Abstract—A magnetic field sensitive elastomer (MSE) is a compound of magnetic particles and non-magnetic elastomers. This is a functional material whose elasticity can be adjusted with an external magnetic field. The final goal of this study is to develop a virtual walking system using a haptic device on soles of feet with the MSE. First, we measured the difference of planter pressures when subjects (3 young healthy students) stepped on two different types of floor (dot-type braille block and flat floor). The differences of the normalized pressures were about 2–4, and these values are one of the development goal of the device. Next, we designed an electromagnet and evaluate the difference of plantar pressure with/without magnetic field on the MSE. According to the results, the difference of the normalized pressure depended on the weight of subjects. The difference of the normalized pressure was 2.3 for a light subject. However, there were not clear differences for heavier subjects. We should consider the basic elasticity of the MSE to develop a practical device.

I. INTRODUCTION

Aging society is one of the most serious challenges in many countries. There are a large number of people suffering from dementia in the aging societies and it is one of the major concerns. There is also a large amount of research on the dementia, which include diagnostic methods, prevalence, incidence, and so on [1–4]. Regarding the method of its prevention, aerobic exercises have statistically positive effects for dementia and cognitive impairments [2–4]. During mild exercises we have the increase of blood volume in our brains and this effect is considered to work well to prevent or slow the dementia [5]. Walking is one of popular, simple and cheap aerobic exercises. According to some interviews for the elderly, most favorite recreations they usually do are a traveling and walking. For people who suffer from physical and/or mental disabilities and who really need 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 by using virtual reality technologies.

There are some mechanical platforms that can display haptic information on users’ feet during walking in virtual worlds. For example, S. Perreault et al. [6] developed a cable-driven parallel mechanism to perform reaction force on users’ feet and legs. As another example on the virtual walking system, H. Schmidt developed a large-scale linkage mechanism [7], and H. Iwata developed a 2 dimensional treadmill system [8]. In any case, they used very large scale system to perform the reaction force not only on users’ feet but also their legs. If we require really immersive experience in the virtual world, we need to use such large systems. However, if we require additional information for the virtual walking in our home to motivate the users to walk, compact and simple devices would be preferred rather than such large scale systems.

Fig. 1. Conceptual drawing of Virtual Walking System with Haptic Device on sole of feet (Main target of this paper is a haptic device shown in the right figure)

As a system that allows users to do mild aerobic exercises, we propose a virtual walking system using a haptic device on soles of feet (Fig.1). In this concept, a sender (a man in the left side) gets the vision, sound and distribution of plantar pressure in the real world and sends them to a receiver (a man in the right side). The receiver watches the vision, listens to the sound, and feels various plantar pressures on his soles of feet.
feet. The receiver can feel like walking with the sender and travel together in the real/virtual environment. The visual and sound system can be constructed with some conventional components. However, the haptic device on the soles of feet is the latest challenges.

Recent trials on haptic interfaces for sole feet with vibration motors [9-10] or voice coil actuators [11] have been seen in literatures. These devices apply a high frequency vibration on feet as a representative of sense of touch. However, we have two types of mechanoreceptors on sense of touch [12], and low frequency change of planar pressures must be important information for reality of walking. A haptic device that mainly stimulates slow-adapting mechanoreceptors of human feet sole is a new challenge and a main target of this study. We propose to use a magnetic field sensitive elastomer (MSE) [13] as an interfacial material of the haptic device on soles of feet that apply low frequency difference of pressure on the slow-adapting mechanoreceptors of feet. The MSE is one of functional materials, which have been newly developed in recent years. Generally, this material is a composite of a polymer elastomer and magnetic fluids or magnetic particles. Its elastic modulus can be controlled with application of external magnetic field. Many attempts to fabricate this material using synthetic polymer [14], silicone elastomers [15-16], rubbers [17], have been performed. However, the increment in the elastic modulus by magnetic fields to the original modulus without the field, was several times or less [18].

In recent years, T. Mitsumata, et al. [13] developed a new class of the MSE that exhibits more than 200 times changes of elastic modulus. This material works as a completely passive element of the haptic interface. It is so safe because it doesn’t include any actuation part. Additionally, it has enough toughness to use as interfaces under feet. Meanwhile few application study of the MSE has appeared so far. Therefore the objective of this study is to develop a haptic device which applies the MSE as the haptic-controllable interface for the virtual walking system.

This paper describes a first trial to develop a haptic interface using the MSE. First we measured the difference of plantar pressures on a flat ground and a dot-type braille block in order to decide a concrete goal of the developing device. We developed a sensor shoe system which has 16 points of force sensor in the insole of the shoe, and visual software to check the distribution of pressure. Plantar pressures were measured with this sensor device and experimental results were discussed to decide a development goal of the haptic device. Next, we developed an electric magnet to apply a magnetic field into the MSE. In the previous study [19], we evaluated the characteristics of the MSE by using permanent magnets. But it is difficult to control fine change of the elasticity of the MSE by using permanent magnets alone.

Then we designed an electromagnet as a magnetic field generator for the MSE. Finally, we evaluate the prototype of the haptic device with the MSE and discussed the results.

II. MEASUREMENT OF DIFFERENCE OF PLANTAR PRESSURE

A. Method

We developed a shoe-shaped pressure sensor to measure the distribution of insole pressure of human sole feet. We used an in-room shoe as a base of the sensor shoe. We put 16 sheet-type force sensors (Flexible Force, A201-25, Nitta, maximum force: 110N, diameter: 9.5mm) inside the shoe and put a flexible insole on them (Fig.2 (a)). The position of the sensors is shown in the Fig.2 (b). Regarding the position of the sensors, we referred to those of the Biofoot® [20], one of the commercially available sensor shoes.

Dynamic changes of the planter pressure were measured with these sheet sensor and logged with a data logger (NR-200, Keyence) in real time (sampling time: 1ms). The logged data were evaluated with custom made software (Fig.3). In this software, the distribution of the pressure is able to be checked with different colors (high: red, low: blue) at each position (upper view). At the same time, we can check specific value of pressure for each position at a specific time (lower view).

We used a dot-type braille block (Fig.4) as a sample ground with a convex-concave pattern. 3 healthy subjects (21-24 years old) tried the tests. In order to normalize the experimental results, we measured the lengths and widths of their right feet (Table 1). The definition of the foot length (L [m]) in this paper is the length from the tip of the first toe to heel. The foot width (D [m]) is the maximum width of each
foot. Their shoe-sizes are same (27cm) and the correspondance between their feet and the sensor positions are almost same.

The subjects wore the sensor shoe on their right feet and put their right feet on the two different types of the floors so as not to drift the feet on the ground. One of the sample grounds is a rigid flat floor, and the other is a dot-type braille block. Subjects were instructed to slowly stride their left feet from behind the right feet to the front of them like they walk with putting their right feet on the sample floors. All subjects could understand on which one they stepped their right foot without any visual information. From the results of the preliminary tests, we selected a sensor numbered 7 as a representative position for evaluation of the difference of planter pressure.

**TABLE I**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Weight ( W ) [kg]</th>
<th>Foot length ( L ) [m]</th>
<th>Foot width ( D ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>68.5</td>
<td>0.260</td>
<td>0.100</td>
</tr>
<tr>
<td>B</td>
<td>87.0</td>
<td>0.255</td>
<td>0.105</td>
</tr>
<tr>
<td>C</td>
<td>85.0</td>
<td>0.270</td>
<td>0.115</td>
</tr>
</tbody>
</table>

![Fig. 4. Dot-type braille block and sensor position](image)

**B. Result**

Figure 5~7 show the experimental results of the 3 subjects. Each subject stepped on the testing floor by 3 times. In these figures, the pressure profiles are shifted on the time axes so as to correspond at the highest peaks, and averaged with 3 profiles of the same conditions.

The figure 5 shows the result of the subject A. The highest peak on the braille block is 82.3 kPa. In contrast, the peak pressure on the flat floor is 11.4 kPa. For the subject B, the experimental results are shown in the Fig. 6. The pressures at the peak of the critical sensor are 153 kPa on the braille block and 19.2 kPa on the flat floor. In the same way, experimental results of the subject C are shown in the Fig.7. The pressures at the peak are 61.0 kPa on the braille block and 14.4 kPa on the flat floor.

**C. Discussion**

We defined a nominal pressure and a normalized pressure to evaluate the pressure values of the subjects who have different size of foot and weight. The definition of the nominal pressure \( P_0 \) [Pa] is as follows;

\[
P_0 = \frac{W \times g}{L \times D}
\]

, where \( W \) is the weight [kg] of each subject, \( g \) is the gravitational acceleration (= 9.81 m/s\(^2\)). \( L \) and \( D \) are the length [m] and width [m] of the right foot of each subject (see Table.1). This value corresponds to an average pressure in the case that the whole body mass applies on a foot area which is calculated as a rectangle with the length, \( L \) and width, \( D \).

Additionally, the differences of the pressure under the representative sensor mentioned in the previous section can be normalized by divided by the nominal pressure. They are shown in the fourth column of the table II. In these experiments, about 2 to 4 of the difference of normalized pressure were shown on the sensor. This value could be one of the development goals of the haptic interface on sole feet.
### TABLE II

<table>
<thead>
<tr>
<th>Subject</th>
<th>Peak pressure on flat floor [kPa]</th>
<th>Peak pressure on braille block [kPa]</th>
<th>Difference of normalized pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11.4</td>
<td>82.3</td>
<td>2.74</td>
</tr>
<tr>
<td>B</td>
<td>19.2</td>
<td>153</td>
<td>4.20</td>
</tr>
<tr>
<td>C</td>
<td>14.4</td>
<td>61.0</td>
<td>1.74</td>
</tr>
</tbody>
</table>

### III. DEVELOPMENT OF PROTOTYPE FOR HAPTIC DEVICE ON SOLE FEET

#### A. Material

The MSE is a composite of polymer solids and magnetic particles. We used polyurethane elastomers and carbonyl irons as magnetic particles (70wt%). Shear modulus of these materials is 10kPa without magnetic field. However, this value rises up to 700kPa with magnetic field.

![Mechanism of elasticity changes of MSE](image)

Mechanism of the elasticity changes of the MSE has not been cleared yet. But one possible mechanism is shown in Fig.8. The left-hand drawing represents this material without magnetic field. In this condition, this material has an isotropic particle network in the matrix, and is flexible to deform to arbitrary direction. On the other hand, when a magnetic field toward the vertical direction is applied to the material, it makes anisotropic structural network and anisotropic elasticity as shown in the right hand of Fig.8.

#### B. Design

We developed an electromagnet as a magnetic-field generator for the MSE. The sectional view of the electromagnet is shown in the Fig.9. The C-shaped magnetic circuit is made of structural steels. Two coils at the left and right of the C-yoke generate magnetic fluxes in the C-yoke. We put a sheet of the MSE on this device, and control its elasticity with the magnetic field applied from the electromagnet.

![Magnetostatic analysis of the magnetic field generator for the MSE](image)

ANSYS Workbench Ver.13 (ANSYS Inc.) was used to analyze the magnetic flux density inside the MSE. The result of the analysis is shown in the Fig.9. A distribution of the magnetic flux density inside the material can be seen. In the simulations, the thickness of the MSE was defined as 10mm. The magnetic circuit and coil were designed so that they can generate at least 0.5T in the magnetic flux density in order to utilize sufficient elasticity changes of the MSE [11]. Table III shows the specifications of the developed electric magnet.

#### TABLE III

<table>
<thead>
<tr>
<th>Specification of Electromagnet</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>110 mm</td>
</tr>
<tr>
<td>Length (Adjustable)</td>
<td>200-300 mm</td>
</tr>
<tr>
<td>Height</td>
<td>55mm</td>
</tr>
<tr>
<td>Turning number of coil (for each)</td>
<td>840mm</td>
</tr>
<tr>
<td>Diameter of magnetic wire (with coating)</td>
<td>0.45mm</td>
</tr>
<tr>
<td>Resistance of coil (for each)</td>
<td>11.4Ω</td>
</tr>
<tr>
<td>Maximum electric current (for each)</td>
<td>1A</td>
</tr>
</tbody>
</table>

#### C. Evaluation

It is difficult to directly measure the magnetic field density under the condition we use the MSE on the device, because when we use a gaussmeter to measure the magnetic flux density, we should measure it in the air space. Then, in order to evaluate the performance of the electromagnet, we re-analyzed the magnetic flux density in the case we do not put the MSE sheet on the device (there is only air on the device), and compared with the measured results with the gaussmeter (Model No.425, Lake Shore, US). Figure 10 shows the analytical result of the magnet in the air. The numbers from 1 to 7 show the positions we measured the magnetic flux density with the gaussmeter.

![Comparison of analytical results and measured values](image)

Figure 11 shows the comparison of the analytical results and measured values. The solid line shows the analytical result and the black dots show the measured values. The magnetic flux density is a vector value in 3 dimensions, but we can only measure that of the vertical direction to the probe of the gaussmeter. Then the values shown in the Fig.10 and 11 are those toward vertical direction of the device.

The values at the probe 4 are almost zero in both analysis and measurement, because the magnetic flux paths through this position in the completely horizontal direction. The values at the probe 3 and 5 show highest among them and both of the analysis and measurement shows similar values. Although there are large error at the farer point from center than the probe 3 and 5, the developed magnet could generate the magnetic flux densities that are close to those of analyses at the positions where the highest value of the magnetic flux densities are shown.
Additionally, we measured the relationship between the stress and strain of the MSE on the developed electromagnet. The compression tests were conducted for the developed device by the same method presented in the previous study [19]. Figure 12 shows the result. The position 1 to 4 corresponds to those of Fig.10.

Two subjects (Table IV) conducted the stepping experiments with / without magnetic field application. The subject D has a light weight. Conversely, the subject E has a heavier weight than the subject D.

IV. EVALUATION OF PLANTAR PRESSURE

A. Method
The prototype was tested by the pressure measurements with human feet. The experimental setup is explained in Fig.13. The MSE was put on the developed electromagnet unit so that subjects step it just with its MP joint of foot. Non-magnetic elastomers whose elasticity is almost the same as that of the MSE were put under the foot so as to make a flat surface. The flexible force sensor sheets used in the sensor shoe were also used in these experiments. Each sensor was put on the sensor position (1~7). These numbers correspond to the probe positions shown in the Fig.10.

B. Result
The pressure profile of the subject D at the sensor position 4 is shown in the Fig. 14. Figure 14 shows the peak pressure of 158 kPa with magnetic field, and 104 kPa without magnet. The difference of the normalized pressure is 2.3. This value is in the same level of the previous experiments conducted with the dot-type braille block and flat surface. This means the MSE has a potential as the haptic interface for the plantar pressure of feet.

The pressure profiles of the subject E at the sensor positions 4 are shown in the Fig. 15. The pressure profiles of the subject E differed from those of the subject D in that there is not a clear difference between the pressures with / without the magnetic field.
C. Discussion

According to these results, this device has a potential to display the change of the sense of touch under the human feet. However, a big problem has remained. The pressure under the normal situation of the device (without magnetic field) is much higher than that on the flat floor. This means the device cannot realize the sense of force which happens on the flat floor. This may be caused by the big difference of the elastic modulus of the sole rubber and the MSE. The MSE without magnetic field is a soft material and it can easily deform. When a foot rides on the MSE, the MSE without magnetic field deforms and fits the shape of the foot surface. In this situation, a higher pressure must be applied on the point which does not normally touch the ground. To solve this problem, we should reconsider the control method of the elasticity of the MSE and structure of the device in the future.

Another problem is a limitation of the weight of users. According to the experimental results shown in Fig.16, the developed prototype did not have a sufficient performance to display the pressure change for users who have heavy weight. We should re-design the device and improve the weight limit of it. For subjects who have heavy weight, the planter pressure of 100 to 200 kPa is normally appears during walking. The device should have a sufficient elastic modulus that can keep a small deformation when the pressure over 200 kPa is applied. For more detailed information, we should conduct more numbers of tests.

V. Conclusion

In this paper, we propose a virtual walking system with a haptic interface on planter surfaces of feet. The main topic of the paper is a difference of the planter pressure on different shaped grounds as a requirement of the haptic interface. A flat floor and a dot-type braille block are selected sample surfaces. The change of the planter pressure is evaluated with the difference of the normalized pressure. A prototype of the haptic interface was developed with a magnetic field sensitive elastomer. The performance of the device was also evaluated.

Acknowledgment

This research was supported by Casio Science Promotion Foundation and Communications R&D Promotion Programme (SCOPE) of Japan.

References