Abstract — In this paper, the role of the human being toe is investigated. The change of the sole pressure distribution using a sole pressure distribution measurement system and that of the toe pressure using a toe pressure measurement system at walk by the existence of a toe are investigated. In order to investigate the change of the whole walking, the affection of a walk posture using a 3D motion capture system by the existence of a toe is also measured. Furthermore, the change of the amount of energy consumption at walk by the existence of a toe is measured by a spirometry system. At last, we investigate the roles of the toe, such as, the efficiency of the big and 2nd toe, and the stabilization of the posture, by the synthesis of these results.

Keywords: Toe pressure, human walking, energy consumption, sole pressure, toe elimination.

1 Introduction

Humans have the capability to walk with two legs, and can move with a complete control according to the circumstances. This is due mainly to the supportive capability of the foot. This one has an important input informational function by sensing the contact with the ground, as well as an important output informational one by executing a balance control when standing or moving.

Recently in robotics field, the development of biped robots like ASIMO (made by Honda Motor Co.) and SDR (made by Sony Co.) is growing up. However, these robot’s walking capability is not yet imitating perfectly that of human beings. If you pay attention to the shape of the robot’s foot, you can notice that it is only one flat plane (without toes), which does not reflect the real shape of human foot [1]. It has also been reported in details the important role played by the toes in the stability of the standing posture [2][3], whereas no such information has been reported for the stability during walking. This is why we have investigated this issue.

In this paper, we have prepared and used several kinds of footwear that eliminate the effect of one or several toes in order to be able to notice the importance of each toe. We have developed a Sole (underside of the foot) Pressure Distribution Measurement System [SPDMS] that was used during the motion action; along with a Toe Pressure Measurement System [TPMS] that measures the change in pressure at the level of each toe. Also, in order to study the influence of the existence/non-existence of toes on the balance of the whole body a 3D motion capture system was used. Moreover and to be able to make the most possible investigation we have used an additional spirometry system for energy consumption measurement. All the conducted experiments were to clarify what is the function that a certain toe play during a walk, and especially the effect of the big and 2nd toe, the contribution of the big toe on normal walk and finally the effect of balance maintaining during walking motion.

2 Measurement of Sole Pressure Distribution

2.1 The developed sole pressure distribution measurement system [SPDMS]

The developed SPDMS consists of a sole pressure distribution measurement sheet, a pressure sensor controller, and a laptop PC (Celeron 400MHz with 64MB). In order to perform the measurement of a walk, as natural as possible, the system is developed in a way that fits the body. In Fig.1 you can see the system when it is worn.

The sole pressure distribution measurement sheet constitutes a flexible printed circuit on which 110 pressure sensors has been attached with 13mm interval between each other. This sheet is then inserted in the below-mentioned footwear. Since the footwear is made of a material that allows change in shape, the material for the sheet has been chosen to be malleable such that to allow for that change also. The thin and soft flexible printed circuit, that has been used, is a product of Sunhayato on which the pressure sensors are attached. An overview of the pressure distribution measurement sheet is shown in Fig.2, and the specifications of this sheet are shown in Table 1. FSR: Force Sensing Resistors (made by Interlink Electronics) are used for the pressure sen-
A controller (named SPDMS controller) was made to collect the data from the sensors. The SPDMS controller consists of twenty 4ch dual multiplexers (HD14052BP made by HI-TACHI), and eight operational amplifiers (LM324N made by National Semiconductor). The controller’s task is to select 8 FSRs from the 110 available ones. This choice is sent to the controller and the measurement data are received through an I/O 8ch card (I/O PCMCIA card made by CONTECT) connected to the laptop PC. The sampling frequency can maximally go up to 300Hz. A battery of 9V was used for power supply. All the wiring and the battery were included in a handy design of one box.

2.2 Measurement conditions

In this work, the virtual situation that one or more toes are eliminated was realized by using specially designed footwear. The footwear is divided into three parts that form the shape of the foot (the big toe, the four remaining toes, and the rest of the foot). Four kinds of footwear were made for the experiments as shown in Fig.3 (A [no toes eliminated], B [only the big toe eliminated], C [2nd–5th toes eliminated], and D [all toes eliminated]). So that the big toe may not touch the floor when using thin footwear, the thickness of the whole footwear is set to 3cm by piling up two rubber slippers; each of 1.5cm thickness. The previously described sensor sheet is inserted between them. To compare the results according to several circumstances of speed and motion, the experiments were conducted in the following four conditions:

1. Slow walking (0.5–0.7m/s, on a 10m straight lines)
2. Normal walking (1.0–1.2m/s, on a 10m straight lines)
3. Fast walking (1.5–1.7m/s, on a 10m straight lines)
4. Upstairs walking (a height of 0.2m and a depth of 0.3m per step)

2.3 Experiment Results

The experiments were conducted with two subjects (24 and 25 years old, men, with foot length of about 26cm) in the previously mentioned measurement conditions. As the detected features were similar for the two subjects, we only show the results of one subject in Fig.4. This figure shows the maximum value of sole pressure, within one walking cycle, near the toes using the constant pressure line representation for every 20kPa. First, in order to investigate the influence of the existence of the big toe we have compared the results of two groups of experiments, one group with the big toe (namely, A and C) and another group without the big toe (namely, B and D). For the case of the 1st group (A and C), the center of the pressure distribution exists near the root of the big and 2nd toe. Whereas, you can see that the center of the pressure distribution moves to the location near the roots of the 2nd–4th toes for the case of the 2nd group (B and D). From these results, when the big toe is eliminated, it can be inferred that the importance of the 3rd and 4th toes (or the roots of the 3rd and 4th toes) increases while walking. Secondly, if you pay attention to the relation between the speed and the change in pressure distribution, the pressures on the big toe and the 2nd toe increase as the speed increases (seen in Fig.4 A–1 [slow walking], A–2 [normal walking], and A–3 [fast walking]). On the other hand, the pressure on the 3rd–5th toes do not increase with the change of speed. From these results, it can be inferred that the big and 2nd toe are the ones that work effectively when all toes exist. Although the need of the propulsive force to speed up and to maintain the body balance can be considered as the cause of such a pressure increase, this could not be discerned from the results of these experiments. Besides, if you consider normal walking condition and the upstairs walking condition for all the cases (A, B, C and D); you cannot notice any big difference between the pressure distributions. Finally, we can conclude that from the sole pressure distribution measurement point of view, the role of the toes is as follows: for the case of a straight line walk the big and 2nd toe act effectively, while the 3rd and 4th toes act effectively when the big toe is eliminated. In both cases, the 5th toe does not appear to be that important.

3 Measurements of Toe Pressure, Gait, and Energy Consumption

The importance of the toes during a walk was showed from the measurements of the sole pressure distribution in

<table>
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<th>Sheet size</th>
<th>200mm × 300mm</th>
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<tr>
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<td>Number of sensors</td>
<td>110</td>
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<tr>
<td>Spatial resolution</td>
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Figure 4: Sole pressure distribution under various conditions around toes

the previous chapter. In order to investigate in details the influence of the existence of toes while walking, the toes pressures, the oxygen consumption, and the change of the gaits were also measured in the forthcoming experiment.

3.1 Measurement conditions

The virtual situation that one or more toes are eliminated is realized by using specially designed footwear just like we have done with the first experiments. This time, five kinds of footwear were made and used (A [no toes eliminated], B [only the big toe eliminated], C [2nd–5th toes eliminated], D [all toes eliminated], and E [3rd–5th toes eliminated]) as shown in Fig.5. Also, to prevent the big toe from touching the floor, the thickness of the footwear was doubled and set to 3cm. The experiments are conducted in the following four conditions:

1. Slow walking (0.56m/s),
2. Normal walking (1.1m/s),
3. Fast walking (1.7m/s),
4. Upslope walking (the inclination angle is 10 degrees and the speed is 1.1 m/s).

3.2 The Toe Pressure Measurement System [TPMS]

3.2.1 Description of TPMS

The developed TPMS consists of toes pressure measurement sensors, a pressure sensor controller, and a laptop PC (Pentium III 750 MHz with 256MB). In Fig.6 you can see the toes pressure measurement sensors when they are worn. Although on the SPDMS, the FSR pressure sensors are fixed on the flexible printed circuit completely, for the sake of a detailed investigation of the pressures of toes, the FSRs are directly attached to the sole in this system. The pressure sensors are attached at eleven points: on the tip of the 1st–5th toes, the 1st–5th head of metatarsal bones, and on the heel. The previous mentioned FSR is used as the pressure sensor. The TPMS controller consists of two 2ch triple multiplexers (TC4053BP made by TOSHIBA), and eight operational amplifiers (LM6144AIN made by National Semiconductor). The controller’s task is to select 8 FSRs from the 11 available ones. This choice is sent to the controller and the measurement data are received through an I/O 8ch card (I/O PCM-CIA card made by CONTECT) connected to the laptop PC. Moreover, the two batteries of 9V are connected and used as power supply.

3.2.2 Experiment Results

The experiments were conducted with two subjects (23 and 24 years old, men, with foot length of about 26cm). In order to make the experiment in a stable state, the subjects are accustomed to the footwear in advance and are asked to practice walking on a treadmill. The results of one of the subjects are shown below. The pressures concerning the tip toes of each walk form in A (no toes eliminated) are shown in Fig.7, and the pressures concerning the toe roots of the walk form 2 (normal walking) in the group with the big toe (namely, A, C and E) are shown in Fig.8, and the pressures concerning the root toes of the walk form 2 (normal walking) in the group without the big toe (namely, B and D) are
shown in Fig. 9. Each graph is showing, in a stable state, the relation between the time and the pressure during a one step period. First, it can be seen that the tip toes pressure increase as the speed increases in A, and the pressure of the big and 2nd toe are many times higher compared to the other toes (seen Fig. 7). It can be inferred also that the big and 2nd toe are the ones that work effectively when all toes exist (this is similar to the result obtained from the SPDM in section 2.3). Although some differences are at the peak values for the straight walk and the slope walk, the evolution over time for the pressure of tip toes is just similar in shape. We can say that when walking up a slope of about 10 degrees inclination, the efficiency of the toes does not change compared with the case of a straight walk. Secondly, if change in pressure around the root of the toes is compared based on the existence or not of the big toe we have:

- The order in which the pressure around the roots approaches zero is from 5th toe → 4th toe, until 3rd, 2nd, 1st toes for the group with the big toe (namely, A, C and E), and it can be seen that during normal walk the trajectory evolvement of the center of pressure starts from the center of the calcaneus, curving laterally to the outer side and ending between the big and 2nd toe.

- For the group without the big toe (namely, B and D), the order in which the pressures around the roots approaches zero is first 5th and 1st toe, then 4th toe and finally 2nd and 3rd [for the case B], while the timing in which the pressure around the roots approaches zero is almost the same for the case D. Then, normal walk is not achieved for these two cases.

From these results, the existence of the big toe is important to enable a normal walk with an ideal trajectory evolvement on the sole.

### 3.3 The 3D Motion Capture System

#### 3.3.1 Description of The 3D Motion Capture System

The VICON (made by Vicon Motion Systems) is used for the 3D motion capture. The VICON can automatically calculate 3D marker’s position by photogrammetry using the video stream from high quality cameras. In this paper, the motion of the waist and the upper half of the body were measured using twelve cameras (120Hz, made by Pulnix). Rigid reflective markers (with 25mm diameter) are necessary and were used fixed to the body by Velcro fastenings such that their motion will not to be influenced by the movement of the clothes. The reflective markers were attached in twenty points: the shoulders (2+1 points), the neck (1 point), the waist (4 points), the knees (2 points), and on the ankles (2 points). Two shoulder markers are attached near the acromial end of the clavicles, and one more marker is attached on the left shoulder to distinguish between the left and the right side. In order to calculate the center of the waist, four markers are attached on the waist, two on the front and two on the back. An overview of the placed markers is shown in Fig. 10 and one motion capture result is shown in Fig. 11.

#### 3.3.2 Experiment Results

Here, the experiments were also conducted with two subjects (23 and 24 years old, men, and 26cm foot length). In order to experiment in stable state, the subjects are also accustomed to the footwear in advance by practicing a walk on a treadmill. The results of one of the subjects are discussed below. During 20 second duration and for each walk form, we calculated the difference in the moving distance of the center of the waist. The results shown in Fig. 13 represent the relative values compared to the value of A. These graphs show that the total moving distance has an increasing tendency along A (no toes eliminated), E (3rd–5th toes eliminated), and B (1st, 5th toes eliminated).

Figure 7: The pressure at the tip of a toe (A)

Figure 8: The pressure at the root of a toe (A, C, E)
eliminated), C (2nd–5th toes eliminated), B (only the big toe eliminated), and D (all toes eliminated) respectively. From this result, the balance maintaining during walking becomes difficult by the removal of toes, and it can also be inferred that the influence of the big and 2nd toes is especially large.

Since the increase rate of the total moving distance for D (all toes eliminated) in the case 4 (upslope walking) is increasing by 15% to 20%, we can say that the toes have a more important role for balance maintaining when walking up a slope.

### 3.4 The Spirometry System

#### 3.4.1 Description of The Spirometry System

Although several parameters should be considered when dealing with energy consumption in human motion, it has been reported in earlier studies that the relative metabolic rate and the calorie consumption amount are almost equal to the amount of oxygen consumption [4]. Many researchers have argued about the amount of energy consumption under walking condition based on the amount of oxygen consumption. In this paper, the energy consumption is also considered by measuring the amount of oxygen consumption when breathing. AEROMONITOR AE-280S (made by MINATO MEDICAL SCIENCE) is used as the Spirometry System. This system can gather the expired gas by the breath-by-breath [BBB] method using a special mask. The BBB method has the special characteristic of being able to measure the inspired oxygen concentration even if this one changes randomly. An overview of the whole measurement experiment is shown in Fig.12.

#### 3.4.2 Experiment Results

The experiments were conducted with seven subjects (between 23 and 32 years old, men, with foot length of about 26cm) for two days. In each trial, the subjects, wearing the sportswear (see Fig.12), walk on the treadmill during 3 minutes after they sit on a chair for 15 minutes. In order to make the experiment in a stable state, the subjects are accustomed to the footwear in advance and are asked to practice a walk on a treadmill. In order not to bias the results, we did not suppose any particular order for wearing the shoes. The average
oxygen consumption for the seven subjects from 1.5 min up to 3 min of each trial is shown in Fig. 14. The amount of oxygen consumption increases as the activity increases. It can be seen that walking up a slope consumes 3 times more energy than the normal walking. However, considering each walking condition apart, there is no big difference between the energy consumption if you consider the standard deviation. From these results, we cannot draw any conclusion about the efficiency of the toes from the viewpoint of the amount of oxygen consumption.

4 Conclusions and Future Work

In this paper, we described the sole pressure distribution measurement system [SPDMS] that was developed for the purpose of investigating the role of human toes, and the change of the sole pressure distribution during a walk by the existence of the toes, as well as the relation between the walking form and the sole pressure distribution was investigated using the SPDMS. The obtained results suggest that the big and the 2nd toe work effectively when all toes exist, whereas the 3rd and 4th toe work effectively when the big toe is eliminated. The result that there was no remarkable difference in the pressure distribution of the straight walk and the upstairs walk was showed. We could also notice that there is no remarkable difference in the pressure distribution between the straight walk and the upstairs walk.

To be able to investigate in details the influence of the existence of toes while walking, the change of the toes pressures, that of the whole walking, and that of the oxygen consumption were also measured. But for this case no confirmation about any aspect related to the efficiency of the toes could be noticed.

The obtained results suggest also that the big and 2nd toe work effectively when all toes exist, the existence of the big toe enables the normal walk and an ideal trajectory evolution on the sole; and the existence of the big toe is important for walk stabilization at the time of upslope walking. Furthermore, we obtained the interesting result that there is no remarkable difference in the toe pressure between the straight walk and the upstairs walk; while no clear difference could be noticed for the oxygen consumption.

To sum up the role of the toes from the obtained results, we can conclude that the big and 2nd toe work effectively while walking, the existence of the big toe is important to realize a normal walk, and the toes have a role in stabilizing the walk.

Since there were few subjects, this was not enough to allow individual difference cancellation. Moreover, the experiment with variability from the specified walking forms has not been conducted. Therefore, we are planning to conduct experiments with many subjects and more walking form conditions.

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References


