particles (carbonyl iron, 2.8 μm in diameter, 70 wt%) and polyurethane elastomer as a haptic interface of the virtual reality walking system, because of its good endurance for environment and pressure. When we use a haptic interface
on sole feet, a high pressure is applied on the material. In such cases, the material should have a high endurance for pressure. As the other special feature of this material, its viscoelasticity is sensitive to the magnetic field. We can easily control the sense of touch only with the control of the external magnetic field without any active element like actuators. This feature helps us to develop a safe device for human.

In this material the magnetic particles disperses evenly in the off-state of the magnet. In this condition, the elastic modulus is less than 10 kPa. On the other hand, when we apply 0.5 T in the magnetic flux density in this material, the magnetic particles make some clusters that go through the direction of the magnetic flux and become stiff material whose elastic modulus is more than 200 times of that in the off-state [4].

As a resource of the magnetic field, we developed an electromagnet. The sectional view of the magnet is shown in Figure 2. The C-shaped magnetic circuit is made of the magnetic material (structural steel). Two coils at the left and right of the circuit generate magnetic fluxes in it. We put a sheet of the MSE (10mm in thickness) on this device, and control its elasticity with the magnetic field inside it. The result of magnetostatic analysis is shown in Figure 2. The magnetic circuit (geometry and coil) was designed so that they can generate 0.5 T in the magnetic flux density at the MSE. The specification is shown in Table 2. Figure 4 shows the results of compression tests with the magnet and MSE sheet. Handy Digital Force Gauge (HF-50, Japan Instrumentation System Co. LTD) with a probe whose diameter is 15mm was attached on a compression test stand, and used. The stress-strain curves in off-state (current input for the coil: I = 0.0 A) and on-state (I = 1.0 A) were measured. The device performed significantly different stresses between the off-state and on-state of the coil current.

We built 2 magnets on users' heels and toes (Figure 3) in order to control different senses on them. When we use this device, we put the MSE sheets on each magnet and evenly fill normal (non-magnetic) elastomers whose thickness is the same of the MSE at the other place.

![Figure 2. Magnetostatic analysis of the electromagnet for the MSE.](image)

![Figure 3. First prototype of the Foot Device (a photo without MSE).](image)

| Table 2. Specification of the magnet. |
|--------------------------------------|
| Width | 110 mm |
| Length (Adjustable) | 200-300 mm |
| Height | 55mm |
| Turning number of coil (for each) | 840 |
| Diameter of magnetic wire (with coating) | 0.45mm |
| Resistance of coil (for each) | 11.4Ω |
| Maximum electric current (for each) | 1A |
| Maximum and average of Magnetic flux density (@max current) | 0.5 T / 0.25T |
3. Method
We used an in-sole sheet pressure sensor (Figure 5, F-Scan II, Nitta) to measure the plantar pressure during stepping on the device. The range of measurable pressure is from 50 to 500 kPa. This is a sheet type force sensor and we can put it even in shoes. This sheet has 955 points of the sensor. Maximum sampling rate is 850 Hz but we sampled the pressure data at 80 Hz in this study in order to reduce the data number.

![Figure 5. In-sole pressure sensor sheet (left) and distribution of pressure (right)](image)

Two young healthy students were recruited as subjects. The dominant foot of both subjects is right foot. Therefore, the targets are their right feet in this research. Table 3 shows information of them. Subject A is a light weight subject and subject B is a heavy weight subject.

| Table 3. Information of target feet (subjects’ right feet). |
|-----------------|---------|----------|----------|
| Subject | Mass (kg) | Foot length (m) | Foot width (m) |
| A     | 49       | 0.245    | 0.083    |
| B     | 90       | 0.255    | 0.105    |

The prototype can control the stiffness of the MSEs on toes and heels, but we controlled only the MSE on the toe in these experiments. We measured the difference between the plantar pressure when subjects stepped on the off-state (I = 0.0 A) and that on the on-state (I = 1.0 A). As shown in Fig.6, we put the sensor sheet on the MSE device, and the subject was instructed to put his right foot without shoes on the sheet. Then the left foot was stridden from behind the right foot to the forward of it. The pressure profiles during this one stride were sampled at 80 Hz with the pressure sensor.
We measured the pressure profiles of all range of soles every trial. But in this work we discuss the average pressures just under the metatarsal head (MTH, Figure 7), because we put the MSE device on this point and this place is the most stressful point on the sole. The average pressures in 2 cm by 2 cm under the MTH were evaluated below. The target sensors were manually adjusted for every subject.

4. Results and discussion

Figure 8 shows the experimental results for subject A and B. For subject A, we can see clear difference of pressure between the on-state and the off-state of the device. However, the difference is not clear for subject B. This means this device has an ability to make stiffness change that can appear clear differences of perceptions under the sole only for light-weight users (~50 kg).

As a comparison, we measured a pressure difference between when the subject A (the light subject) stepped on a dot-type braille block (the height of the dots were 5mm, see the left of Fig.9) and a flat floor by the same way of the previous section. As shown in the right of Figure 9, the difference is
significantly bigger than the result of previous experiment on the MSE device. This experiment also shows the insufficient performance of the 1st prototype.

As shown in Figure 9, the device should support at least 400kPa in 2 cm by 2 cm with a small deformation in order to perform feasible perceptions on foot. We believe that the most critical reason of this insufficient performance of the device is the insufficient magnetic field inside the MSE. We use open air structure in the 1st prototype (Figure 2) and this result in the insufficient intensity of magnetic field. Now we are designing a new version of the device with the MSE. In the new structure, we will sandwich the MSE with magnetic materials and make a close loop of the magnetic flux that completely passes through the MSE and make higher intensity of the magnetic flux density.

5. Conclusion
In this research, we have developed a haptic interface by using a magnetic field sensitive elastomer (MSE). The performance of the 1st prototype is not sufficient but we can find a possibility of the device. We are now designing a new version of the device.

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