Basic Study on Intelligently Haptic Controllable Shoes with Magnetic-Field Sensitive Gel

Takehito Kikuchi, Yasunobu Masuda, Tetsu Mitsumata, Suguru Ohori

Graduate School of Science and Engineering, Yamagata University

ABSTRACT

Magnetic-field sensitive gels (MS-gels) are polymer gels containing magnetic fluids or magnetic particles. The MS-gel used in this paper exhibits remarkable changes of elasticity under magnetic field. The objective of this paper is to develop a walking guidance system by using the MS-gel as a haptic-controllable part of intelligently haptic controllable shoes. As a preliminary trial of the development, we conducted sensory evaluation tests under conditions that the MS-gels which have different thicknesses and structures are put with / without a permanent magnet. 5 healthy students tried to perceive differences of haptic information by pushing the gel with their fingers or heels. The experimental results show significant differences in the finger-pushing group, but not in the heel-pushing group. As a next challenge, we also conducted foot test in which we use two MS-gels under a toe and a heel of subjects. In this test, subjects tried to perceive differences of haptic information between toes and heels. The results of this experiments show significant differences. This fact expresses a potential to use this material as a haptic interface of a walking guide system.

KEYWORDS: Haptic Control, Walking Guidance System, Intelligent Shoes, Magnetic-Field Sensitive Gel, Sensory Evaluation.

INDEX TERMS: J.3 [Computer Applications]: Life and Medical Sciences—Health

1 INTRODUCTION

Magnetic-field sensitive gels (MS-gel) [1] are kinds of functional materials that have been newly developed in recent years. Generally, this material is a composite of a polymer gel and magnetic fluids or magnetic particles. Its elastic modulus can be controlled with application of magnetic field from outside. Many attempts to fabricate this material using synthetic polymer [2], silicone elastomers [3-4], rubbers [5], have been performed. However, the increment in the elastic modulus by magnetic fields, to the original modulus without the field, was less than double [1].

In recent years, Mitsumata, et al. [1] developed a new class of the MS-gals that exhibits up to 500 times changes of elastic modulus by using carrageenan gels and carbonyl iron particles. The objective of this study is to develop a walking guidance system by using this material as a haptic controllable part of intelligently haptic controllable shoes.

So far, application studies on the magnetic sensitive gels have been focused on vibration control devices [6] or smart structure [7]. Application of the MS-gel to the haptic controllable shoes is a new initiative.

Several trials on shoe-shaped haptic devices have been conducted by using vibration motors [8-9], or pneumatic powers [10]. However, these devices have less feasibility, because these require mounting some electric circuits, sensors, actuators and batteries on shoes, and some times, connecting to outside. The intelligent shoes which utilize the MS-gel do not require any other extra parts on the shoes and connection to outside (Fig.1). This fact makes this system so feasible. In order to complete this system, we should find out sensory characteristics of human when they touch this material. Additionally, effective uses of this material should be considered according to sensory evaluations. In this paper, we describe experimental results of the sensory evaluation as preliminary trials of the MS-gels.

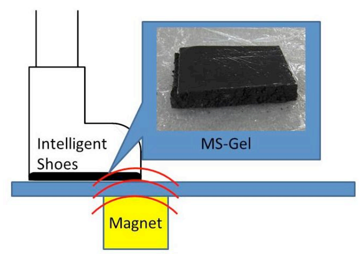

Figure1. Concept of intelligent shoes and walking guide system with magnetic field sensitive gel

2 MAGNETIC-FIELD SENSITIVE GEL (MS-GEL)

As mentioned in the introduction, MS-gels are composites of polymer gels and magnetic particles. In the MS-gel used in this paper, we used polyurethane as a gel and carbonyl iron as magnetic particles. The polyurethane and 70wt% carbonyl iron particles were mixed at room temperature. This pre-gel was poured in a casting mold, cured at 70 degrees Celsius for 3 hours, and cooled off. We prepared two types of the MS-gel sheet whose thicknesses are 10mm (sample 1) and 5mm (sample 2) and a non-magnetic gel sheet whose thicknesses is 5mm (sample 3). We used these materials by itself or combination. Shear modulus of these materials is 10kPa without magnetic field. However, in the case of the MS-gel, this value rises up to 700kPa with magnetic field.

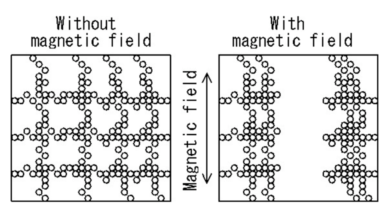

Figure2. Mechanism of elasticity changes of MS-gels [1]

4-3-16 Jonan, Yonezawa 992-8510 Japan (corresponding author to provide phone & fax: +81-238-26-3892; e-mail: t_kikuchi@yz.yamagata-u.ac.jp)

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Mechanism of the elasticity changes of the MS-gel has not been cleared yet. But one possible mechanism is shown in Fig.2 [1]. The left-hand drawing represents this material without magnetic field. In this condition, this material has an isotropic particle network within the matrix, and is flexible to deform to arbitrary direction. On the other hand, when a magnetic field toward vertical direction is applied to the material, it makes anisotropic structural network and anisotropic elasticity as shown in the right hand of Fig.2. Especially, elastic modulus of the vertical direction is heightened in this structure.

3 MATERIAL TESTS OF MS-GEL

3.1 Material, Setup and Method

In this section, we conduct material tests of the MS-gel sheets (sample 1, 2 and combinations with sample 3 mentioned in the section 2) to figure out basic characteristics of these materials. Test specimens are shown in the table 1 and Fig.3. We prepared 4 kinds of samples. In the case 1 and 2, only sample 1 and 2 are used. In the case 3 and 4, we used non-magnetic gel whose thickness is 5mm and elastic modulus is same level of that of the sample 2 at free-state (sample 3). In the case 3, we put the sample 2 on the sample3. On the other hand, in the case 4, we put the sample 2 under the sample 3. These two are considered to find potentials of combinational utilization of different kinds materials.

Table 1. Experimental conditions

Case 1	Sample 1 (thickness 10mm)
Case 2	Sample 2 (thickness 5mm)
Case 3	Sample 2 (upper) on Sample 3 (non-magnetic, thickness 5mm)
Case 4	Sample 2 (lower) under Sample 3

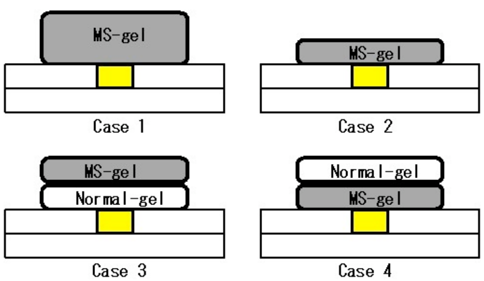

Figure3. Experimental conditions

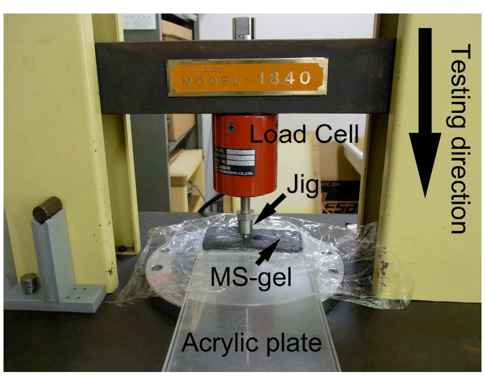

Figure4. Testing machine and compression jig

As shown in Fig.4, we conducted compressing tests with a material testing machine (AIKOH ENGINEERING, MODEL-1840, maximum range of load cell: 500N). The diameter of the compression jig is 6.5mm. We prepared a permanent magnet (neodymium magnet, diameter: 20mm, height: 10mm, surface magnetic flux density: 0.435T, residual magnetic flux density: 1.25T, magnetic coercive force: 907kA/m) as a magnetic resource. The magnet is embedded in an acrylic plate with a flat surface (Fig.5). In a condition, the MS-gel sheets were put on the magnet. In the other condition, the sheets were put on the acrylic plate without magnet. In the case with the magnet, we selected three places as a testing point: (1) center of the magnet, (2) 10mm from the center, and (3) 20mm from the center (Fig.6).

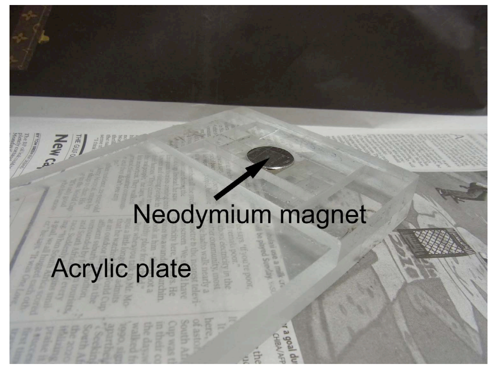

Figure5. Permanent magnet embedded in plate

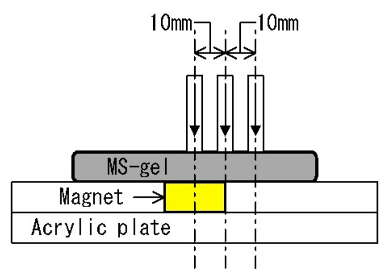

Figure6. Method of material tests

3.2 Results

Experimental results for the case1 through 4 are shown in Fig 7 through 10, respectively. The vertical value, stress was calculated from measured forces divided by the area of the compression jig. On the other hand, the horizontal value, strain was calculated from displacements divided by the thickness of the original sample. An important point in these results is that these data are not basic characteristics of this material, because these relate to distributions of magnetic field, shapes of sheets and so on.

As shown in Fig.6, in the case of the Case 1, the stresses at the same strain gradually decrease depending on the displacement from the center of the magnet. Additionally, the stress at 20mm from the center is same level of that without magnet.

The distribution of the stresses of the Case 2 is different from that of the Case 1. The stress at 10mm from the center of the magnet shows same level of that at the center of the magnet. On the other hand, the stress at 20mm from the center is nearly same level of that without magnet. Additionally, the average value of the stress in the Case 2 is about half of that in the Case 1.

In the Case 3, we can find same level of the stress in the Case 1, on the center of the magnet, but different distribution of the stress in regard to the distance from the center of the magnet.

On the other hand, in the Case 4, the difference of the stress in regard to the distance is quite low.

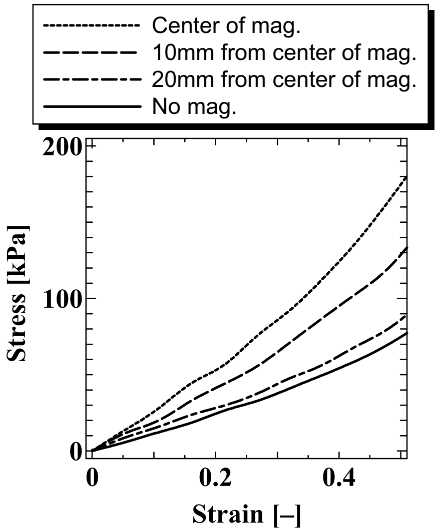

Figure7. SS-curves of Case1

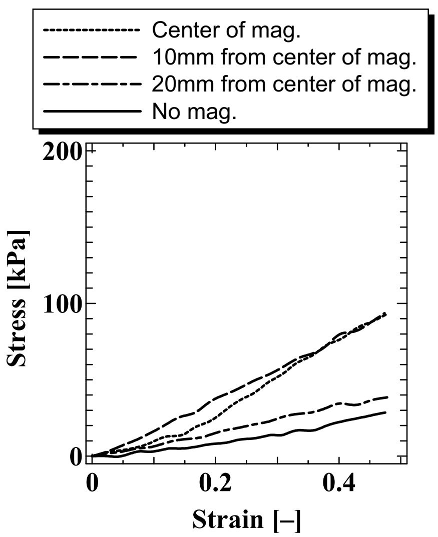

Figure8. SS-curves of Case2

3.3 Discussion with magnetostatic analysis

In order to figure out the differences in the S-S curves of the Case 1 through 4 presented in the Fig.7 through 10, we analyzed the distributions of magnetic field by using FEM software (ANSYS Workbench Ver. 12, ANSYS Inc.). For calculations of non-linearity of the material characteristics, we used the B-H curve data of the MS-gel (Fig.11). The characteristics of the permanent magnet are mentioned in the section 3.1.

The analytic results for the Case 1 trough 4 are shown in the Fig 12 through 15, respectively. We can especially confirm great difference between the distribution of magnetic field of the Case 1 and that of the Case 2. In the Case 2, the range of high level intensity of the magnetic filed is broader than that of the Case 1. This would cause the broad range of high stiffness area in the SS-curve as shown in Fig.8 and obfuscate the haptic information or spacial difference of elasticity on the surface of the gels.

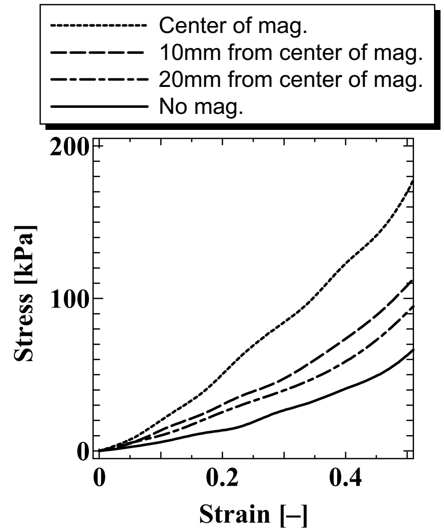

Figure9. SS-curves of Case3

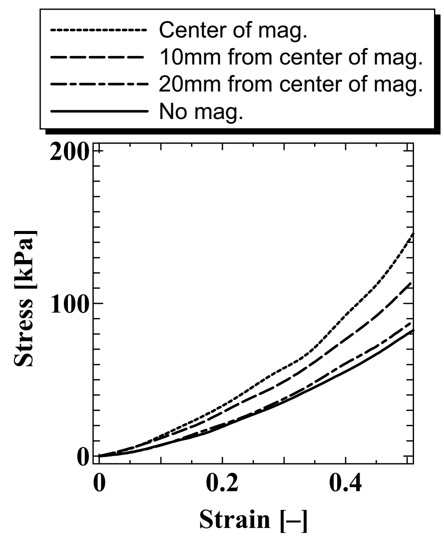

Figure10. SS-curves of Case4

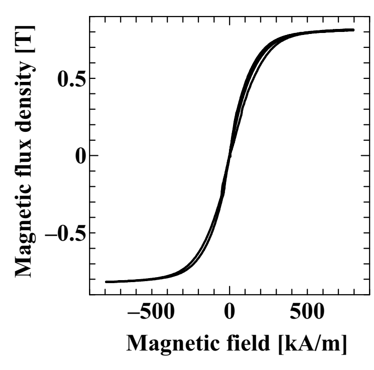

Figure11. B-H curve of the MS-gel

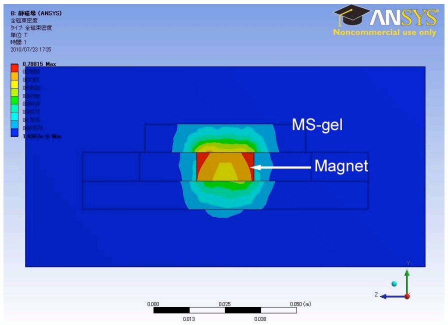

Figure12. Magnetostatic analysis of Case 1

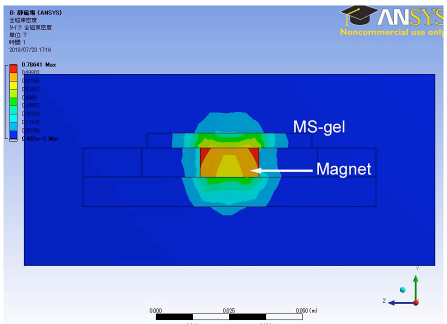

Figure13. Magnetostatic analysis of Case 2

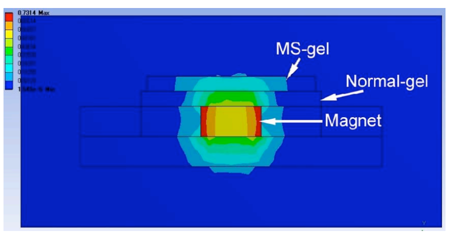

Figure14. Magnetostatic analysis of Case 3

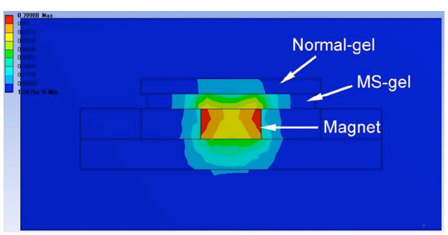

Figure15. Magnetostatic analysis of Case 4

4 SENSORY EVALUATION OF MS-GEL (FIRST TRIAL)

4.1 Setup and Method

As a first trial to figure out sensory characteristics when human touch these materials, we conducted sensory evaluation tests. 5 healthy male students (22-23 years old) touched the MS-gel sheets (Case 1 ~ 4) with / without a permanent magnet. The same setup shown in the Fig.5 was used in the tests.

We instructed each subject to touch (1) the MS-gel sheet with magnet and (2) the sheet without magnet, alternately. Each subject put an eye mask on their eyes for blind tests, and touches them by his index finger (left hand of Fig.16) or feel (right hand of Fig.16). The order of (1) and (2) was set at random. We required each subject to answer which one is harder, and recorded the number that they answered the sample with magnet was harder than without magnet. 13 trials for each condition were conducted.

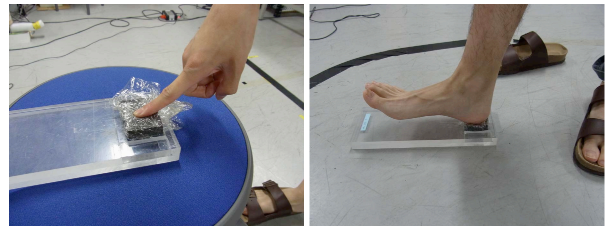

Figure16. Methods of sensory evaluation

(left: index finger, right: heel)

4.2 Statistical Analysis

We utilized statistical analysis to understand significant differences between haptic information of the MS-gel sheet under magnetic / non-magnetic situations of each sample and touching method.

The null hypothesis (H_0) in this case is that there is no difference between the two kinds of the haptic information from the MS-gel sheet under magnetic / non-magnetic situations. In other wards, the probability (p) that the answer of the tests mentioned in the section 4.1 is equal to 0.5,

$$H_0 : p = 0.5. \tag{1}$$

In this case, the distribution of the event is a binomial distribution in which the possibility of success (p) is 0.5 and the possibility of failure (q = 1-p) is 0.5.

We use χ^2-distribution instead of the binomial distribution, because the number of trials is greater than 10. The χ^2-value in this case can be calculated as follows;

$$\chi^2 = \frac{(s-e)^2}{e} + \frac{((n-s)-e)^2}{e} \tag{2}$$

where, n is the number of all trials (=13), e is the expectation value (=n*p=6.5). The relationship between the number of success (s) and the χ^2 value is shown in the table2. According to the χ^2-distribution table (degree of freedom: 1) [11], the χ^2-values that are greater than 3.84 can reject the null hypothesis for 5% level of significance, and 2.71 for 10% level of significance. As shown in the table 2, s values greater than 11 are required for the 5% level of significance (dark-gray colored), and 10 for 10% level of significance (light-gray colored).

Table 2. Chai-square values of this test

s	χ^2
0	13.0
1	9.31
2	6.23
3	3.77
4	1.92
5	0.692
6	0.0769
7	0.0769
8	0.692
9	1.92

10	3.77
11	6.23
12	9.31
13	13.0

4.3 Results

Experimental results (success number) and results of the statistical analysis mentioned in the table 2 are presented in this section. The table 3 and 4 show the experimental results by index finger and heel, respectively. The numbers shown in these tables are the numbers of success in the trials. The dark-gray-colored cells in these tables show 5% level of significance and the light-gray-colored cells show 10% level of significance.

As shown in the table 3, almost all of subjects could perceive differences of the haptic information (changes of elasticity) of the MS-gel sheets between different situations of magnetic field even in the 5% level of significance. In particular, the case 1 shows the most significance of all.

On the other hand, as shown in the table 4, the case of the heels shows less significance than the case of the fingers. However, when we include the cells that show 10% level of significance, the case 1 is the most potential way to display haptic information.

Table 3 Result of sensory evaluation (index finger)

Subject	A	B	C	D	E
Case1	13	13	12	12	13
Case 2	12	13	4	13	2
Case 3	13	12	10	13	12
Case 4	11	8	11	11	8

Table 4 Result of sensory evaluation (heel)

Subject	A	B	C	D	E
Case 1	11	10	7	10	8
Case 2	10	10	5	3	10
Case 3	7	5	4	5	11
Case 4	6	9	8	6	7

5 SENSORY EVALUATION OF MS-GEL (SECOND TRIAL)

Our final goal of this study is the development of a walking guidance system with the intelligent shoes using the MS-gel. In the previous section, we conducted a first trial of haptic interface for food. However, demonstrations just only on heel did not show sufficient perceptions. Then, in this part, we set two MS-gel under the toe (front part of the foot) and the heel (rear part of the foot). By using these two gels, we expect that subjects can use their sensitivity of the different parts at once and compare them.

5.1 Setup and Method

We used the same magnet and the sample 1 of the MS-gel used in the section 4, because the sample 1 shows the greatest significance for heel. As mentioned above, we simultaneously use two parts of the foot to have subjects compare different sensitivity of the different part of the foot. As shown in the Fig.17 and 18, we put two MS-gel under the toe and heel. To make a broad distribution of the magnetic field (it generate a broad distribution of the hardness). The experimental conditions conducted in this section are shown in the table 5. As shown in the table, we put magnets only on the toe or heel in each condition.

As a reference, 5 healthy male students (22-23 years old) stepped on the MS-gel without any magnets by their toe and heel at the first part of each trial. After the references, the subjects stepped on the magnetized gel with the condition of the Case 5 or 6. We requested the subjects to answer which part of the foot is harder than another. The numbers they succeed to perceive the change of the gels are recorded. The method of statistical analysis is same as shown in the previous tests.

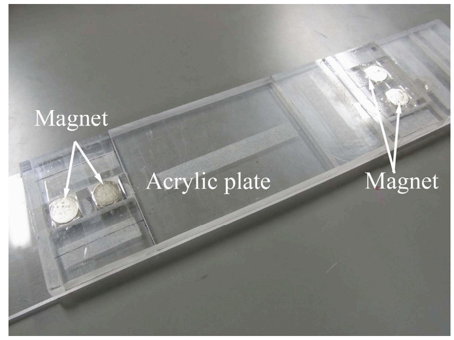

Figure17. Experimental setup for foot test

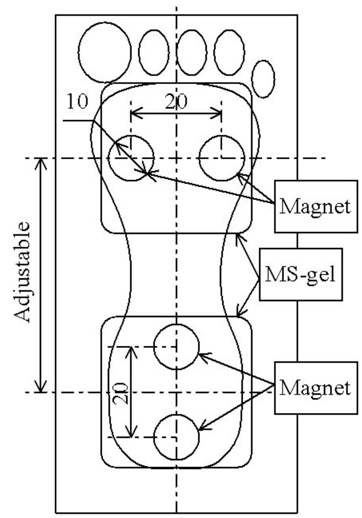

Figure18. Alignment of magnets and MS-gels for foot test

Table 5. Experimental conditions for foot test

Case 5	**Toe: magnet** / Heel: no magnet
Case 6	Toe: no magnet / **Heel: magnet**

5.2 Magnetostatic analysis for decision of magnet alignment

As shown in the Fig.18, we use two magnets under the toe or heel. In this case we have two choices on how to use the magnets; a same-side up alignment, in which the same poles face the MS-gel, and a different-side up alignment, in which the different poles face it. In order to decide which alignment we should use, we conducted magnetostatic analyses on these alignments. The results of the analyses are shown in the Fig.19 and 20.

According to these results, when we use the same-side up alignment, the distribution of the magnetic field makes two separated peaks in the gel because of the repulsive magnetic resources. On the other hand, when we use the different-side up alignment, the two attractive magnetic resources make one peak in the middle of the gel and increase the intensity of the magnetic field on the surface of the gel. From these results, we decided to use the different-side up alignment as the alignment of the two magnets used in the experiments.

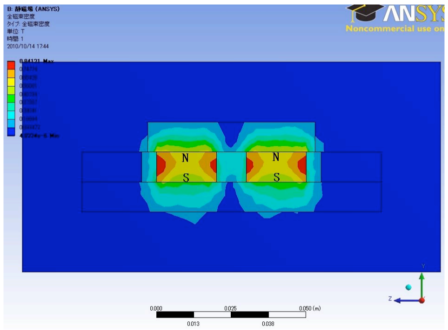

Figure19. Same-side up alignment

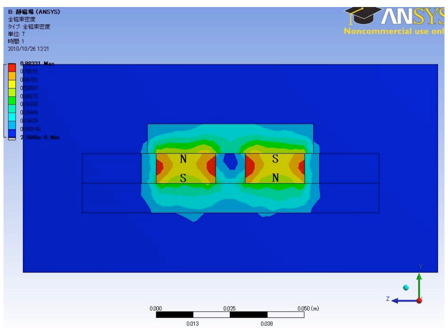

Figure20. Different-side up alignment

5.3 Results

The table 6 shows the experimental results of the foot test mentioned in the previous section. As the same manner of the table 3 and 4, the numbers shown in the table are the numbers of success in the trials. The dark-gray-colored cells in these tables show 5% level of significance and the light-gray-colored cells show 10% level of significance. As shown in the table, almost all of the subject could understand the correct situation and succeed the trials.

Table 6 Result of sensory evaluation in foot test

Subject	A	B	C	D	E
Case5	13	11	13	12	10
Case6	11	11	11	8	13

6 Discussion

According the results of the first trial, the best way of the four cases we proposed (Case 1 trough 4) was the Case 1. However, there is room to enhance the elastic changes by utilizing more powerful magnetic circuits. Off course, the improvement of the MS-gel is strongly required to improve haptics and reduce the intensity of the magnetic field (it causes down-sizing of the magnetic resources and cost-reducing).

According to the results of the second trial, we confirmed that the MS-gel has a sufficient potential as a haptic surface to express at least two different conditions on the bottom of the foot. By using left and right foot, we may be able to the express at least four different types of the haptic information as the intelligent shoes (haptic shows). By giving a correspondence of these four different types of haptics to the different guidance information, we may be able to fabricate practical intelligent shoes that can express different types of the guidance information. As an example we show the way to the direction indication of the intelligent shoes with the MS-gel. In the future, we will try to realize the intelligent shoes by attaching the MS-gel as a sole or insert of the shoes and confirm its functions.

Table 7 The way of the direction indication of the intelligent shoes with the MS-gel

	Go	Stop	Left	Right
Left	Toe	Heel	Toe	Heel
Right	Toe	Heel	Heel	Toe

7 Conclusion

In this paper, we proposed the usage of the magnetic-field sensitive gels (MS-gel) as a haptic controllable surface. As one of the examples, we proposed intelligently haptic controllable shoes with the MS-gel for a walking guidance system. We conducted material tests for the MS-gel sheet and the results shows different elasticity with/without magnetic fields. Its change depends on the structures and thicknesses of the sheets. We also conducted two different tests to evaluate sensory properties by using the MS-gel. According to the experimental results, we could show a significant potential to use this material as a haptic controllable surface of the intelligent shoes. At the final part of the paper, we proposed an example of the way to realize the intelligent shoes with the MS-gel as soles or inserts of the shoes.

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