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Effect of High-Heeled Shoes on Gait: A Micro-Electro-Mechanical-Systems Based Approach

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Abstract**—**The accelerations generated by the shoes in the body should be known in order to prevent balance problems, degradation of body shape and to spend less energy. In this study, it is aimed to investigate the effects of the shoe heel height on the human body. The working group has been created as five women (range 27-32 years) with different characteristics and five shoes with different heel heights (1, 3.5, 5, 7 and 9 cm). Individuals in the study group wore shoes and walked along a 20-meter racecourse. The accelerations created by the shoes are measured in three axes (30.270 accelerometric data) and analyzed. Results show us that; while walking with high-heeled shoes, the foot is lifted more; in this case, more effort has been spent. So, more weight has occurred at ankles and joints. Since high-heeled shoes cause greater acceleration, women wearing high-heeled shoes tend to pay more attention when taking a step. As a result, for foot and body health, shoe heel must be designed to absorb the reaction from the ground. High heels disrupt the structure of the foot and it is damaging the body shape. In this respect, this study is considered to be a remarkable method to find of effect of high-heeled shoes on gait by using accelerometer in the literature.

Keywords**—**Acceleration, sensor, gait analysis, high shoe heel, micro-electro-mechanical-systems.

I. Introduction

ACCELEROMETERS sense the acceleration on single or multiple axes (X, Y, and Z) on Cartesian coordinate system, and provide either digital or analog signal outputs. It is possible to measure the vibrations that occur in the body with the aid of a sensor while walking.

Walking action is displacement of the body in space properly maintaining the minimum level of energy consumption. Kinetic and potential energy are conserved since the changes in the center of gravity are low while walking [1].

Walking consists of a highly complex cycle of movements occurring on the legs, which are continuously repeated [2]. The first foot is lifted just after the other is set down while walking (Fig. 1). While one of the feet is on the ground, the knee is almost fully straight as it is keeping the distance from hip to ankle constant. The body rises and falls (d distance) by about three centimeters in each step. The body reaches the maximum height (tall) when the leg is straight and vertical.

A body moving in an arc of circle causes accelerations towards the center of the circle. This acceleration is calculated as (speed^2)/radius. At step 2 (Fig. 1 (b)) the acceleration is vertically downwards. The walker cannot drop with an acceleration greater than gravitational ‘g’ [3]. High-heeled shoes increase the radius (and the L distance), thus they directly affect the acceleration of the body.

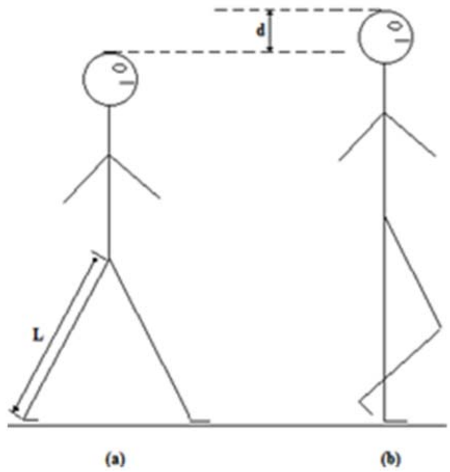

Fig. 1 Walking cycle (a) step 1: each foot is on the ground, (b) step 2: a foot is on the ground, the other is lifted (L: the radius is leg length, d: the rise and fall distance of the body) [3]

Preferred type of shoe for daily use is very important for the body balance and the skeletal health. Unbalanced shoes may cause several undesired situations such as gait disorders, the formation of the foot swelling and bone curvature, body balance and spinal cord problems. Heel height affects balance of body independently. Increasing the shoe heel height can i) decrease an individual’s balance, as shown by worsened postural balance; ii) limit the individual’s stability in terms of excursions and directional control, and iii) decrease functional mobility. Moreover, high heels can overload more effort on the calf muscles (gastrocnemius medialis, gastrocnemius lateralis), tibialis anterior muscles, and vastus lateralis muscles [4]. Wearing high-heel shoe is hazardous for individuals with spinal problems and cervical troubles, due to the muscle activations [5].

In this study, the effects of the shoe heel height on the human body and gait are analyzed with a different method from the literature (using MEMS-based acceleration sensor system).

II. Materials and Methods

A. Study Groups

The study group consists of five women with different

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characteristics ([mean] age, 29.2; height, 158.8 cm; and weight, 69.62 kg). General characteristics of the study group are shown in Table I.

TABLE I
GENERAL CHARACTERISTICS OF THE STUDY GROUP (N=5)

Subject No.	Height (cm)	Weight (kg)	Sex (F/M)	BMI (kg/m^2)	Age (year)
M_1	162	65.3	F	24.88	28
M_2	169	68	F	23.8	27
M_3	155	72	F	29.96	32
M_4	163	83	F	31.23	30
M_5	145	59.8	F	28.44	29

F: female

The shoes with different height of heels were worn by women and the women walked along a 20-meter racecourse. The sensor was connected to every woman's right ankle; the acceleration values at this point were measured during walking and recorded for further comparative analysis. The recording time and the number of data (2018 data) were held constant for each individual to avoid any outliers. A total of 30.270 data (including all axes) were analyzed for this study. The shoe types used in the study are shown in Fig. 2.

Fig. 2 Shoes used in the study

Dynamic accelerations were recorded on an SD card during walking and subsequent analyses were analyzed at the computer. While the X-axis provides the data about the stride length, Y-axis provides data for the balance and The Z-axis provides the data about the height of step. So we can obtain data about the number of steps (from Z-axis data) and the spent energy for each step.

The ethics committee of Ondokuz Mayis University faculty of medicine clinical research unit approved the developed device and the method of this study is numbered as 2015/123. For each subject of this study, Patient Informing Consent Form was filled out and the subjects were verbally informed about the study.

B. MEMS (Micro-Electro-Mechanical-Systems) Based Acceleration Sensor

MEMS and semiconductor technology are combined on a single chip. The ADXL345 is one of the MEMS based 3-axis accelerometers with digital output. It is manufactured by Analog Devices Inc. in the U.S. Fig. 3 shows the structure of the sensor.

The ADXL345 is one of MEMS based 3-axis accelerometers with digital output. Technical specifications are described in [7]. So, this combination of features makes the ADXL345 the most appropriate accelerometer to our study. MEMS based accelerometers are used for various locations of military areas, as well as health care industry [8]-[11].

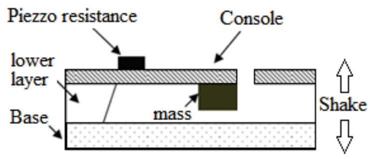

Fig. 3 The structure of an accelerometer [6]

The accelerometers can be used for measuring gait parameters in a real life [12]. They have recently become more available for research purposes. These devices have been widely used in various contexts, including gait analysis [13], [14].

C. Measurement Device and Software

As a first step, a data acquisition card is designed. In the card, the sensor, which has ability to define position by using 3-axis Cartesian coordinate systems, is used to measure the accelerations that occur in right foot. The measured data from the sensor are either recorded on the eeprom or sent to the computer via a USB. These raw data, which are transferred to the computer, are grouped according to their axes (X-Y-Z) and plotted with the help of interface program. Fig. 4 shows the structure of data acquisition card.

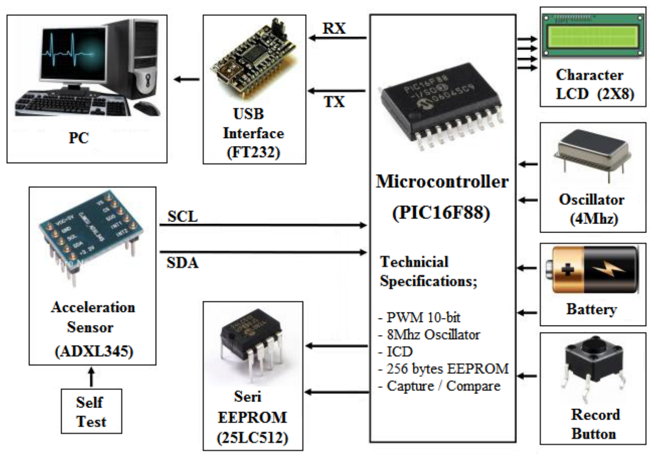

Fig. 4 The block diagram of designed and realized system

The system's sampling frequency is 20 Hz. Each 32-bit of float received data are composed of X, Y and Z data. Thereby, the amount of data transferred is 20 x 3 x 32 = 1920 bits/sec and it is suitable for a wireless transmission.

PIC16F88 microcontroller has been chosen to control the data acquisition card. The PIC16F88 features 8 MHz internal oscillator, 256 bytes of EEPROM data memory, a capture/compare/Pulse Wide Modulation (PWM), an addressable universal synchronous/asynchronous receiver/transmitter (USART), a synchronous serial port that can be configured as either 3-wire Serial Peripheral Interface (SPI) or the 2-wire Inter-Integrated Circuit (I²C) bus, 7 channels of 10-bit Analog-to-Digital (A/D) converter and 2 Comparators that make it ideal for advantage analog / integrated level applications in automotive, medical, appliances and consumer applications. Other components of the system are 2x8 character Liquid-Crystal Display (LCD) (used to see acceleration values in real time), accelerometer sensor(ADXL345), button (used to start a recording), crystal oscillator (4Mhz), eeprom memory component (24LC512, manufactured by The Microchip Technology Inc.) and data transfer circuit card(The USB interface, consists of ft232 circuit). The required power for the entire circuit has been obtained from a circuit containing a 9V battery and LM7805 regulator. The accelerometer is extended via a cable (usb type of cable) during the tests.

As a second step, an interface program was developed by using Microsoft Visual C# 2010 (version 10.0.40219.1 SP1Rel) programming language as given in Figure 5. The program transfers the acceleration values from the developed system to the computer. This program provides opportunities for saving the data measured as a text file or for plotting the graph of the previously recorded data. Custom computer services (CCS) software was used to program the PIC16F88 microcontroller.

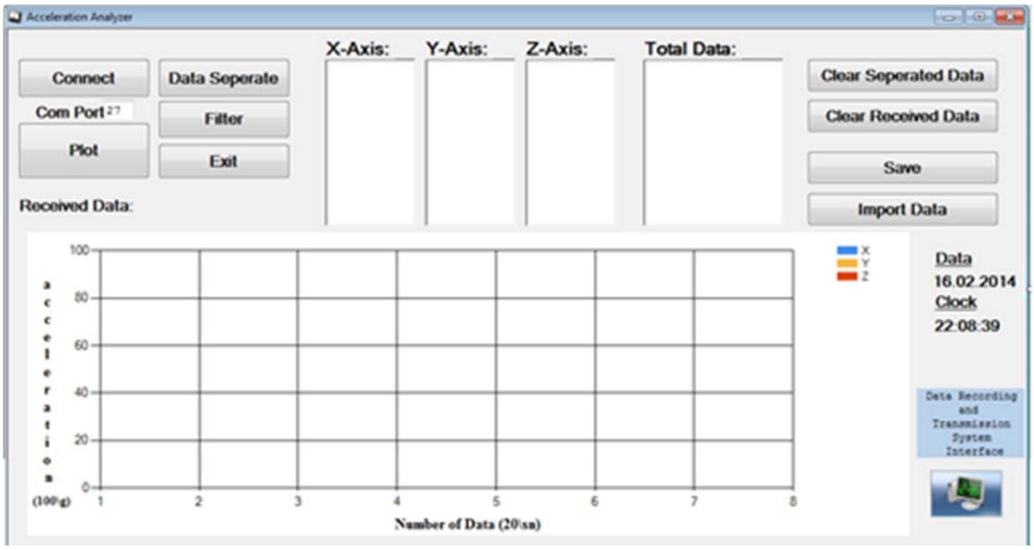

Fig. 5 Interface program (prepared by using C # programming language commands)

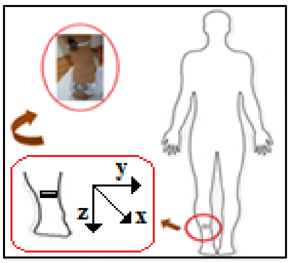

Fig. 6 Positioning the sensor on the women

All data are transferred to the computer with the help of this interface. The interface program consists of a lot of parts such as; system date and clock, save button, import data button, connect button, exit button and plotting. Filtering was needed for analyzing. MATLAB is the most convenient and widely used program for filtering and analyzing. So, analyses were done in MATLAB (version 7.12.0.635 (R2011a) 32-bit win32).

The sensor is placed on the women's right foot so as to XY-plane lies parallel to the ground and the Z-axis is positioned perpendicular to the ground, as seen in Fig. 6.

The sensor is placed in front of the right ankle, because this point is the area of maximum oscillation of the body during walking.

III. Results

The acceleration values of each individual were measured using ADXL345 acceleration sensor along a 20-meter racecourse. The mean acceleration values of study group were shown in Table II.

TABLE II
THE MEAN ACCELERATION VALUES OF ALL STUDY GROUPS

Type of Shoe	Participants														
	M_1			M_2			M_3			M_4			M_5		
	X(g)	Y(g)	Z(g)	X(g)	Y(g)	Z(g)	X(g)	Y(g)	Z(g)	X(g)	Y(g)	Z(g)	X(g)	Y(g)	Z(g)
S_1	-1.05	0.03	-0.35	-1.05	0.03	-0.37	-0.96	0.03	-0.05	-0.99	0.23	-0.29	-1.00	0.19	-0.30
S_2	-1.15	0.25	-0.16	-1.17	0.26	-0.30	-0.96	0.02	-0.04	-0.93	0.20	-0.20	-1.16	0,19	-0.25
S_3	-1.11	0.21	-0.11	-1.17	0.23	-0.18	-0.96	0.01	-0.03	-0.10	0.30	-0.19	-1.11	0.20	-0.18
S_4	-1.13	0.29	-0.09	-1.14	0.30	-0.10	-0.95	0.08	-0.01	-1.12	0.21	-0.09	-1.11	0.19	-0.07
S_5	-1.17	0.30	-0.02	-1.18	0.30	-0.09	-0.98	0.07	-0.09	-1.12	0.22	-0.03	-1.12	0.22	-0.01

While significant oscillations were observed along the X and Z axes, substantial movements were no detected in the Y-axis. The recorded acceleration values were transferred to the computer and the peaks of the signals obtained from the X-axis for each shoe were analyzed using the MATLAB.

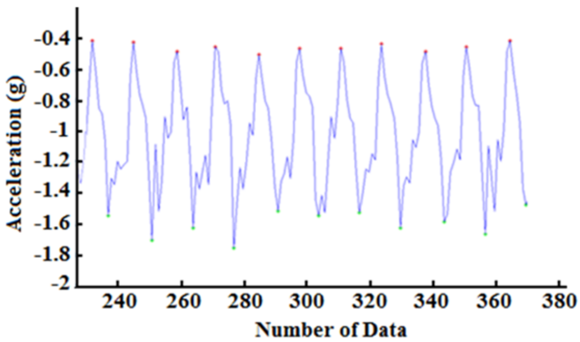

Fig. 7 Determination of the number of steps from the recorded data

In Fig. 7, the points with red at the peak of signal represent the number of steps. When the right foot is raised during walking, it is reflected as a change in the vertical axis. The accelerometer measures the maximum points while the foot moves upwards and measures the minimum point while the leg is lowered. These changes are shown in Fig. 7. Thus, looking at the top of the X-axis, the number of steps for each shoe type was found and Fig. 8 was obtained. While the heel height was increasing, the distance between the two steps was decreasing and the walking speed was reducing so, the number of steps was increasing.

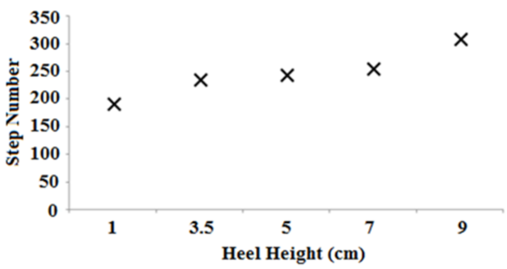

Fig. 8 Step Number-Heel Height graphics (from M_1)

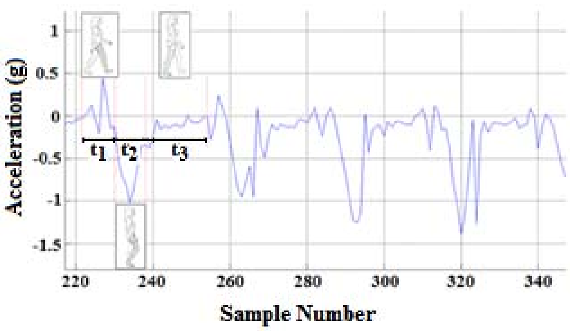

Fig. 9 The gait analysis example according to the data obtained X-axis

It is possible to find total number of steps, walking time and spent time for a step from X-axis data as shown in Fig. 9. Here, the time between t_1 and t_3 shows the period between two steps.

According to Fig. 9, the maximum acceleration (gmax) was measured as 0.43 g (sample number is 227, t_1= 11.35 second). Similarly, the minimum acceleration (gmin) was measured as -1.1 g (sample number is 235, t_2= 11.75 second). The number of steps was determined by counting the peaks of signal in the graph. There were five peaks in the graph throughout 6.5 seconds. Thus, step frequency was calculated as 0.769 step/sec. Although the person's step length can change according to the physical structure of body, a normal person is taking mean two steps per second. On average, walking speed for adult males in the age of twenties is 139.3 cm/s and for women are 140.7 cm/s [15]. In light of these data, it is understood that the woman's walking speed is a little slow at graphic.

Z-axis gives us an idea about the power and energy consumption during walking. While shoe heel length was increasing, the average value of the acceleration in the Z-axis was increasing too. While the women are walking with high-heeled shoe, her feet are rise more up at the moment of stepping, so they spend more effort, and more weight occurs at ankles and joints. This may lead to the emergence of many diseases about foot, ankle and spine in the future.

The graph of the average acceleration was obtained for all the measurements and was shown in Fig. 10. The graphs were plotted taking into consideration the Z-axis.

Once Fig. 10 was analyzed carefully, it was understood that while the heel height was increased, the average acceleration values in the Z-axis were also raised. In consequence, since the greatest acceleration was measured from the highest heeled shoe, women with high heels were taking more careful steps and they tend to pay more attention while taking the steps. Although this was not very important for flat heels and the middle high heels, there was a threat that high-heeled shoes can cause ankle sprains and ankles fractures.

At a similar study [16] (this study consists of three shoes, but our study consists of five shoes), it is investigated to influence of shoe heel height on venous function in young women. Filho at al. focused on that high heels reduce muscle pump function, and their continued use may provoke venous hypertension in the lower limbs, possibly representing a predictive factor of venous disease symptoms. Our study is also find to similar results and is consistent with analyzed the literature about to be harmful of high heeled shoes and is demonstrates a different method.

IV. Discussion

The preferred shoe heel height is very important for the body health. High heels can cause a number of biomechanical disorders (thumb deformity, calf pain, foot pad disorders etc.). In addition to the diseases of the legs, the general biomechanics of the body and normal walking can deteriorate; corrosions can occur in stools and spine. As shoes with heel heights of 3 cm, 5 cm, and 7 cm had been used in previous studies, but the present study was used the different high heeled shoes (1 cm, 3.5 cm, 5 cm,7 cm and 9 cm). So, more data were analyzed (30.270 data including all axes) and more remarkable results were obtained using a different method from the literature that micro-electro-mechanical-systems (MEMS) based approach.

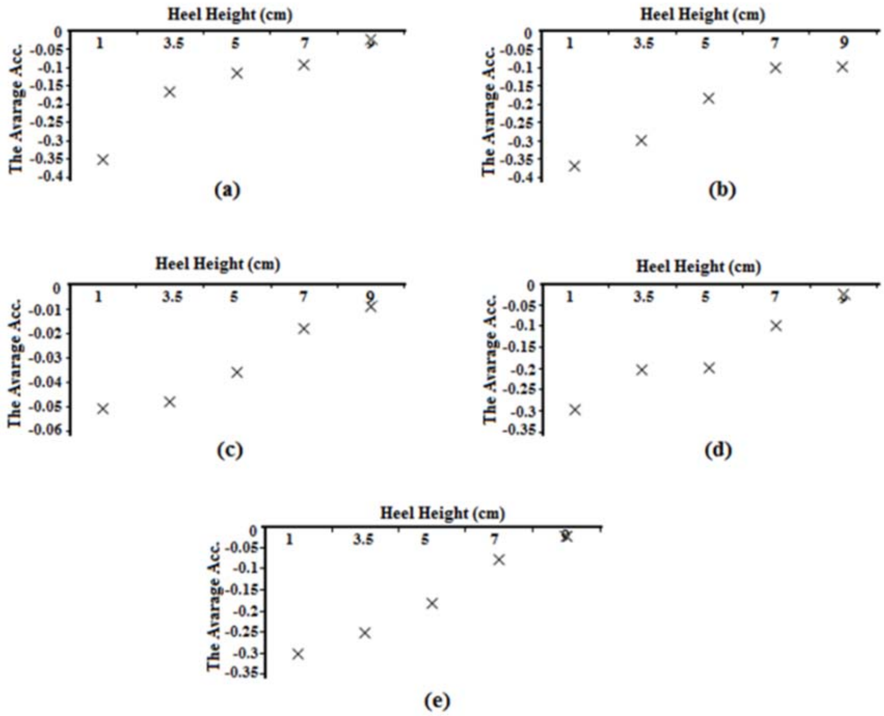

Fig. 10 The graph of the average accelerations obtained from (a) M1, (b) M2, (c) M3, (d) M4, (e) M5

V. Conclusion

In conclusion, we think that the acceleration sensors can be used as a reliable tool in the analysis of gait and in diagnostic of some walking diseases.

The effect of the shoe heel height on the body balance and the skeletal health is very important that may cause several adverse situations such as gait disorders, the formation of the foot swelling and bone curvature, body balance and spinal cord problems. Because heel height and wearing experience affect standing balance independently. In addition, we are able to show that our data measurement and acquisition device is very suit to gait analyze and our measurement method is easy to use and does not contain any danger (e.g. radiation exposure, electromagnetic hazard) and can be used safely at home.

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