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Development of a Foot Pressure Distribution Measurement Mat

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In order to study the shock absorption mechanism of foot pressure distribution, a measurement(FPDM) mat was developed by using the force transducer of piezoelectric film, one of the recently developed new materials. The FPDM developed so far using force transducers such as capacitors, strain gauges, and piezoelectric ceramics are somewhat inappropriate for the measurement of fast movement. Knowledge of the mechanical function of feet during fast movement is essential because foot injuries occur frequently at that very moment.

The sensor used in this study has the dimension of 8mm×10mm with 28-mm thickness and the structure coated both sides in silver ink as electrodes and mylar coverning of 5/1,000 inches.

The FPDM mat has total area of 350×250 and thickness of 15mm with 5 layers. It has embedded sensors of 16×24 array which results in 384 channels with resolution of 10mm×20mm.

In the measuring system, the input data are processed as follow: the data are multiplexed and amplified by the input scanning method and A/D converted; the stored data are processed by the signal processing technique to allocated proper colors according to the data size; the resulted graphic images are represented on the display as are printed materials.

INTRODUCTION

The vertical ground reaction force acting on a human body during walking was found to be as 2-3 times of his body weight(Cavanagh and Lafortune, 1980; Elliot and Blanksby, 1979). If one considers a marathoner repeating his steps about 30,000 times to complete his race, it is not so difficult to understand the amount of impact on the body. Researchers have reported that during walking or running an acceleration of 29-50 g is generated on the heel region depending on the ground conditions and the shoes worn(Guenther, 1967; Cavanagh, et al., 1981). Light et al(1980)., for example, reported that an acceleration of 2~8 g occurs on the tibia region when one is walking in shoes with different sole material.

The above mentioned reports implicate the various impacts on the foot during movement. Research to minimize the impacts has been conducted focusing on the following three points:

(1) Reduction of the maximum acceleration generated by foot; different materials for soles and cushions of shoes are investigated.

(2) Analysis of the pronation of foot.

(3) Functional correlation between the shape of foot and the tendency to foot injuries.

In spite of many researches on the shock absorption mechanism, the relevant information is still insufficient and some results are contradictory. Therefore knowledge of the pressure along the plantar location should be provided to give a complete picture of the functional details of the anatomical structure of the foot.

The FPDM methods develped to date could be classified into two categories: (1) methods to measure forces during slow motion using capacitors and (2) those during fast motion. However, most of the measuring devices are of the first class and inappropriate to investigate the injury-related functions of foot.

Recently a new material, piezoelectric film (PF), has been developed in the United States and used in various research areas. Utilizing the advantages of PE such as linearity, resolution, and flexibility, a new device for FPDM is developed in this study.

Basic Principles of the Piezoelectric Film

PF is the engineering plastics that a polymer of CH-CF units is processed to film with mechanical stretch ad electric polling to enhance piezoelectric effects. If PF is used as sensor both sides must be coated with electrode materials as shown in Fig. 1. Different coating methods and electrode materials are used for specific applications, but silver and aluminum are most common.

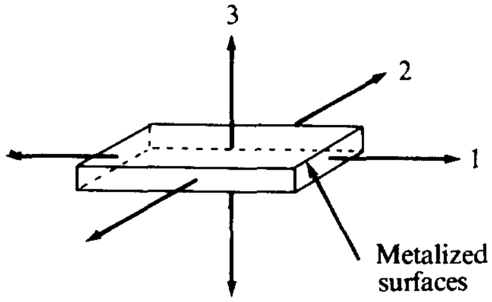

Figure 1. Structure of piezoelectric film sensor

PE with electrodes on both sides virtually makes a capacitor. The equivalent circuit(Fig. 1) as a sensor is:

$V = g_{3,1}\ P_1$ ······································· (1)

Where V=output voltage

$g_{3,1}$=stress constant

p_1=pressure on '1' direction

t=film thickness

The generated voltage can be determined from the following relation.

$V = (pt/\varepsilon)\triangle T$ ······································· (2)

where v=output voltage

t=film thickness

p=pyroelectric constant

ε=film permitivity$=106\times10^{-12}$ C/Vn

$\triangle T$=temperature change(°k)

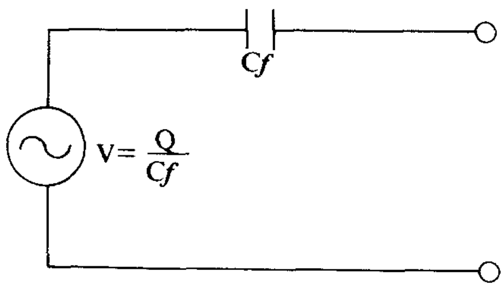

Figure 2. Equivalent circuit of piezoelectric film

METHODS

1. Pressure Distribution Measurement System

(1) Sensor

It is indicated that the PF sensor is preferred for the measurement of fast movement or dynmic force during a short cycle of time. Compared to sensors, the PF sensor is less expensive, and have favorable characteristics in frequency, linearity, output, and resolution. There is lower interference between PF sensors. The sensor can be placed on either flexible or curved surfaces so that it can meet all the requirements as a sensor for FPDM.

The sensor used in this study is very small, having the dimensions of 8×10mm with 28-μm thickness and the structure coated both sides in silver ink as electrodes and mylar covering of 5/1,000 inches. The sensors for this study is type d_{31} mainly used for flexible materials and can resist temperatures up to 65℃.

(2) Sensor Mat

The sensor array, for instant, could be inserted into the shoes worn by the subject in movement for FPDM. But such design would cause some problems : for example, the long cable connecting the sensor in the subject's shoe and the measuring system will cause response delay due to the capacitances and result in signal distortion through noise input, and also restrict free movement of the subject.

To eliminate these disadvantages and to obtain more accurate measurements, a sensor mat shown in Fig. 3 is designed in which the subject is independent of the measuring system.

The FPDM mat so designed has a total area of 350×250mm and a thickness of 15mm with 5 layer structure. It has the embedded sensors of 16×24 array which results in 384 channels with resolution of 10×20mm.

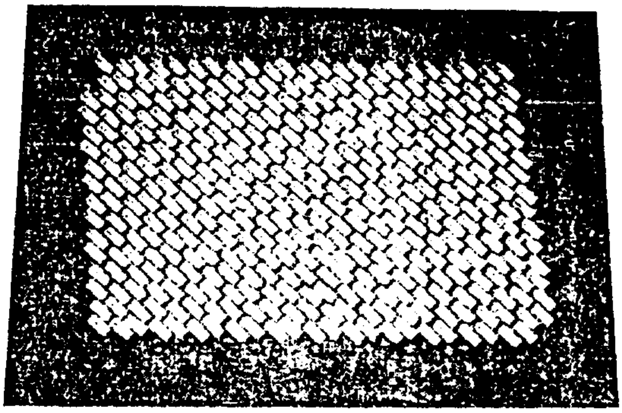

Figure 3. Sensor mat

When embedding the PF sensors in the silicone rubber, the region of connection terminals between film and output lines occupies nearly half the sensor area by virture of the film feature, which will lower its measuring resolution. If an increased thickness compensates the reduction in the surface area, the remarkable loss of output sensitivity can be minimized, as the thickness of the film sensor is practically the same as that of the terminal of 1.0mm.

To further attack problems with A/D conversion and interfacing in the multi-channel structure, the input scanning method is employed and the sensor mat is viewed as the image data of an image camera, and the rapid-changing dynamic input signals are processed by the high-speed A/D conversion as well as the image processing technique.

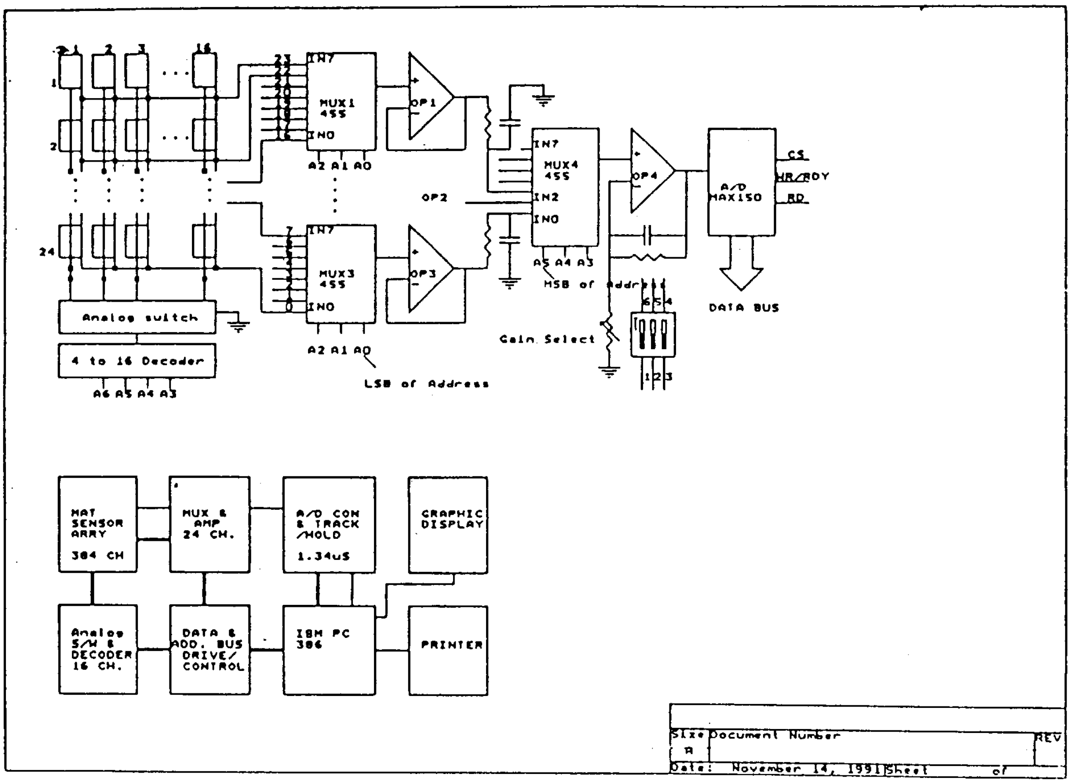

Figure 4. Diagram of the system

2. Study of the System

The overall configuration of the measuring system is shown in Fig. 4 as a block diagram. The weak signal generated from the sensor mat and protected from disturbance is multiplexed and amplified by the input scanning method. Then the A/D converted values are stored in the memory of a personal computer interfaced with a parallel bus, and the stored data are processed by the signal processing technique to allocate proper colors according to the data size. Finally, the resultant graphic image are represented on the display as well as in printed materials.

(1) Transducer

The transducer converts the pressure caused by the ground contact of the subjec's foot into an electrical signal. The transducer used in this study is constructed in mat-type sensor arrays making the most of the sensitivity of signals and the convenience of system operations. The equivalent circuit of the PF sensor used in the mat is already shown in Fig. 2. The PF is the piezoeletric element that generates a voltage signal immediately in proportion to the pressure it receives.

In the scanning method of signals from 384 channels to make inputs, as shown in Fig. 4, the output lines from the sensors are interfaced with the A/D converter in groups rather than individually, that is, 24 parallel channles of 16-sensor groups are multiplexed. Thus a sequential input of the signals from 16×24 sensors is achieved to minimize the required parts reduction of loads on the hardware.

(2) Pre-processing

As mentioned above, the PF is a dynamic sensor which originally generates the output voltage up to a considerable amount instantly when it is once deformed by pressure. As the film cell used in the system, however, is as small as 8×10mm and embedded in the rubber structure in 5 layers, most of the pressure effect is absorbed in the matrix. Thus only weak signals of less than 1 volt are generated and they must be amplified in two stages before A/D conversion. By virtue of the scanning features, however, OP-amp. has to respond within A/D converting time. So in the first stage of amplification, a voltage follower mode is used which has a unity gain, and the required gain is acquired in the second stage. A gain controller is installed in the final stage to maintain the proper signal range for the A/D conversion because the mean intensity of signals varies with different subjects.

In order to convert the continuous analog signals to corresponding digital values, a series of the analog signals sampled at certain time intervals have to be kept undistorted during their conversion. Fortunately, the A/D converter used in this system processes the overall conversion within a very short period of 1.23ms and also has its own track/hold function, so it does not need an extra sample/hold circuit.

(3) A/D Conversion and Output

The A/D converter used is a hybrid IC for processing of image signals and has the built-in multiplexer with 8 channels and OP-amp. as shown in Fig. 4. Since three MUX455 selects signals from 24 channels and one MUX455 again selects three MUX455, the number of channels can be extended to 64. Therefore, with 16 input-scanning mode, an extension of 1024 channels is possible, and with 64 input-scanning mode, that of 4096 is possible.

As an image data of CCD, the series of data generated from all the channels are transmitted to the PC memory through the data bus and then processed thereafter.

(4) Software

The above mentioned hardware such as input scanning circuit multiplexer, and A/D converter that are used for processing signals from the sensor mat, are incorporated into the board of an IBM-PC and connected with the slots of the PC. All the controls of hardware and the input-output of data are manipulated by software. The micro-assembler is used as the programming language to control promptly since the speed of the A/D converter is very fast. Turbo C is used for the output and storage of converted signals and image processing on the MS Window.

CALIBRATION

There is the final problem in the quantification of foot pressure distribution;the actual pressure generated must be transmitted as it is to the measured data taken through the system. The consistency is largely dependent on the linearity of the output voltage of the sensors caused by the pressure exerted. Because the PF sensor in particular is more sensitive to impact force than to slow change in pressure, the calibration by software is needed to compensate the gaps.

To calibrate, the values of the voltage level generated from the sensors can be expressed in terms of the relative ratios between the values of the elements or directly translated into force values. The latter method is used in this study. The ground reaction force on the plantar and the pressure distribution are calculated in details in terms of force, and processed to display in graphic images as shown in Fig. 5 for a better grasp in details.

Two methods are available for the translation of voltage into force; the direct method bypassing the A/D converter into force values. The latter method is used in this in this study to convert the digital values into corresponding force values.

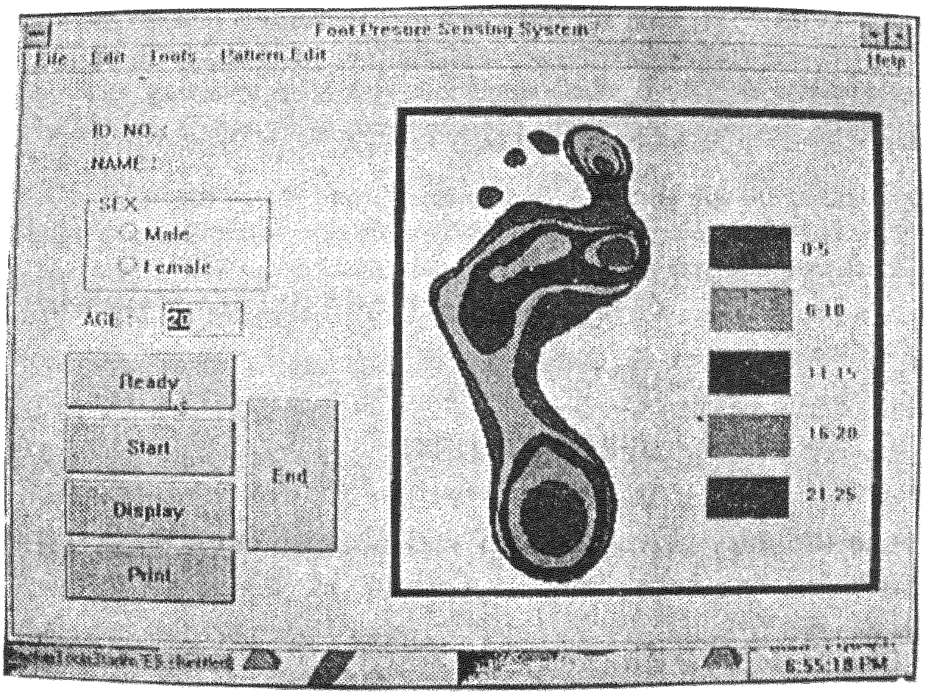

Figure 5. Foot pressure distribution during walking

Primarily the sampling rate is matched to reconcile the processed values through the measuring system with the output of the sensor mat. The interpolation method is used if the number of output values from touch-in to take-off is inconsistent. The digital values from the pressure distribution measurment system and the values of the vertical ground reaction force from the sensor mat are used in the regaression equation to convert the digital values into force values.

REFERENCES

Cavanagh, P.R. and Lafortune, M.A.(1980). Ground reaction forces in distance running. J.Biomech. 13: 397-406

Cavanagh, P.R, Williams, K.R., and Clarke, T.E.(1981). A comparison of ground reaction forces during walking barefoot and in shoes. In Biomechamics III-B, Morocki, etal(eds.), Baltimore: University Park Press, PP. 151-156.

Elliot, B.C. and Blanksby, B.A.(1979). A biomechanical analysis of male jogging action. J. Human Movement Study. 5: 42-51.

Guenther, R.(1967). Ueber Stosserschuetterungen beim gang des menschen Unpublished doctoral dissertation Universitat Saarbruecken.

Light, L.H., Melellan, G.E., and Klenerman, L.(1980). Skeletal transient on heel strike in normal walking with different footwear. J. Biomechanics, B 447-480.