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# Six-axis Force Sensing Footwear for Natural Walking Analysis*

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**Abstract** – *This paper describes "Six-axis Force Sensing Footwear" which is a sensor designed analyze the natural walking dynamics of a human being. The system fixes to the shank link and uses prosthetic feet, which have flexible soles for walking. We verified the system in a comparison experiment of force plate with footwear. Most of the walking data using the system can be considered as the same as normal data because of moment and force pattern. We conducted the walk experiment also on uneven ground. Measures of walking patterns such as knee joint moment are the same when wearing the sensor as when walking naturally. The comparison showed that the system can be used for natural waking analysis.*

**Keywords:** force plate, six-axis force sensor, natural walking analysis

## 1 Introduction

3-D motion capture system and force plates are widely used in walking analysis. We also have utilized those systems to build our humanoid robot walk more stable, faster and more energy efficient. We made a success building a bipedal locomotion model of the human being, and adopted it to our humanoid robot H7 [1].

However, force plates have several problems. At first, they are embedded in the floor, and subject must precisely push on it, so that it is difficult to change the arrangement. Therefore, it is difficult to measure walking in many different locations. At the second, the force plates have constraint on analysis. Subject must step on one force plate by one foot, so that subject walk is limited. Finally, the large force plates have low eigenfrequency.

On the other hand, the sensor that is worn on foot is distributed pressure sensor [2]. The pressure sensor cannot measure tangential forces and moments. Therefore, it cannot calculate ZMP position.

In order to measure appropriate step in various environment (such as on sand or on uneven surface), we developed "six-axis force sensing footwear", which covers the shortcoming of force plates.

## 2 Development System Design and Implementation

### 2.1 Development System Design

At the beginning, we developed metal footwear like a Japanese wooden footgear (see Figure 1) [3]. It is necessary to place a rigid sensor between a foot and the ground, so that the footgear has large influence when the subject walks. Additionally, the sensor also takes in strain of the metal footwear itself, and the sensor has detected the force that does not exist really.

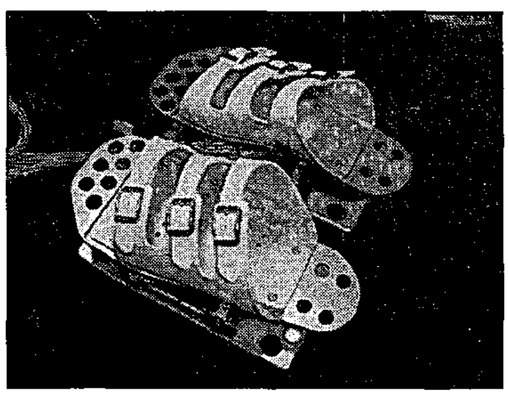

Figure 1. Metal footwear

In order to overcome the above problems, we developed six-axis force sensing footwear which is a force plate worn on a foot. The footwear system fixes to shank link and uses prosthetic feet for amputees (see Figure 2).

The human's ankle joints are fixed. This system uses ankle joints of prosthetic feet instead of joints of human in order to secure the stability of a walk.

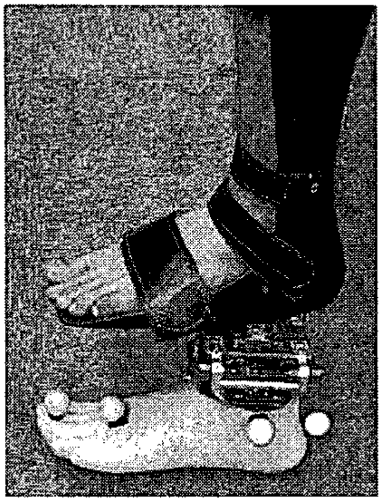

Figure 2. Six-axis force sensing footwear

### 2.2 Six-axis sensing unit

The sensing unit, which measures six-axis force in this system, is the same as the sensor of legs of our humanoid robot H7 [4]. The sensor uses strain gauges, and measures six-axis force, which is different range. The sensing unit is interposed between a prosthetic foot and a human foot (see Figure 2). They are concluded with the screw.

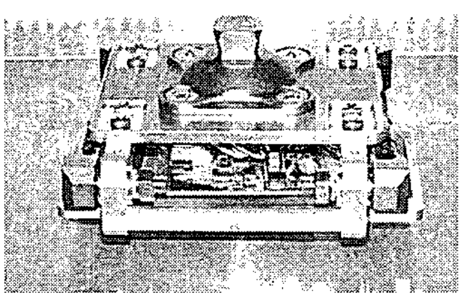

Figure 3. Sensing unit

The force plate has capability that is the scanning rates 50 to 5000[Hz] and that is the force resolution 10 to 1000[mN]. The developed system has capability that is the scanning rates 44[kHz] and that is the force resolution 30 to 80[mN]. This system uses high-speed AD/DA simultaneous sampling board that is developed by AIST [4] (see Figure 4).

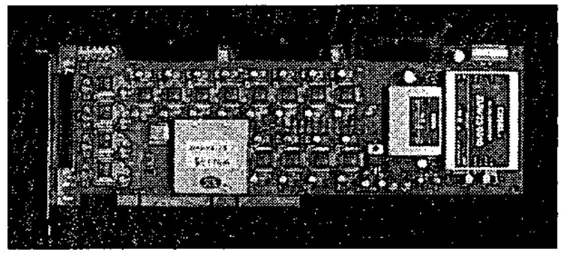

Figure 4. High-speed AD/DA simultaneous sampling board

## 3 Experiment

### 3.1 Influence this system affects a walking

In order to check up on influence this system affects a human walking, we measured walk with footwear and without footwear. We used optical 3-D motion capture system (Motion Analysis Corporation) and force plates (AMITI). A subject is male with a height of 1.78[m] and a weight of 65[kg]. The optical ball markers were applied to the top of head, acromion, hip joint, anterior superior iliac spine, lateral epicondyle of femur, lateral malleolus, heel, head of fifth metatarsal bone, toe and each part of arms (see Figure 5). When a subject walked with footwear, the markers were applied to the prosthetic foot. In order to calculate the biodynamic constant [6], such as center of gravity or body segment weight, we use Ehara model [7] as a human body model.

Figure 5. Marker position

### 3.2 Footwear Influence Examination

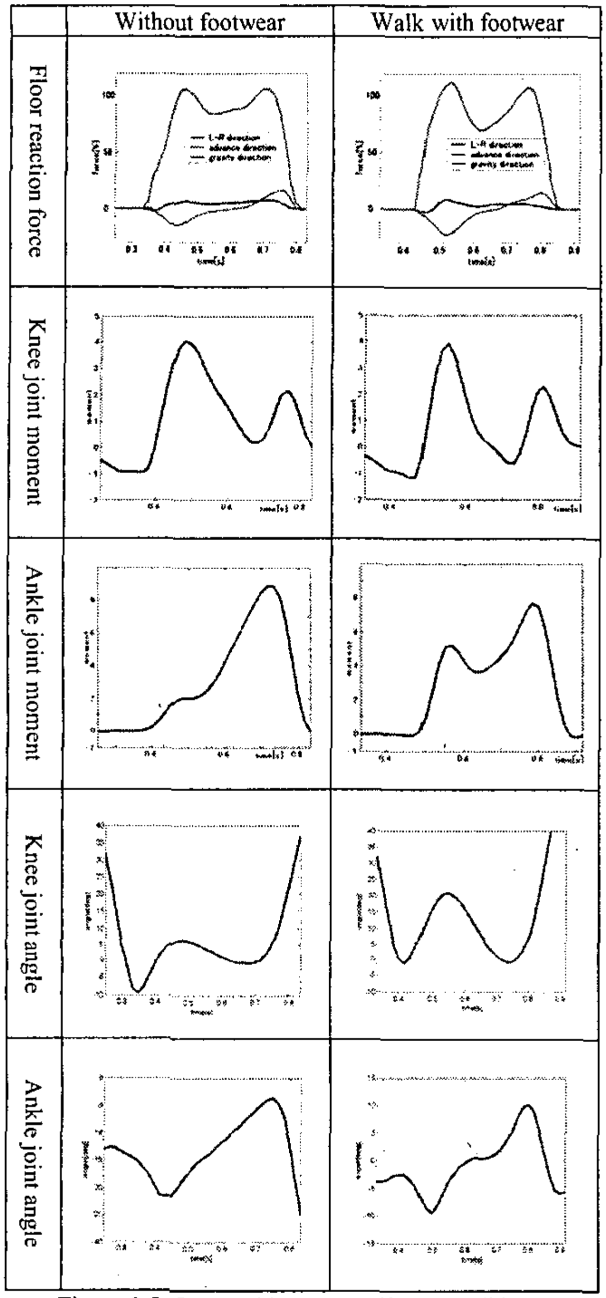


Figure 6. Influence this system affects a walking

The graphs other than ankle joint moment and angle can be considered similar. In the graphs of floor reaction force, the red line, which shows the force of the gravity direction, marks two peaks known as double knee action effect. Those graphs of knee joint moment is similor very well. Even if shank link length extended about 20 [cm] and the weight of shank increases about 2 [kg], there are few differences in the knee joint moment.

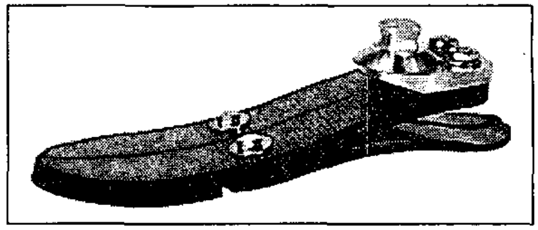

Figure 7. The blade spring in a prosthetic foot (Allurion - Pacific supply corporation)

The graph of ankle joint moment shows difference. The graph of footwear marks two peaks. Normal walk marks one peak. This is produced by the difference in the structure of foot. Human's ankle joints behave actively, but the prosthetic feet behave passively for the blade spring (see Figure 7). When the heel contacts floor, shock absorber is anterior tibial muscle, but in the prosthetic foot, the absorber is the blade spring of heel. In the graph of ankle moment with footwear, the second peak is smaller than the peak of the graph without footwear. The moment that seen in the second half of graph is produced by triceps surae muscle. Therefore, the force with a blade spring is weaker than the force by muscle. In the graph of ankle joint angle with footwear, the line has not become straight line-like, since a blade spring cannot behave like muscle.

Figure 8. Footwear toe lift

The graphs of knee joint angle are similar. However, the motion of knee joint with footwear behaves more than the motion without footwear. It is thought that the motion of an ankle is covered with this motion. Since the shank link is extended, it is also compensated with the knee joint motion.

## 3.3 Walking analysis with footwear

In order to use the footwear instead of force plate, we measured walk with footwear. A subject is the same. The motion of human body were measured by motion caputure system. The optical ball markers were applied to the same position as a previous experiment. In this experiment, all the markers on feet were apllied to the

prosthetic feet. When calculating a joint moment, we use the value from force plates and from footwear. We use the same data of motion when calculating.

## 3.4 Result of walking analysis with footwear

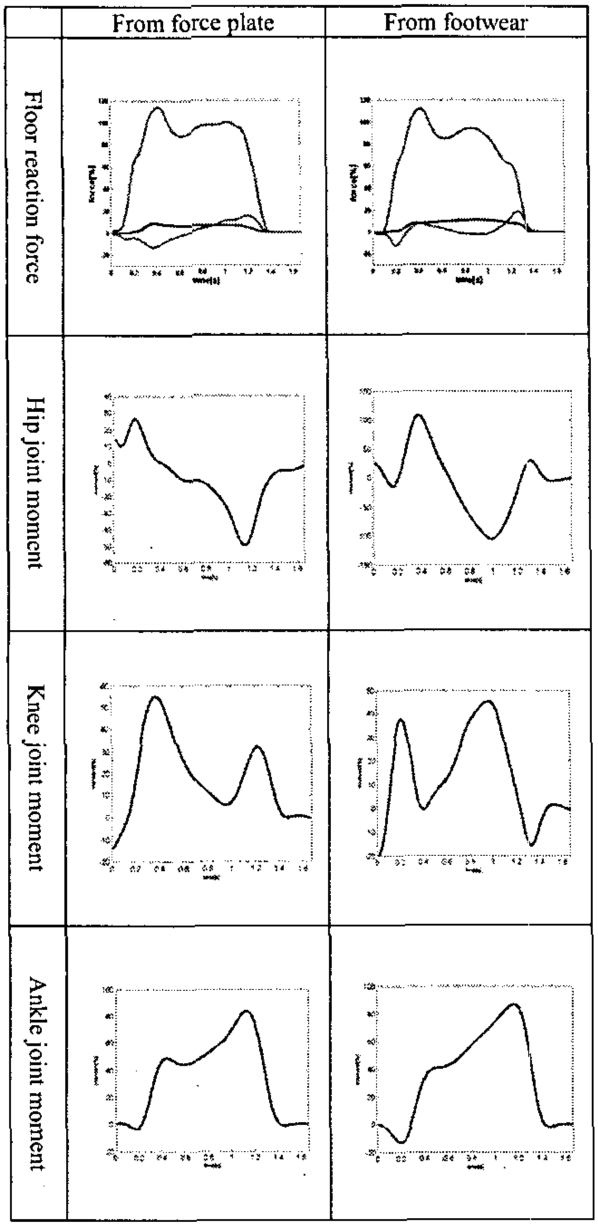


Figure 9. Walking analysis with footwear

The graphs of moment are similar. In the graphs of hip joint moment, the line increases in the early stage of standing, and it decreases in the middle stage and returning near the zero in the latter stage. In the graphs of knee joint moment, the line shows two peaks. The graphs of ankle joint moment are similar.

## 3.5 Walking in various environments

We experimented in walking on uneven ground. The term of 'uneven ground' is the environment where is what is stepped on and walked on a floor. We put 1) the stairs (Figure 10) and 2) the wooden box on the floor, and measured motion that human stepped on them. The difference level of stairs is 100[mm], and the size of wooden box is 250 x 220 x 100[mm]. Usually, in order to measure floor reaction force at the time of a stairs walk, it is necessary to install force plates on the stairs upper surface, or to use the stairs specially manufactured so that one step might ride on one force plate. However, we used footwear as a force plate instead of special stairs in this experiment.

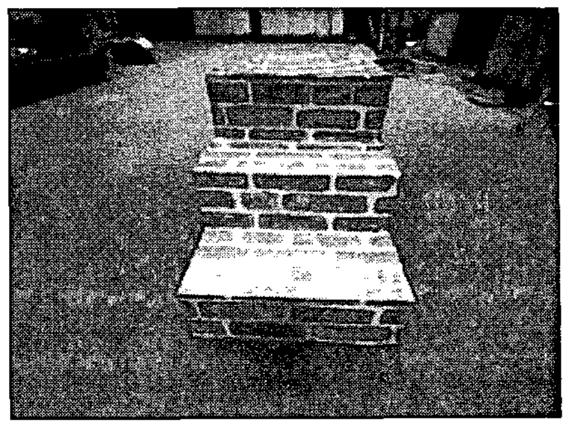

Figure 10. Stairs for an experiment

1) Walking on the stairs

In the graph of step on stairs (Fig. 11), the green line, which shows advance direction, is almost flat in the early stage of standing. The green line shows peak in the latter stage. It shows that the subject did not land from the heel but landed by the whole sole. In addition, the force of advance direction is smaller than the force of normal walk. Because the force of the gravity direction is required in order to step up the stairs.

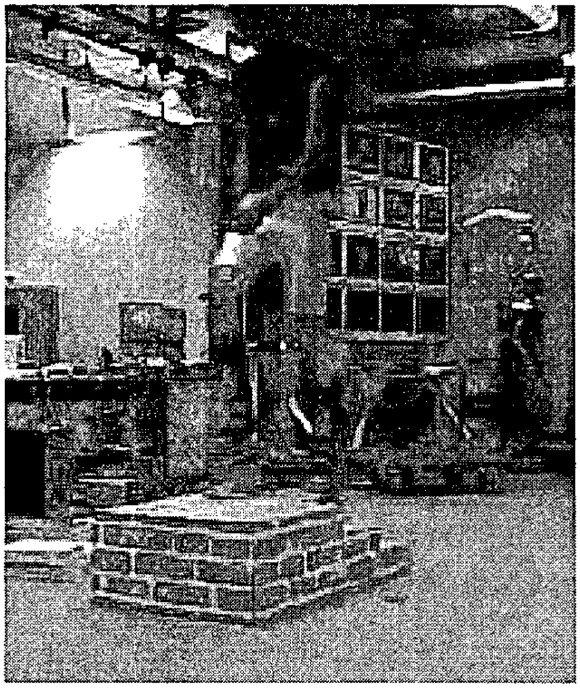

Figure 11. 1) Step on stairs with footwear

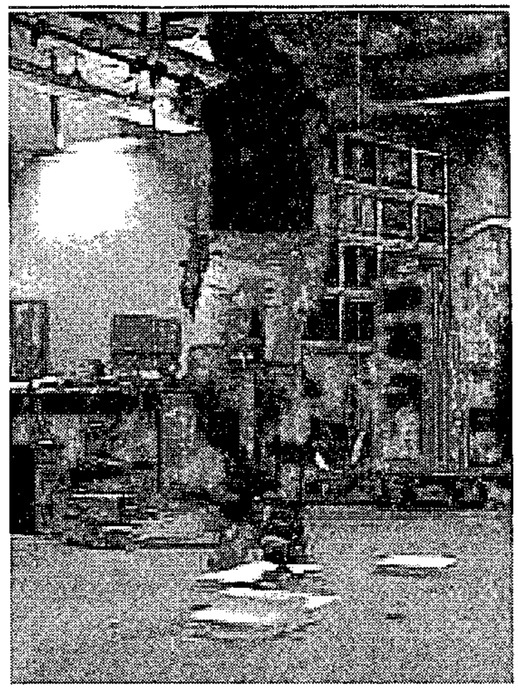

Figure 13. 2) Walking on uneven ground

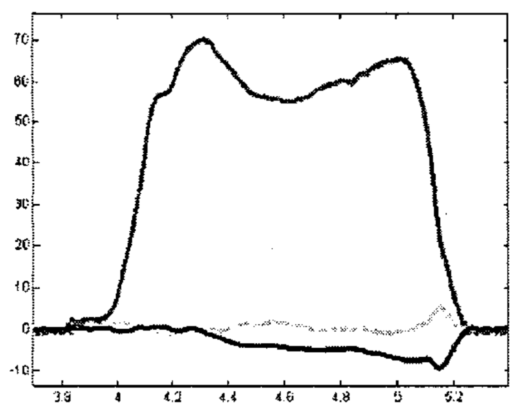

Figure 12. 1) FRF of step on stairs

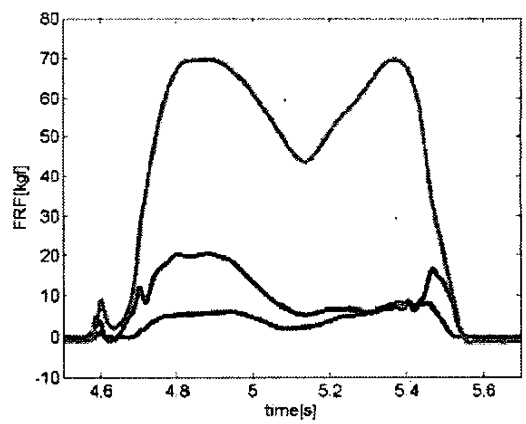


Figure 14. 2) FRF of walking in uneven ground

2) Walking on uneven ground

As the subject stepped on the box on toe, he walked. Therefore, in the graph of FRF (Fig. 14), the green line shows different from normal walk.

# 4 Conclusions

We developed six-axis force sensing footwear for natural walking analysis. It has a prosthetic foot that has a flexible sole. The developed system has capability a scanning rate of 44[kHz] and has a force resolution of 30 to 80[mN]. The footwear can overcome the shortcomings of force plates when measuring human walking. This

system can provide measurement even on uneven ground. The sensor has little influence on walking pattern on flat surface. This paper describes that influence a system affects a gait on flat surface and experiment using. this system on the uneven ground. However, it is thought the system will influence walking pattern on uneven ground.

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