공학석사 학위논문

Correction of temperature measured by insole sensors for diabetic foot diagnosis based on pressure effect reduction

당뇨발 진단을 위한 신발 내 체온
모니터링에서의 압력 보정에 관한 연구

2014 년 8 월

서울대학교 대학원
협동과정 바이오엔지니어링 전공
류 호 석

A thesis of the Master’s degree

당뇨발 진단을 위한 신발 내 체온 모니터링에서의 압력 보정에 관한 연구

Correction of temperature measured by insole sensors for diabetic foot diagnosis based on pressure effect reduction

August 2014

Interdisciplinary Program for Bioengineering,

Seoul National University

Ho Suk Ryou

당뇨발 진단을 위한 신발 내 체온 모니터링에서의 압력 보정에 관한 연구

지도교수 박 광 석

이 논문을 공학석사 학위논문으로 제출함

2014 년 8 월

서울대학교 대학원

협동과정 바이오엔지니어링 전공

류 호 석

류호석의 공학석사 학위논문을 인준함

2014 년 7 월

위 원 장　　　김 희 찬　(인)

부위원장　　　박 광 석　(인)

위　　원　　　최 영 빈　(인)

Correction of temperature measured by insole sensors for diabetic foot diagnosis based on pressure effect reduction

By

Ho Suk Ryou

A thesis submitted to the Interdisciplinary Program for Bioengineering in partial fulfillment of the requirements for the Master's degree in the Interdisciplinary Program for Bioengineering at Seoul National University

July 2014

Approved by Thesis Committee:

Professor ___Kim, Hee Chan_____Chairman

Professor ___Park, Kwang Suk___Vice chairman

Professor ___Choy Young Bin____

ABSTRACT

Correction of temperature measured by insole sensors for diabetic foot diagnosis based on pressure effect reduction

Ho Suk Ryou

Interdisciplinary Program for Bioengineering
The Graduate School
Seoul National University

Introduction: The foot health monitoring gives clues about body's overall health and it has been known that by monitoring pressure and temperature of plantar foot, the early diagnosis of diabetic foot ulcer is possible. Because of this, monitoring plantar foot in daily life using sensor-embedded insole has been researched; however, there are factors that affect in monitoring plantar foot skin temperature which bear error in the result especially when comparing the temperature difference of corresponding points (Toe, 1st, 3rd metatarsal and Heel) between left and right foot (≥1.2 C˚ difference for early diagnosis of foot ulcer). In this study, we only focused on pressure as the only factor that affects foot plantar skin temperature and we investigated how the pressure affects the skin temperature in plantar foot and propose the function to correct the error caused by the pressure.

Methods: We performed calibration for each thermistor before the experiment in the temperature range from 25 to 40°C. We used thermistor-embedded insole in measuring skin temperature of corresponding points which are toe, 1st, 3rd metatarsal and heel from both feet. We used pressure sensor and three stages of pressure (No pressure, standard, focused) were applied on plantar foot surface and in each stage, the voltage values were received and converted into the temperature values using the equations obtained from calibration by using Matlab. Once the data were received, we analyzed the trend of temperature changes as the pressure increases. Also, by investigating relationship between the amount of temperature changes and that of pressure changes, we were able to get the pressure-error-correction function. By using this function, we applied this to the subjects while they put more pressure on either left or right foot, so that we can check if the function can reduce the error.

Results: The experimental results show that as the pressure increases, the temperature decreases. This implies that because of less blood flow caused by pressure applied on the plantar foot surface, the skin temperature decreases and this trend is similar to those on other parts of the body. When we applied the pressure-error-correction function to the subjects, the errors were reduced and this shows that by using this method, we were able to reduce the false alarm.

Conclusions: This study proved that as the pressure on the plantar foot surface increases, the plantar foot skin temperature decreases. We were also able to reduce the error in skin temperature monitoring caused by the pressure using pressure-error-correction function and showed that it can be applied to sensor-embedded insole independent from the person's standing habit.

Keywords: healthcare, non-invasive measurement, skin temperature, pressure-error-correction function, foot ulcer

Student number: 2012-23291

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 2

Chapter 3

LIST OF ABBREVIATIONS

SSE	The sum of squares due to error
RMSE	Root Mean Square Error
PTC	Positive Temperature Coefficient
NTC	Negative Temperature Coefficient
ADC	Analog-to-Digital Converter
SKT	Skin Temperature

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The foot is one of the body parts that bears weight and plays important role in locomotion. The foot also gives the clue about the person's overall health. By monitoring foot health such as temperature, sense and color, we can tell the possibilities of diseases such as kidney and heart diseases that the person might have. This is the reason that regular foot checks are recommended to be part of the health care. One of the main applications in monitoring foot health is diabetes. The diabetes is one of the serious illnesses that more than 371 million people, which are more than 20% of the world population, are diabetic patients [1]. Most of all, half of diabetic patients did not know they have diabetes until they go to see the doctor. Also, one of the serious issues in diabetes is its complications. One of them is foot ulcer which about 25% of diabetic patients have and nearly 90% of them are unaware they have it [2]. The foot ulcer is caused by breaking-down of soft tissue that damages both tissue and skin. The ulcers are often treated with replacement therapy using bio-engineered tissue or skin substitute; however, no therapy is still completely healing the ulcers. The cost of treatment is also major burden for patients that in the United States, nearly 33% of 116 billion dollars in treatment of diabetes are for foot ulcer and as the ulcer progresses; it costs nearly 8 times higher than the people with low-grade ulcers [3]. This is the reason that it is very important to keep monitoring the foot health to prevent further progress of the foot ulcer, and many researchers try to find the method for early diagnosis.

1.2 Noninvasive monitoring of diabetic foot ulcer

Some researches were done in soft tissue or cell manner, but they were invasive and impossible to monitor the foot health in daily life. Therefore, the researchers tried to find the way of monitoring the foot health non-invasively and two of the proposed solutions were monitoring foot plantar pressure and skin temperature.

For the diabetic patients, abnormally high pressure under the foot is detected [4]. The high pressure causes the compression between bony prominences and external surfaces and this may lead to destruction of deeper tissues and causes foot ulcer [5]. By using pressure measuring systems, it was possible to monitor abnormal pressure on foot plantar surface.

The skin temperature of human body can also tell the condition of the human body. The human skin plays important role in thermoregulation and the temperature is the result of thermal balance between energy supplied from body and energy lost to the environment by radiation or evaporation [6].

Therefore, if there is abnormal increase or decrease in skin temperature compared to normal patients, it is possible that there is something wrong in the body. Most of all, it is said that there is the increase in skin temperature in the site of wound infection and this is why that monitoring skin temperature of plantar foot can be used as effective way to prevent the ulceration [7, 8, 9]. Another method of using skin temperature monitoring system was proposed which is by comparing left and right plantar foot skin temperature. The difference in skin temperature of corresponding points between left and right foot can determine early diagnosis of foot ulcer. It is determined that elevated temperature of nearly 2.2 C° [10] or 1.2 C° [11] were considered risk stage of ulceration. It is also proved that monitoring plantar foot skin temperature reduced the risk for diabetic foot ulceration significantly and it is more effective than the evaluation by physicians [12]. Therefore, it is important to monitor plantar foot skin temperature in daily life and to do this, monitoring skin temperature non-invasively is important. There are researches about monitoring plantar foot skin temperature by using thermograph [13, 14], but the patients need to go to hospital which is impossible for patients to be monitored in daily life. One solution is by using insole that by embedding the temperature sensors in the insole, it is possible to monitor plantar foot skin temperature ubiquitously [15, 16]. This is important because although it is possible to monitor the foot once a day, the person has to be aware of it and it is more likely for person without diabetic foot to feel unnecessary to measure their plantar foot skin temperature every day. This will lead to the doctors to give less accurate feedback because of lack of medical record about the person's plantar foot skin temperature data. Therefore, by using sensor-embedded insole, the temperature data can be received and be monitored ubiquitously without even noticing.

1.3 The problem and purpose of this study

However, using sensor embedded insole in monitoring skin temperature has several factors that affect the monitoring results. One of these factors is pressure on the plantar foot because when the person steps on the insole, there will be pressure on the plantar surface. When the pressure is applied to surface of human body, the blood flow decreases [17] and there are also researches that shows the blood flow and skin temperature have relationship that as the skin temperature increases, the blood flow increases as well and the opposite effect also occurs [18, 19]. However, no studies have yet investigated how the person's pressure on plantar foot surface affects skin temperature. Since there are blood vessels in the plantar foot and when the pressure is applied, the blood flow will be decreased. This will lead the skin temperature to be decreased as well, and this will give error in the monitoring results especially for monitoring the temperature difference between left and right plantar foot skin temperature. We need to reduce this error by considering the pressure effect on the plantar foot skin temperature while using the insole. Hence in this study, we prove that there are pressure effects on monitoring skin temperature and also propose the pressure-error-correction function to give more accurate temperature monitoring result.

CHAPTER 2

MATERIAL AND METHODS

2.1 System Design

2.1.1 Thermistor

The thermistor is the temperature sensitive resistor composed of semiconductor materials. The thermistor we used is PR302J2 (US Sensor, USA) and its specific information is in table 1.

Table 1. The specific information of thermistor

Resistance	3000 Ω
Temperature Rating	-55 to +80 C°

The reason that we chose this thermistor is that it has long life, high accuracy and high stability, and is inexpensive. The thermistor follows general rules,

$$\Delta R = k\Delta T \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where ΔR is the change in resistance, k is first-order temperature coefficient of resistance and ΔT is the change in temperature. As shown in Equation (1), depending on classification of k, the types of thermistor can be classified. When k is positive, as the resistance increases, the temperature increases, and this is called positive temperature coefficient (PTC) thermistor. Most thermistors; however, are negative temperature coefficient (NTC) thermistor which the k value is negative that the resistance decreases with increasing temperature. PR302J2 is NTC thermistor and it is made of semiconductors that when the temperature rises, they increase the number of active charge carriers which caused the material to conduct more current.

2.1.2 Circuit Design

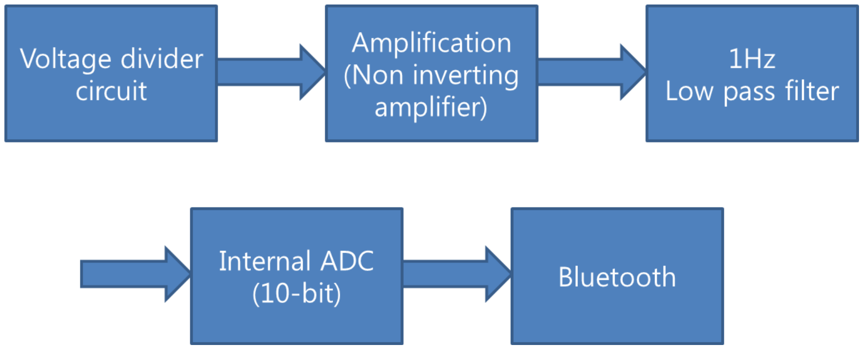


Figure 1. General block diagram of circuit

The general block diagram is shown in figure 1. The type of circuit that we used is voltage divider to calculate the voltage value from resistor inside the thermistor. The voltage divider uses number of resistors as shown in example in figure 2 and because of this, the input voltage can be divided depending on the resistance values and since we are able to change the resistance values, we are able to get the voltage value that we want.

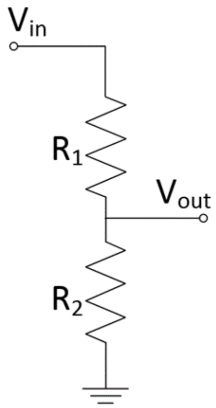


Figure 2. The voltage divider with two resistors

Since we need to amplify the signal from thermistors, we used non-inverting amplifier as shown in figure 3.

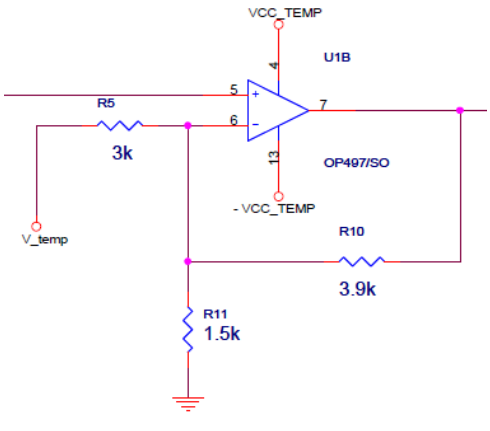
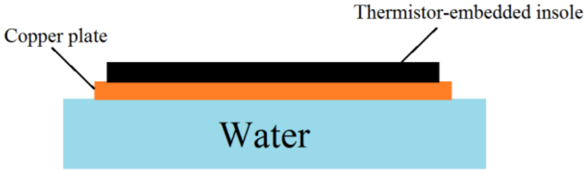


Figure 3. Example of non-inverting amplifier

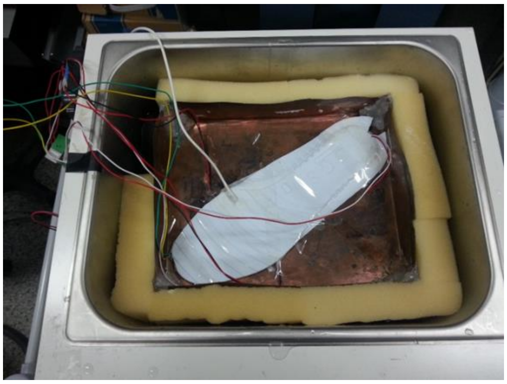
We used OPA497 for amplifier. We also need to remove the noise and most of them are in high frequency. This is why we need to filter these noise. To do this, we used low pass filter and since the frequency range of the temperature is within 1 Hz, we used 1 Hz low pass filter. The signal then goes through analog-to-digital converter (ADC) to be able to be sent wirelessly to computer through Bluetooth.

2.2 Calibration

We performed calibration for conversion from voltage to temperature. For calibration setup, we used water bath system to control the temperature. We also used copper plate which has higher heat conduction so that the heat from the water can be transferred to the surface of the copper plate well enough to be sensed. We filled water into the water bath system and putted copper plate on the water. Then thermistor-embedded insole was putted on the copper plate and make sure that all the thermistors were contacted with the copper plate surface as shown in figure 4.



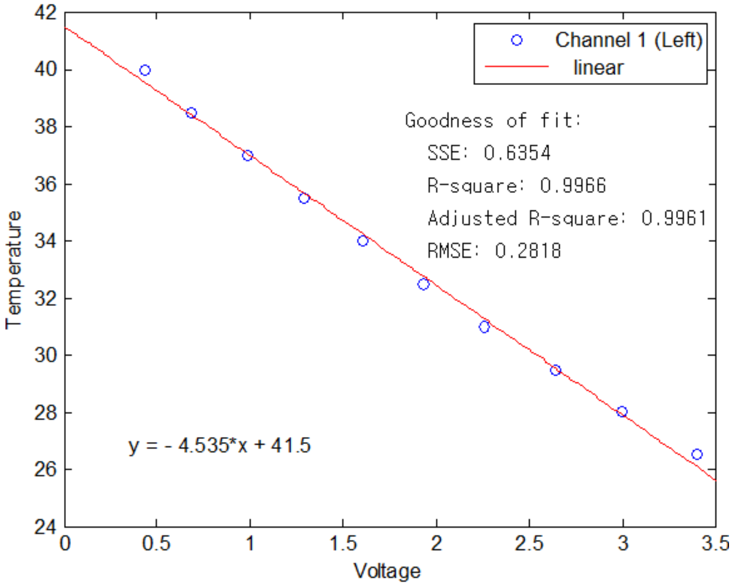
(a)



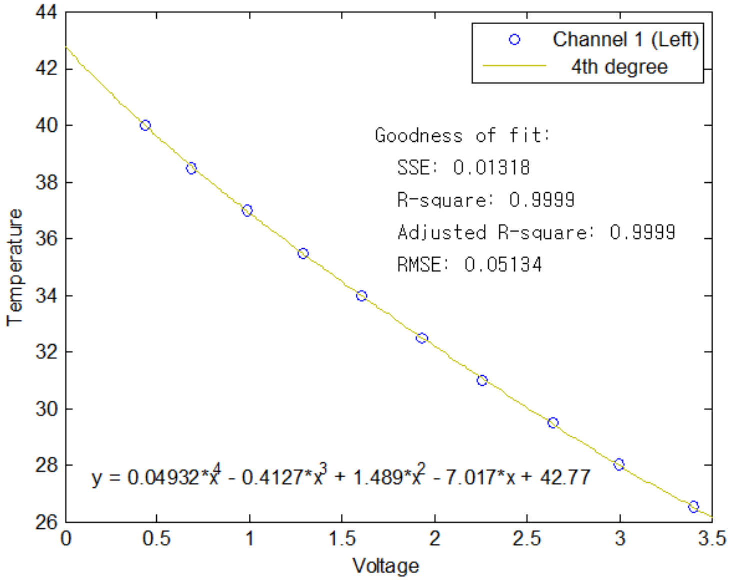
(b)

Figure 4. The calibration setup (a) Side view (b) Top View

For the reference, we used Bionomadix Dual-channel wireless skin temperature transmitter & receiver (BIOPAC, USA). The resolution of this sensor is 0.01 C° and the signal is ranged from 13 to 51 C°. We putted reference sensor under the insole and the temperature is raised by 1.5 C° from 25 to 40 C°. The temperature we measured is the temperature of copper plate because the thermistors are contacted with the copper plate, not the water inside of the water bath system. This is why we monitor the temperature data from reference sensor instead of monitoring the temperature shown by water bath system, because the temperature of copper plate is different from that of the water. The data are recorded for 30 seconds when the voltage value from the thermistor becomes stable and those data are then averaged. Once all the data from 25 to 40 C° were received, we used Matlab for calibration by using 4th polynomial curve fitting. One of the characteristic of NTC thermistor is that in small changes in temperature, the resistance is nearly proportional to the temperature; however, because of environment effect or human mistake, linear calibration was less accurate than other interpolation were as you can see in figure 5.



(a)



(b)

Figure 5. Curve fitting in calibration as (a) 1st interpolation and (b) 4th interpolation

We also used 4th degree rather than other degree interpolation because it was the most accurate polynomial fitting type for calibration. From 4th polynomial fitting, we were able to get constant values (K) to be used in later experiment. Since we are using 4th polynomial fitting, we get 5 K values from each channel, so we get total 20 K values from each foot. Then we use these K values into 4th interpolation equation to get the temperature values. The example of 4th interpolation equation to convert voltage values into temperature is shown in Equation (2).

$$K_{Ch1} = [K_1 \quad K_2 \quad K_3 \quad K_4 \quad K_5]$$
$$T_{Ch1} = K_1 \times V_1{}^4 + K_2 \times V_1{}^3 + K_3 \times V_1{}^2 + K_4 \times V_1 + K_5 \quad \cdots\cdots\cdots(2)$$

where V_1 is the voltage from channel 1, K_{Ch1} is the constant values calculated from calibration from channel 1 and T_{Ch1} is the converted temperature value from voltage from channel 1.

Since we received data from 4 channels from each foot, we used 8 equations individually. The 4th degree polynomial equations for all measuring locations in left and right foot are shown in figure 6(-1, -2) and in figure 7(-1, -2). Although the thermistors that we used are same type, each of their resistor values are not exactly same, the 4th polynomial equations are different from each other and by doing this, we were able receive more accurate temperature data from each thermistors. To be more accurate, we performed calibration 3 times and selected the 4th polynomial fitting equations that are most accurate since the error rate between trials are small.

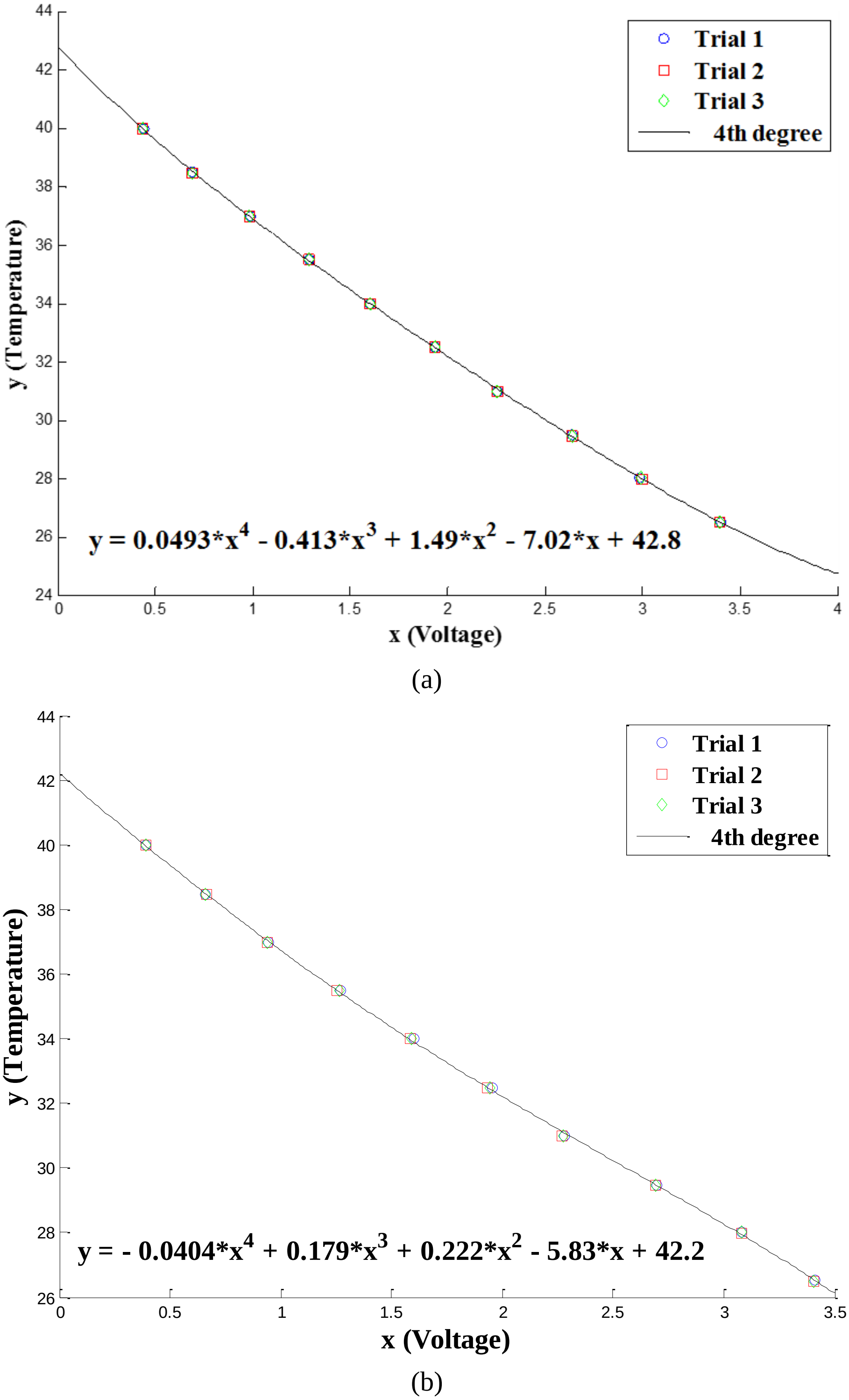
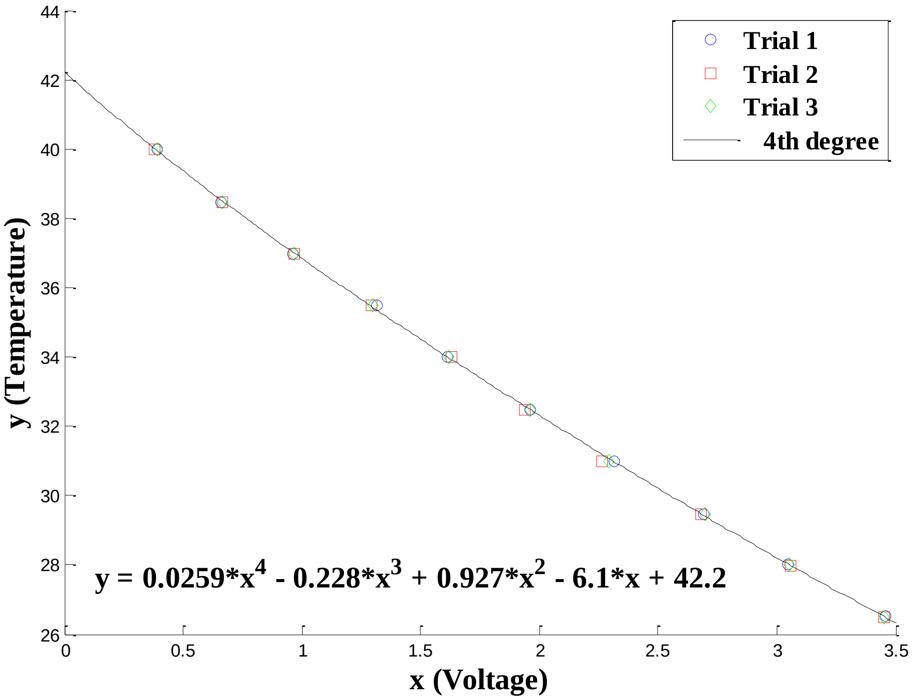
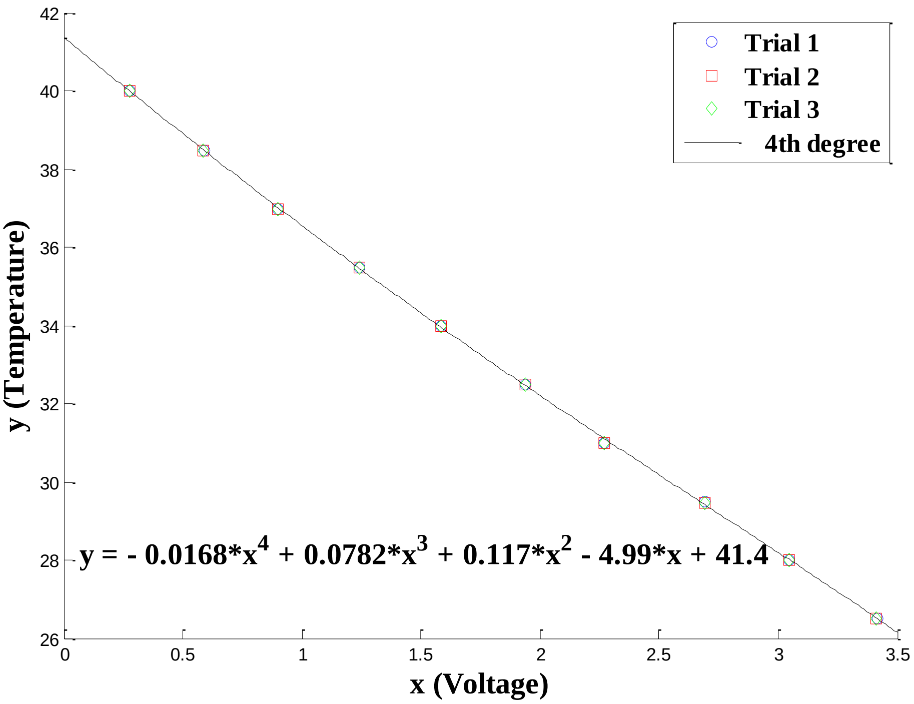


Figure 6-1. 4th degree polynomial equations for left foot (a) Toe (b) 1st metatarsal

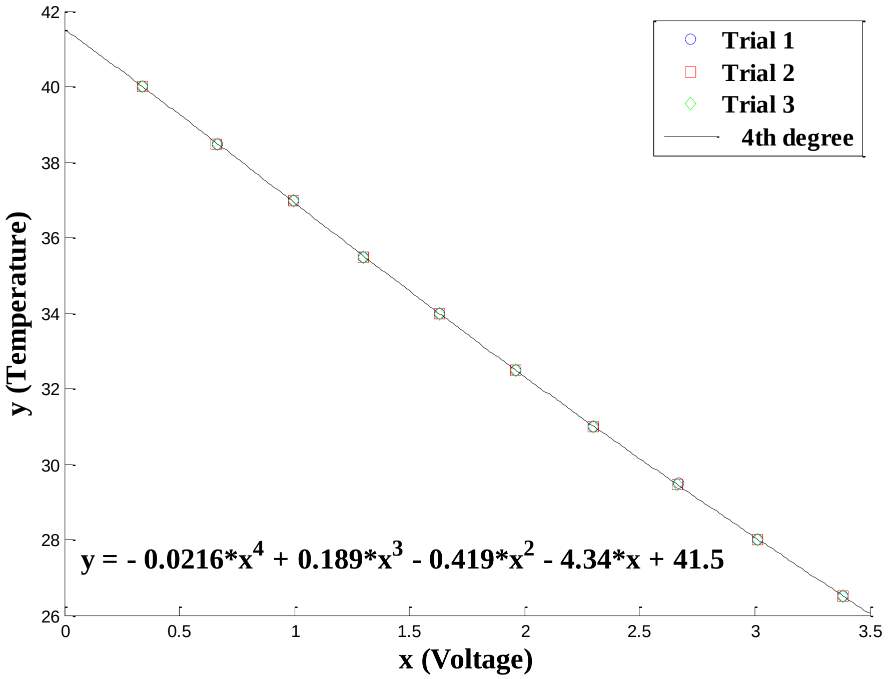


(a)

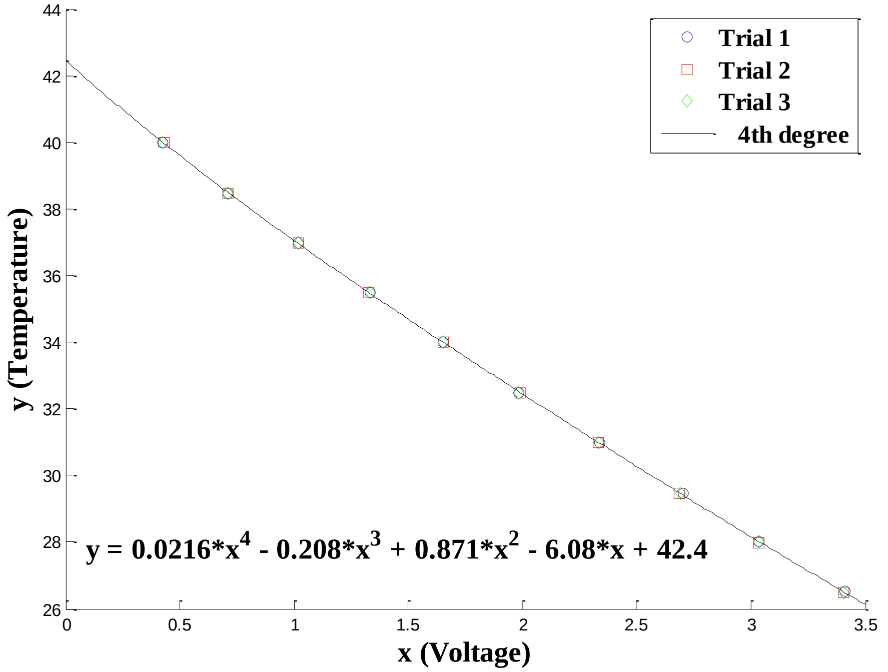


(b)

Figure 6-2. 4th degree polynomial equations for left foot (a) 3rd metatarsal (b) Heel



(a)



(b)

Figure 7-1. 4th degree polynomial equations for right foot (a) Toe (b) 1st metatarsal

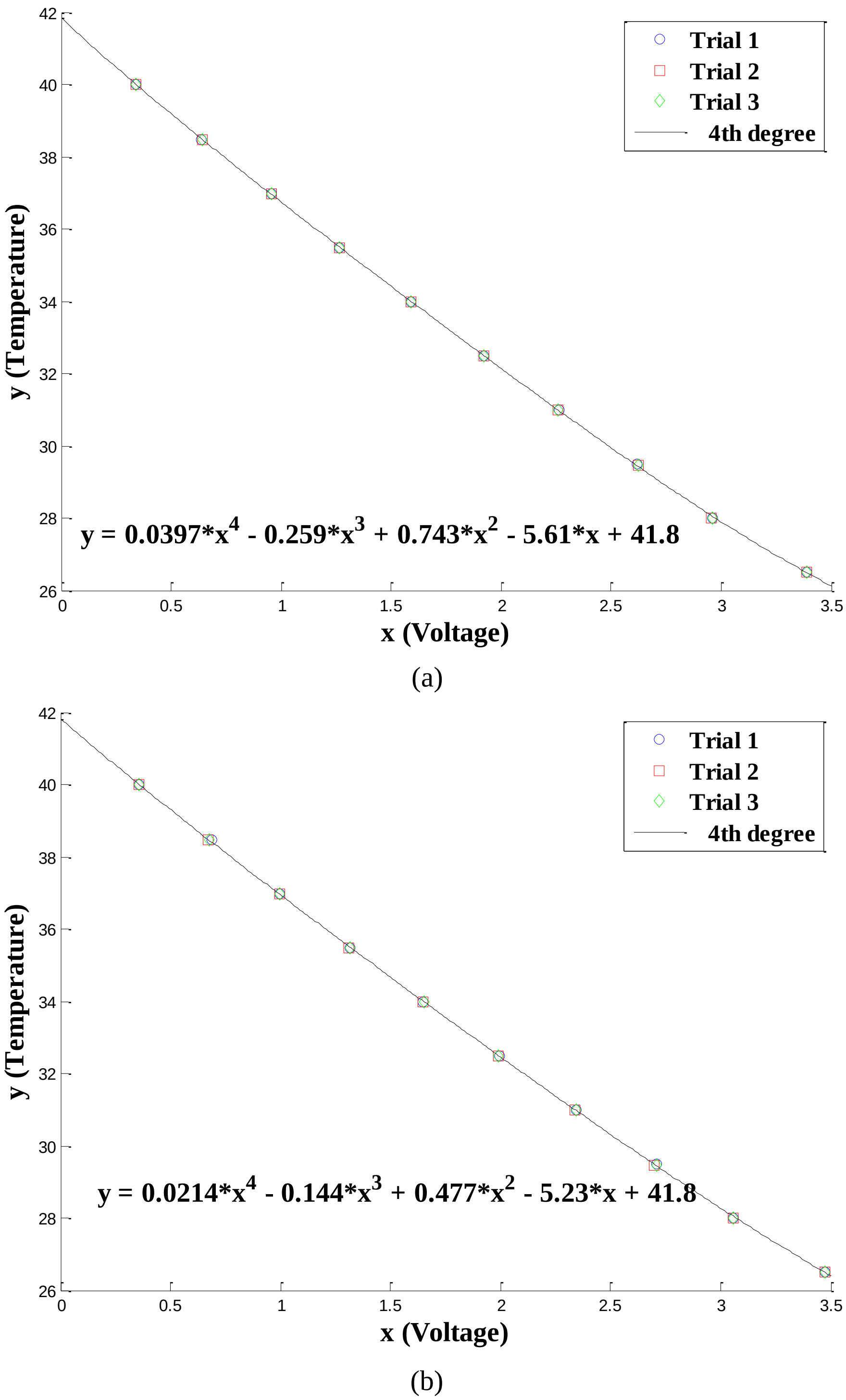


Figure 7-2. 4th degree polynomial equations for right foot (a) 3rd metatarsal (b) Heel

2.3 Experimental Setup

2.3.1 The trend between pressure and temperature

This study included 10 volunteers (8 males and 2 females) who had no history of diabetes or other related diseases. The range of age was from 24 to 30 years old, and that of weight was from 49 to 82 kg. The measuring locations of plantar surface for both left and right foot were toe, 1st metatarsal, 3rd metatarsal and heel as shown in figure 8.

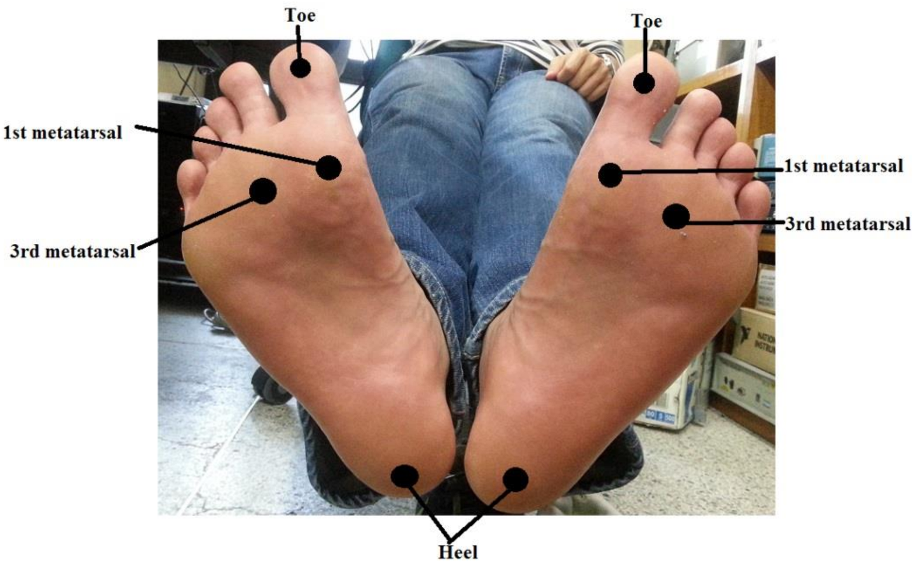


Figure 8. Measuring locations of plantar foot

The mid-foot was not investigated because this is the site where the surface does not contact with insole. This part may be investigated in later research. The thermistors were embedded in the insole and located at corresponding sites of measurement. Since we measure both skin temperature and pressure at the same location and same time, we putted sensor-embedded insole on the pressure sensor and did the experiment as shown in figure 9.

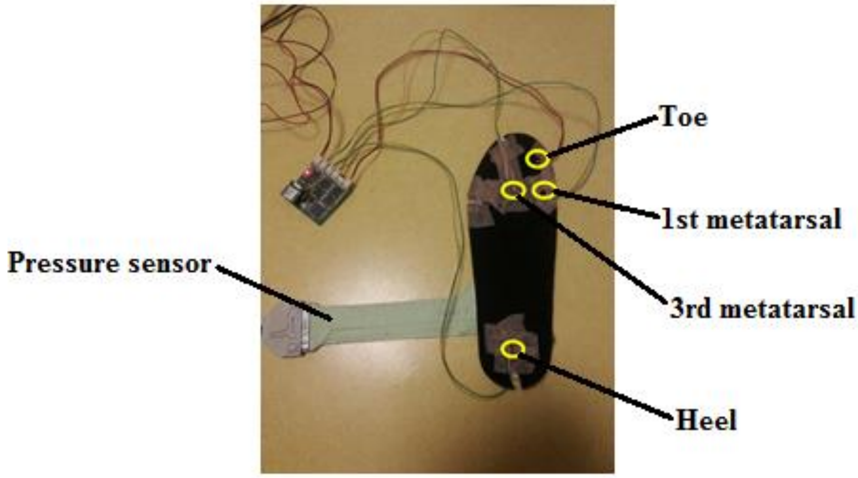


Figure 9. Thermistor-embedded insole on the pressure sensor

We did not use pressure sensor that can be embedded in the insole like how the thermistor was embedded, because it was impossible to measure both of them at the same location unless there was the sensor that can measure both temperature and pressure at the same time.

We used 3 stages of pressure which are no pressure, standard and focused. The standard stage means when the person stands, and the focused stage means when the person walks or runs. To decide the range of pressure to be measured, we examined the possible pressure that the person can produce on the pressure sensor while the person stands, walks and runs. For the toe, the standard stage is ranged from 20 to 100 kPa, and 100 to 220 kPa in the focused stage. For the 1st, 3rd metatarsal and heel, the standard stage is ranged from 100 to 220 kPa, and larger than 220 kPa in the focused stage.

The experiment was conducted in the room temperature of average 24.5 C° and before we measured the plantar foot skin temperature we measured the corresponding points by using infrared thermometer and the average of each measuring locations from subjects are shown in table 2.

Table 2. Average temperature of measuring locations from both feet

	Left (C°)	***Right (C°)***
Toe	35.28	35.08
1st metatarsal	36.32	36.33
3rd metatarsal	36.46	36.42
Heel	35.96	36.00

Since no subject had diabetic foot, there were only small temperature differences between left and right foot.

After measuring the plantar foot skin temperature, the subjects were asked to put their left foot on the insole and to apply pressure on the measuring location in accordance with each stage. Since the pressure only needs to be in the range according to the pressure stage that we were interested in, although the pressure value fluctuates, the fluctuations are small and we can just average them to be used in the data analysis. The subjects applied the pressure until the voltage value from thermistor became stable and when it does, we continue the procedure for 30 seconds and then the subjects were asked to remove their foot from the insole. This 30 second section is where we received both temperature and pressure data that we will use for analysis. The process was same for right foot. As shown in figure 10, these are the examples of temperature data from one subject's 3rd metatarsal from left foot in three stages of pressure amount.

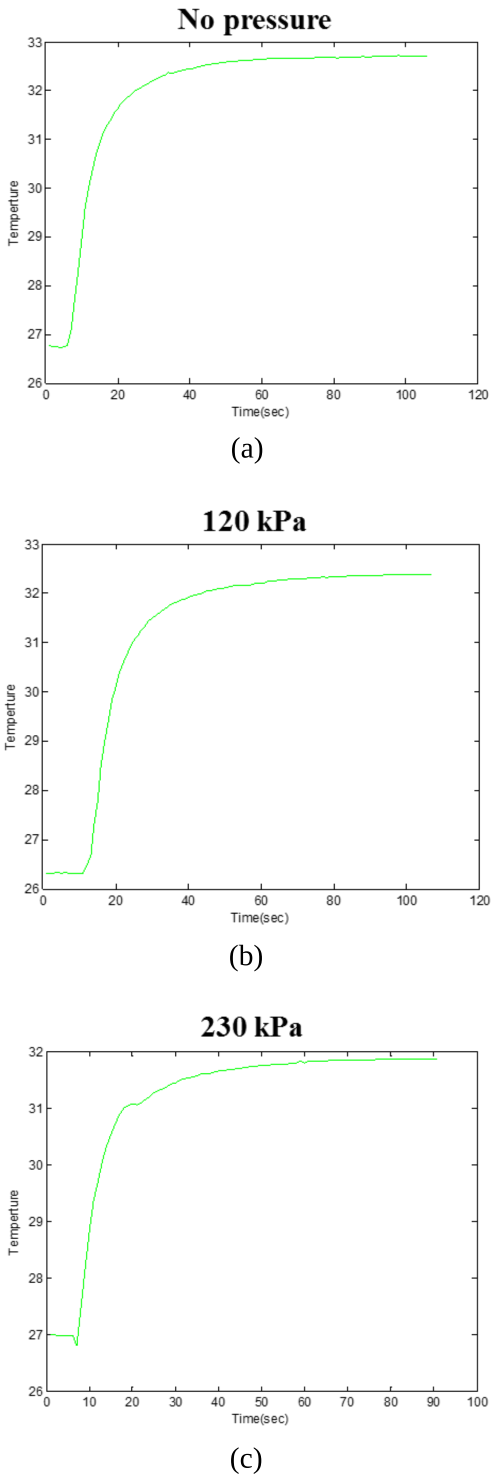


Figure 10. The example of temperature data from left 3rd metatarsal in accordance with (a) No pressure (b) Standard (c) Focused

The temperature with no pressure was lower than the temperature that was measured by infrared thermometer because the insole had much lower temperature than the subject had and this caused the plantar skin temperature to be cooled down. The temperature started to rise when the subject's measuring location contacted the thermistor and in certain temperature, it became stable. This is when we recorded the temperature. These values were used for getting trend in the relationship between pressure and skin temperature. Also for the repeatability, two subjects among 10 subjects were tested twice in different days to see whether the trend is similar and if it does; it shows that all the other subjects can be tested once.

When all the data were received, we used Matlab and excel for data analysis. We used the constant values from the calibration that we did before and converted voltages into the temperature. The temperature we were interested in is when the temperature is in stable stage as we did in the calibration. For the pressure, we averaged the pressure that each subjects applied on the insole in every pressure stage. Then we recorded the temperature and averaged the pressure values into excel and made scatter plot. To investigate the trend, we used trend line from each scatter plot. In the data analysis, we investigated two types of scatter plots. One was to investigate the trend of temperature values as the pressure increases on each measuring locations. Another was to investigate how much the temperature changes as the pressure increases and from this trend line, we get the general pressure-error-correction functions.

2.3.2 Applying pressure-error-correction function

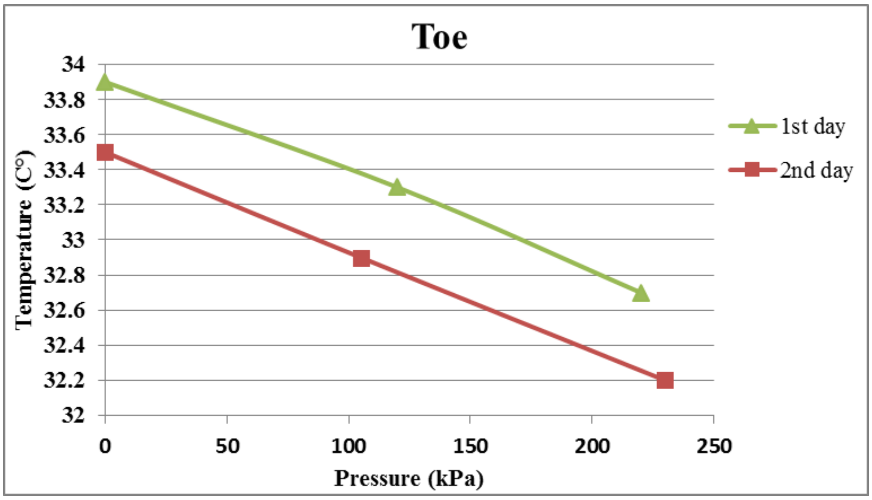
We also tested whether the pressure-error-correction function actually works or not. We first measured both feet's measuring locations to check if there are any big differences between collateral sites. After checking that they are normal, the subjects were asked to stand on the insole; however, they must put more pressure on either left or right foot and put pressure on another foot as small as possible. Once we received the data, we recorded the temperature at stable state and the average pressure value. These two data then were used as the values in the pressure-error-correction function and were analyzed if the differences between left and right foot for all measuring locations are smaller than the differences before we used pressure-error-correction function. Additionally, we used mean absolute error to check the deviations between the expected temperature differences and measured temperature differences between left and right foot before and after we applied general and individual pressure-error-correction function. Also, we calculated specificity to check how the general and individual pressure-error-correction functions improved the monitoring results

CHAPTER 3

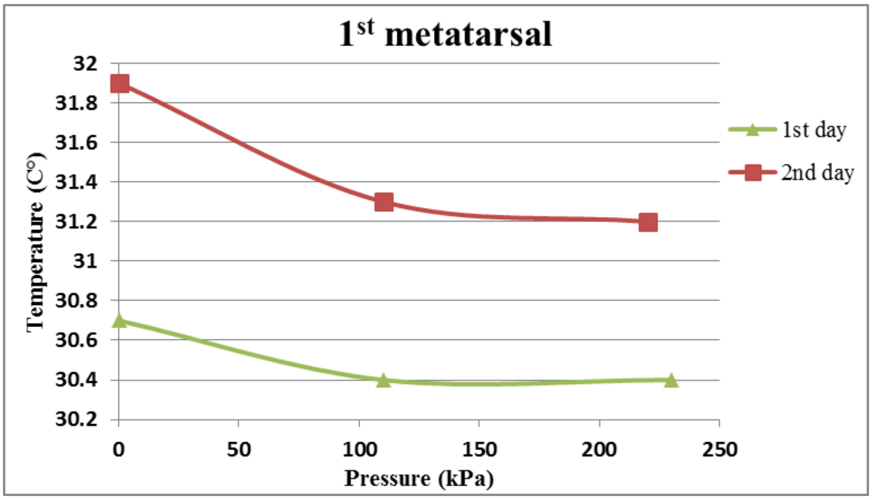
RESULTS

3.1 Repeatability Check

We first investigated two subjects who were tested twice to see repeatability of this experiment. As shown in figure 11(-1, -2), the trend is similar for all measuring locations. The temperature values were different; however, this was because the starting temperatures were different due to different ambient temperature. However, we were only focused on the trend, and these results proved that this experiment has repeatability, other subjects can be tested once.

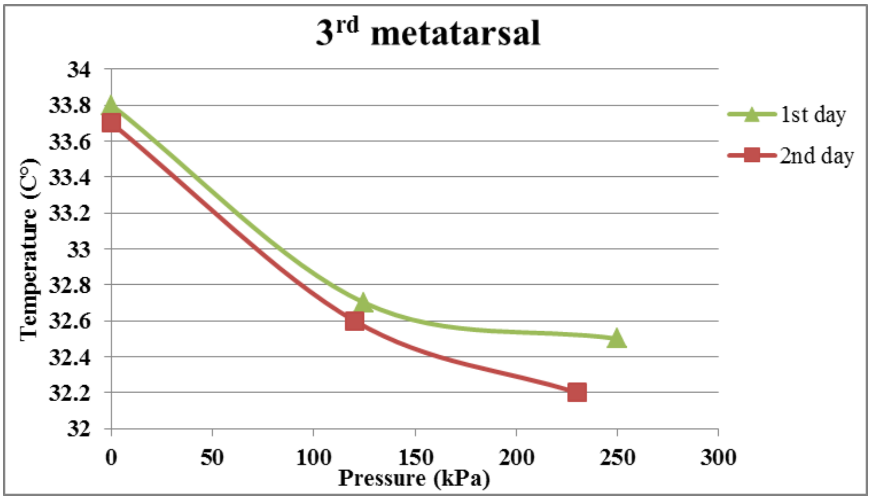


(a)

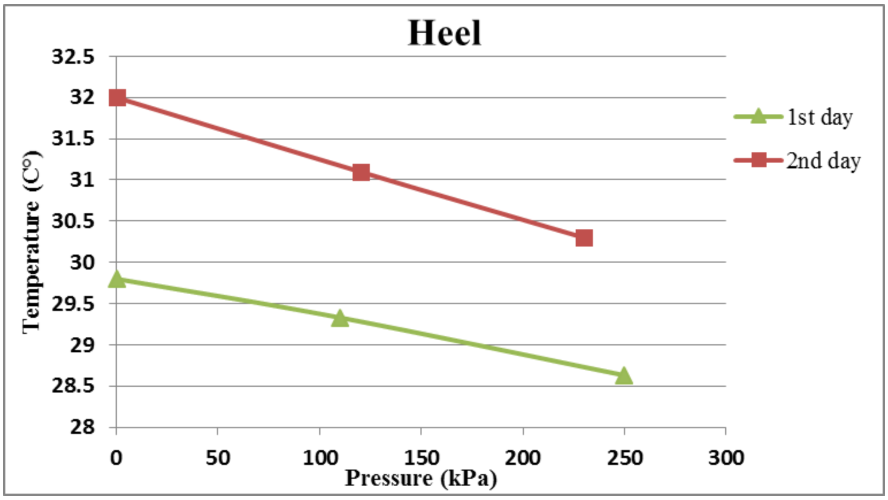


(b)

Figure 11-1. The repeatability of trend from measuring locations (a) Toe (b) 1st metatarsal



(a)

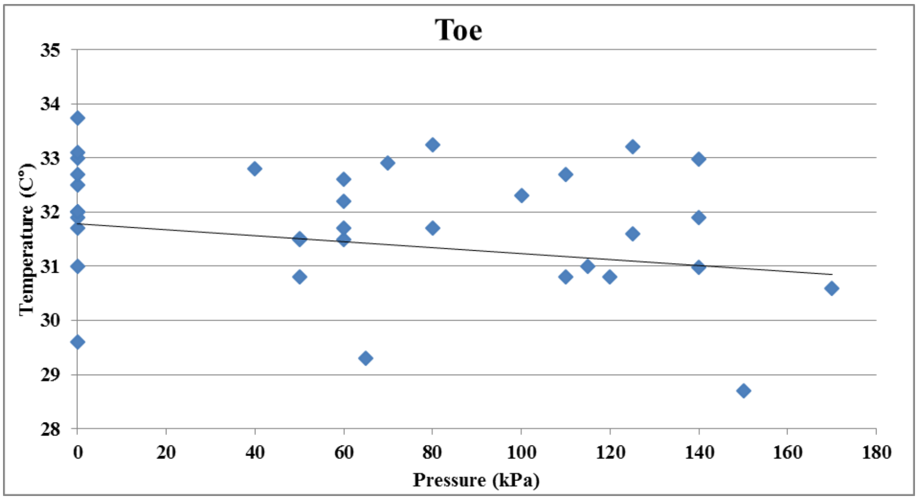


(b)

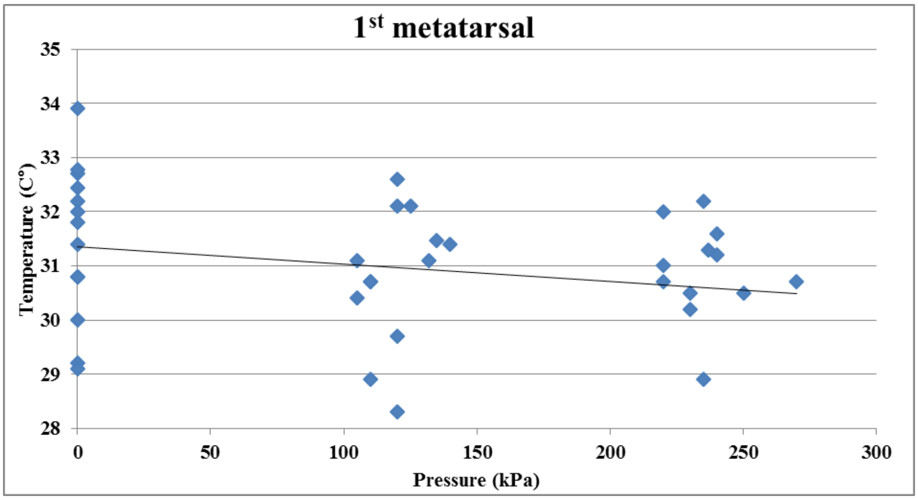
Figure 11-2. The repeatability of trend from measuring locations (a) 3rd metatarsal (b) Heel

3.2 The trend between pressure and temperature

As shown in figure 12(-1, -2) and in figure 13(-1, -2), the slopes of fitting line from all measuring locations were negative.

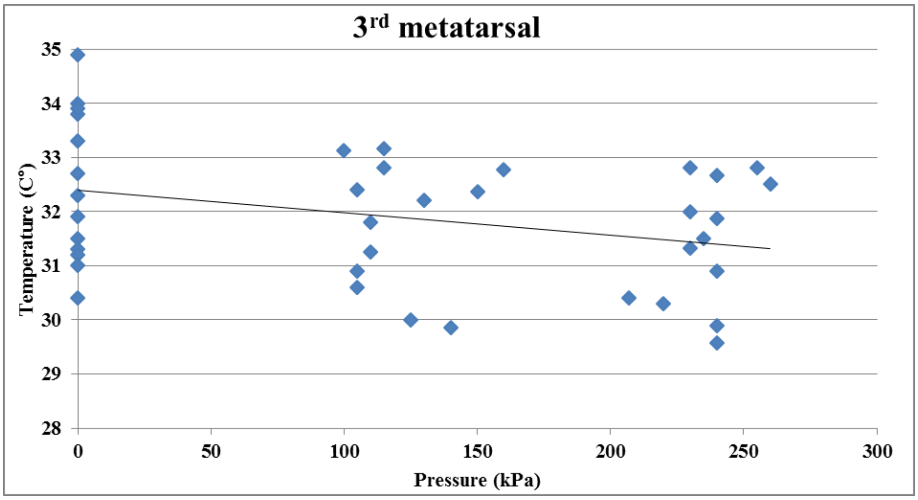


(a)

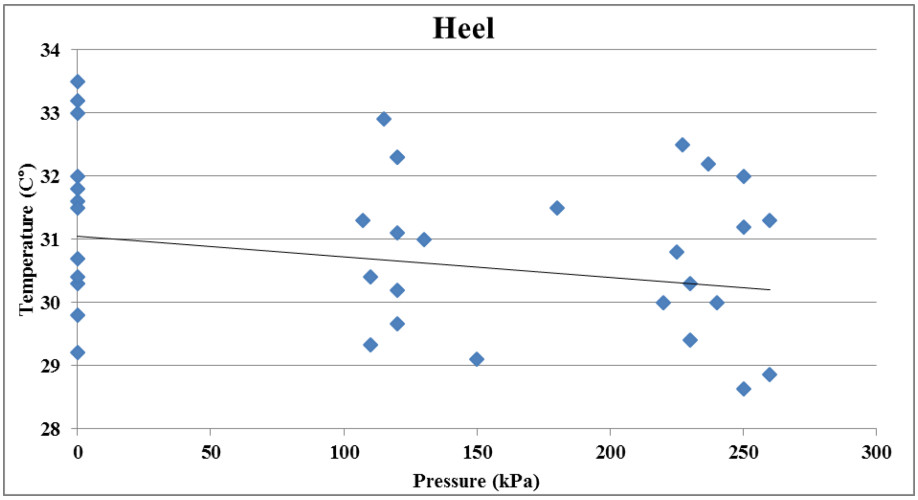


(b)

Figure 12-1. The trend of the relationship between pressure and temperature from measuring locations from left foot (a) Toe (b) 1st metatarsal

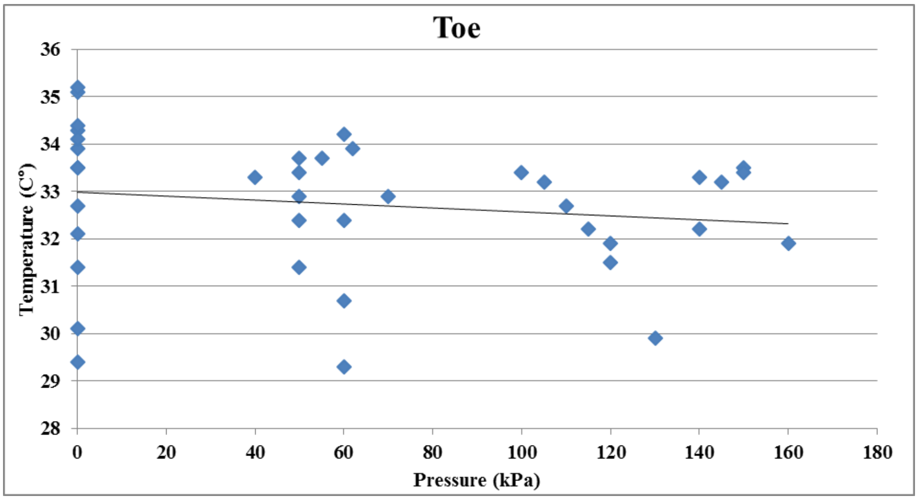


(a)

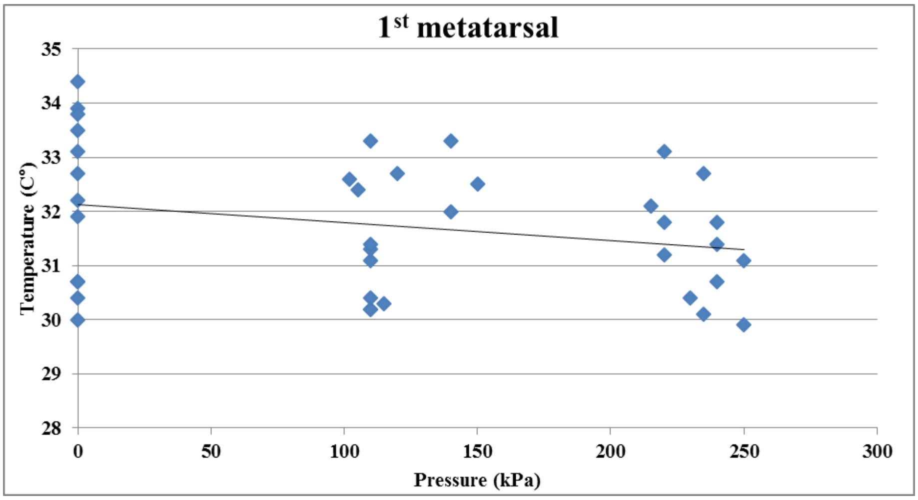


(b)

Figure 12-2. The trend of the relationship between pressure and temperature from measuring locations from left foot (a) 3rd metatarsal (b) Heel

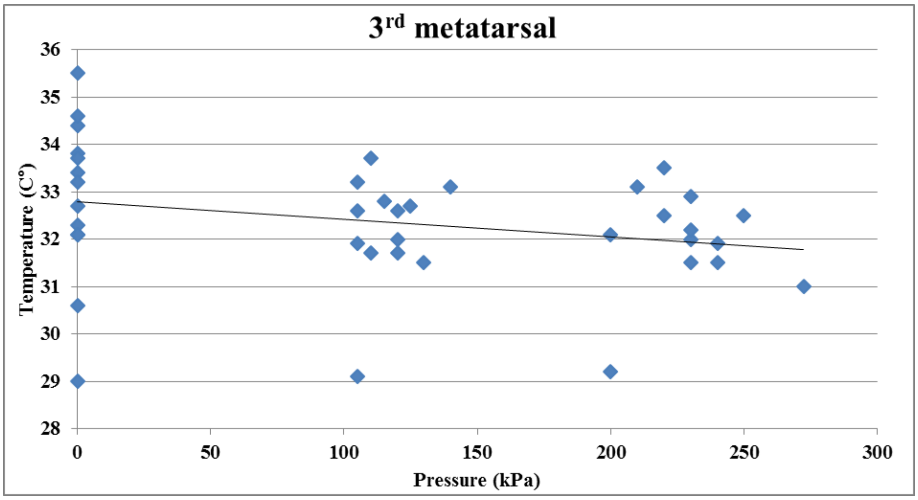


(a)

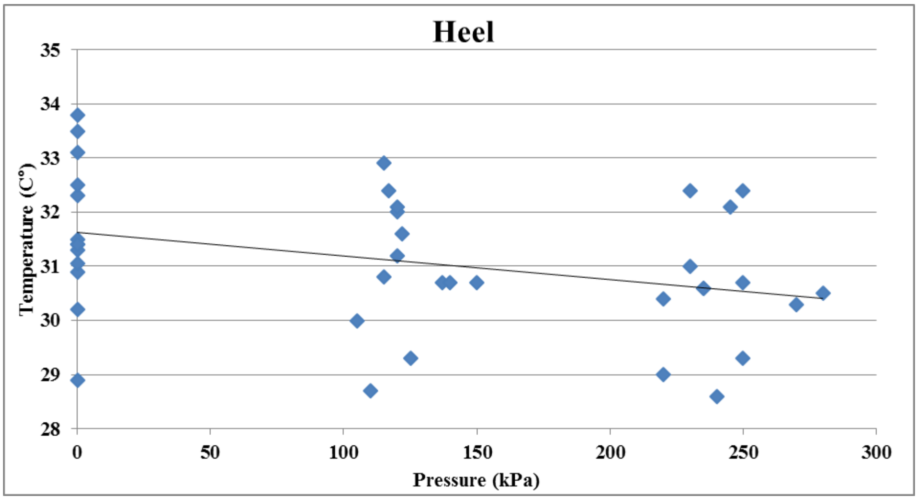


(b)

Figure 13-1. The trend of the relationship between pressure and temperature from measuring locations from right foot (a) Toe (b) 1st metatarsal



(a)



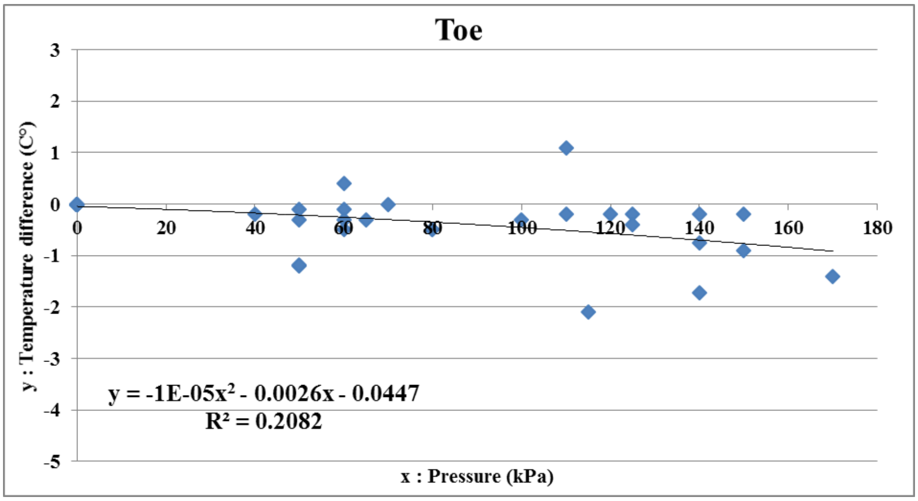
(b)

Figure 13-2. The trend of the relationship between pressure and temperature from measuring locations from right foot (a) 3rd metatarsal (b) Heel

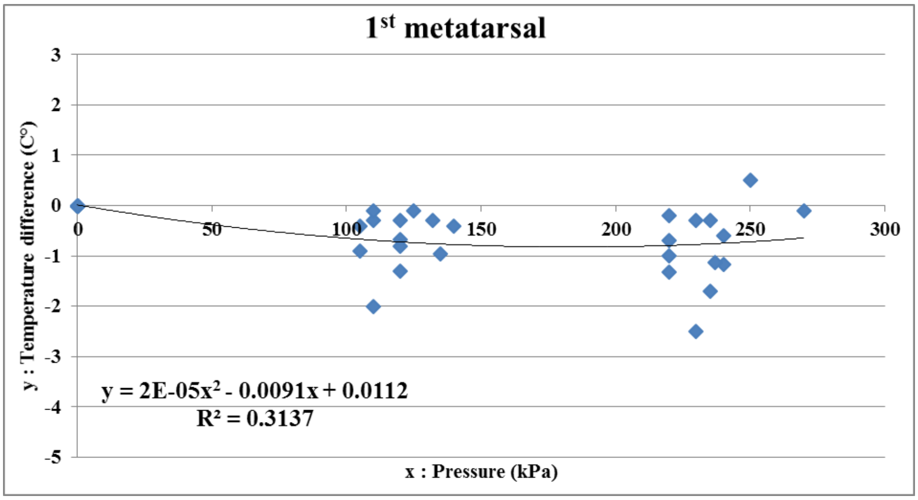
This proved that as the pressure on plantar surface increases, the plantar foot skin temperature decreases.

3.2 Applying pressure-error-correction function

The 2nd interpolation was used in this test because it had higher R^2 and gave less temperature difference than when 1st interpolation was used. Figure 14(-1, -2) and figure 15(-1, -2) represent how much the temperature changes from the temperature without pressure to the temperature with increased pressure on the plantar surface, and general pressure-error-correction functions are in table 3 and 4.

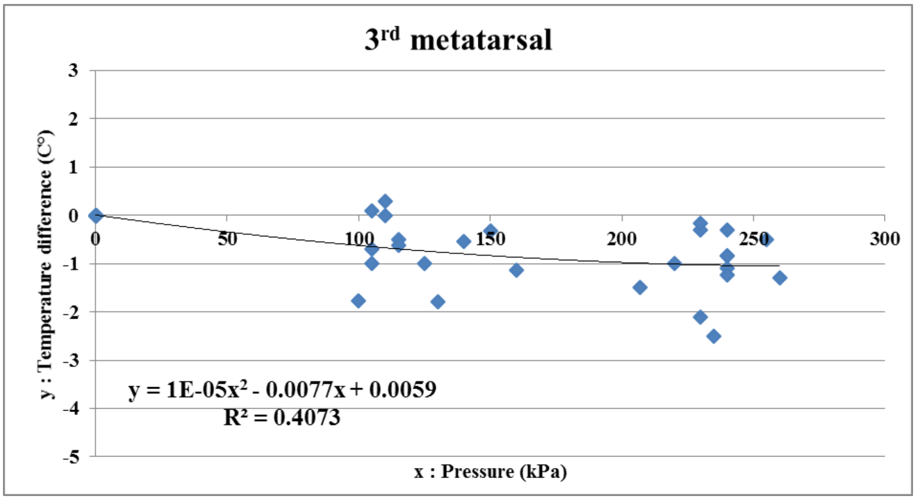


(a)

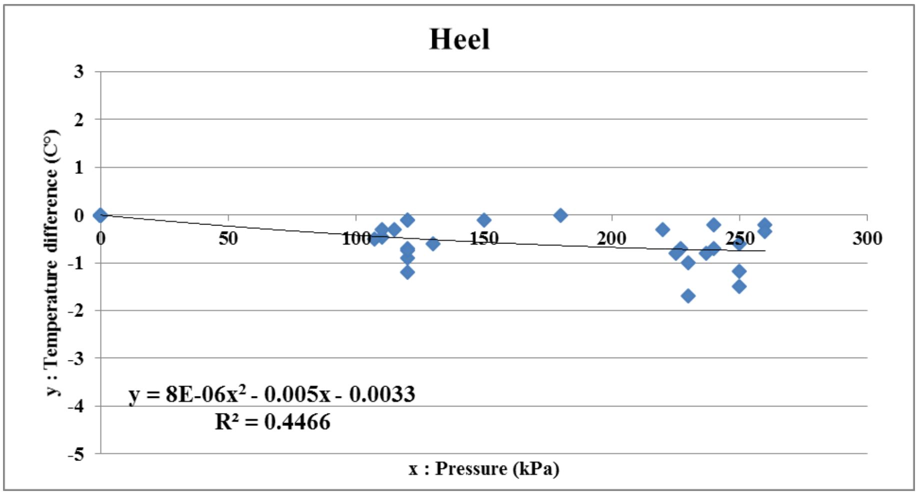


(b)

Figure 14-1. The trend of the relationship from left foot between amount of temperature changes and amount of pressure applied (a) Toe (b) 1st metatarsal



(a)

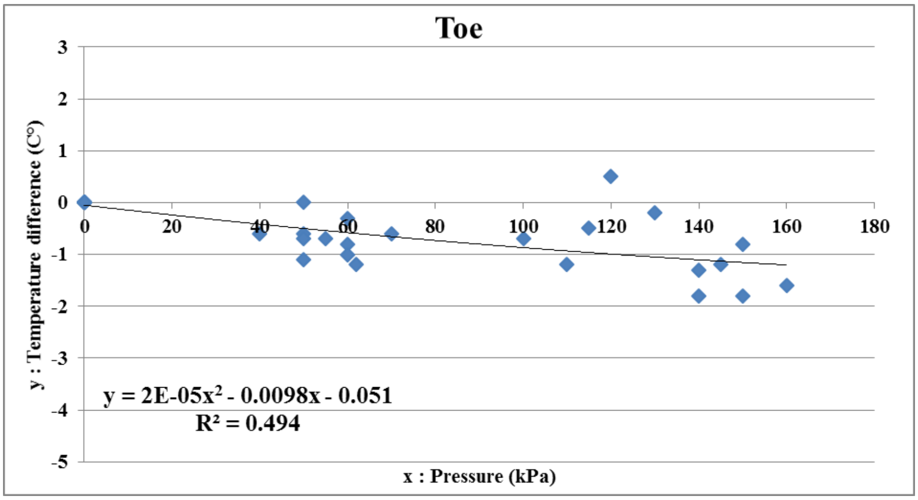


(b)

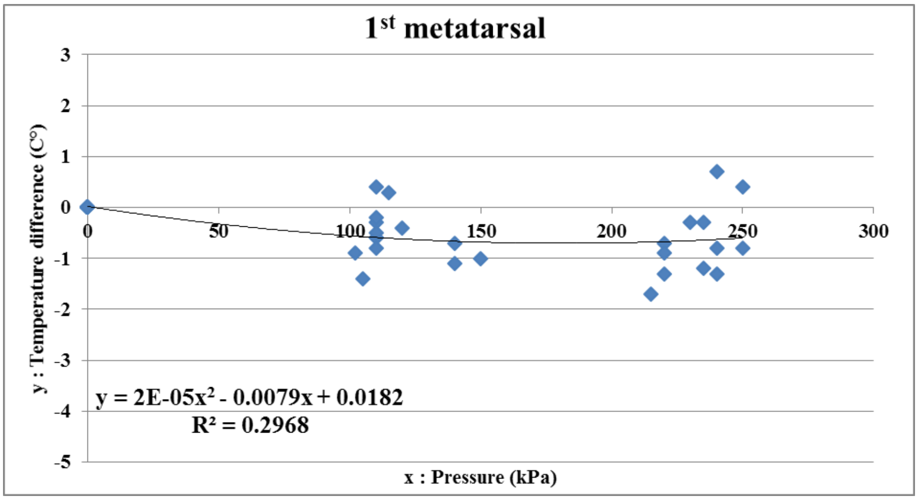
Figure 14-2. The trend of the relationship from left foot between amount of temperature changes and amount of pressure applied (a) 3rd metatarsal (b) Heel

Table 3. General pressure-error-correction function for left foot

Left	Pressure-error-correction function
Toe	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (-1\mathrm{E}^{-5} * x^2 - 0.0026 * x - 0.0447)$
1st metatarsal	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * x^2 - 0.0091 * x + 0.0112)$
3rd metatarsal	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * x^2 - 0.0077 * x + 0.0059)$
Heel	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (8\mathrm{E}^{-6} * x^2 - 0.005 * x - 0.0033)$

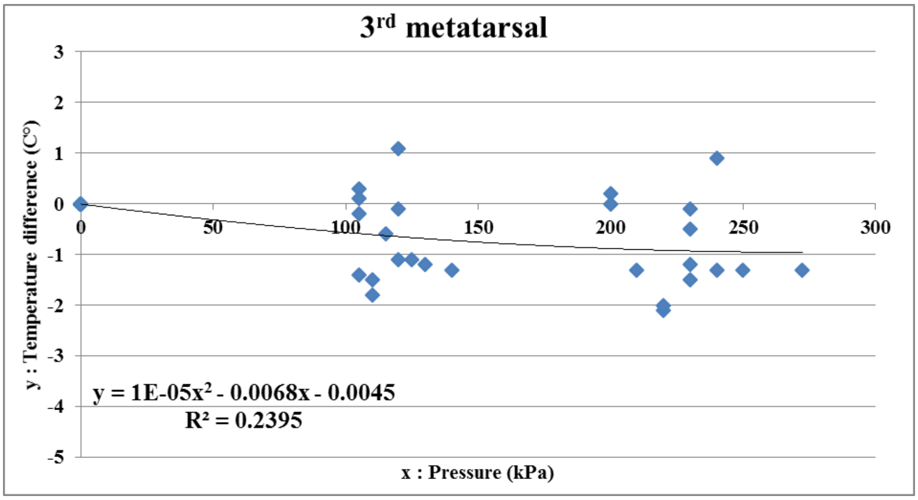


(a)

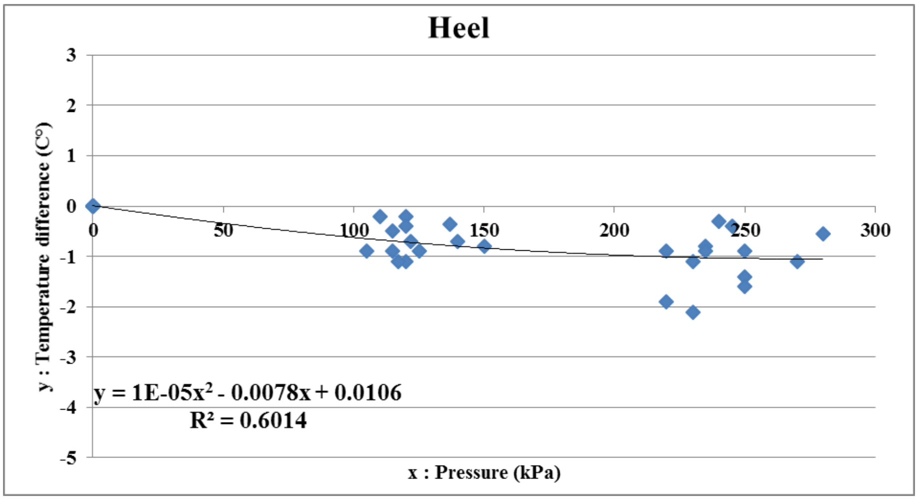


(b)

Figure 15-1. The trend of the relationship from right foot between amount of temperature changes and amount of pressure applied (a) Toe (b) 1st metatarsal



(a)



(b)

Figure 15-2. The trend of the relationship from right foot between amount of temperature changes and amount of pressure applied (a) 3rd metatarsal (b) Heel

Table 4. General pressure-error-correction function for right foot

Right	Pressure-error-correction function
Toe	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * x^2 - 0.0098 * x - 0.051)$
1st metatarsal	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * x^2 - 0.0079 * x + 0.0182)$
3rd metatarsal	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * x^2 - 0.0068 * x - 0.0045)$
Heel	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * x^2 - 0.0078 * x + 0.0106)$

The trends from all measuring locations were negative. Each equation represents the general pressure-error-correction functions and R^2 means how well the data were fitted into the model. However, since R^2 values are low, this means that the general function is not good enough to be used generally. This means that the pressure-error-correction function has to be made individually. Therefore, by using individual data, we got individual pressure-error-correction function and applied. To check whether the pressure-error-correction function actually reduce the error or not, we first asked subjects to put more pressure on either left or right foot and nearly no pressure on another foot, and the pressure distribution example is shown in figure 16.

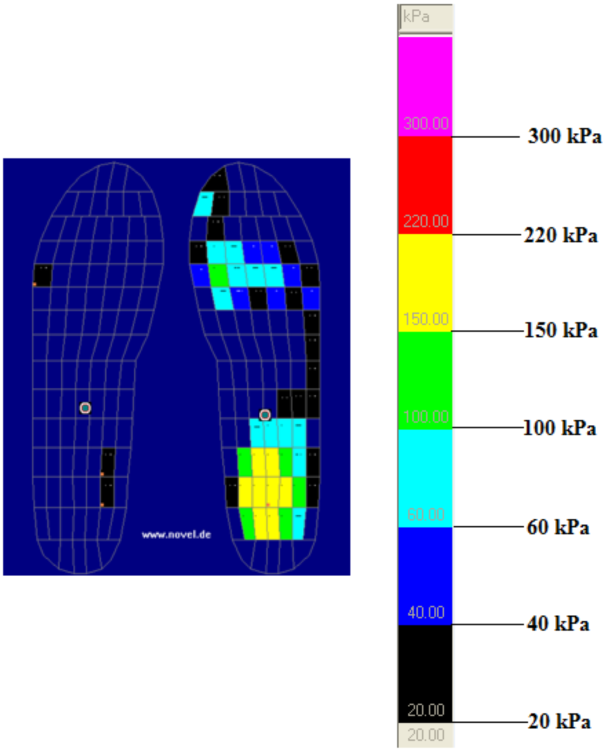


Figure 16. The pressure distribution when the subject puts more pressure on right foot

The differences between left and right foot before individual function was applied and the differences after individual function was applied are shown in table 5, 6, 7 and 8. All the pressure-error-correction functions are in Appendix (A).

Table 5. The differences between left and right toe before and after both general and individual pressure-error-correction functions are applied

	***Before** (C°)*	***After Correction (General)** (C°)*	***After Correction (Individual)** (C°)*
Toe			
Subject 1	0.80	0.25	0.01
Subject 2	0.70	0.29	0.03
Subject 3	1.10	0.33	0.28
Subject 4	0.80	0.23	0.13
Subject 5	0.50	0.17	0.16
Subject 6	0.80	0.31	0.02
Subject 7	0.40	0.24	0.08
Subject 8	1.20	0.79	0.26
Subject 9	0.50	0.05	0.22
Subject 10	0.90	0.24	0.02
Average	**0.77 ± 0.26**	**0.29 ± 0.19**	**0.12 ± 0.10**

Table 6. The differences between left and right 1st metatarsal before and after both general and individual pressure-error-correction functions are applied

	Before	***After Correction (General)** (C°)*	***After Correction (Individual)** (C°)*
1st metatarsal			
Subject 1	0.50	0.20	0.10
Subject 2	0.45	0.01	0.03
Subject 3	0.60	0.14	0.14
Subject 4	0.30	0.17	0.17
Subject 5	0.60	0.03	0.28
Subject 6	0.70	0.11	0.04
Subject 7	1.30	0.67	0.43
Subject 8	0.30	0.40	0.29
Subject 9	0.40	0.20	0.03
Subject 10	0.90	0.31	0.49
Average	**0.61 ± 0.31**	**0.22 ± 0.20**	**0.20 ± 0.17**

Table 7. The differences between left and right 3rd metatarsal before and after both general and individual pressure-error-correction functions are applied

	Before (C°)	*After Correction (General) (C°)*	*After Correction (Individual) (C°)*
3rd metatarsal			
Subject 1	0.40	0.11	0.01
Subject 2	0.70	0.27	0.01
Subject 3	1.40	0.92	0.04
Subject 4	0.50	0.21	0.00
Subject 5	1.10	0.81	0.40
Subject 6	0.50	0.02	0.01
Subject 7	1.00	0.45	0.18
Subject 8	1.30	0.60	0.11
Subject 9	0.60	0.22	0.13
Subject 10	1.20	0.47	0.06
Average	**0.87 ± 0.37**	**0.41 ± 0.28**	**0.10 ± 0.12**

Table 8. The differences between left and right heel before and after both general and individual pressure-error-correction functions are applied

	Before (C°)	*After Correction (General) (C°)*	*After Correction (Individual) (C°)*
Heel			
Subject 1	1.10	0.12	0.09
Subject 2	1.70	0.43	0.34
Subject 3	0.40	0.67	0.10
Subject 4	0.60	0.65	0.18
Subject 5	1.40	0.15	0.04
Subject 6	0.90	0.18	0.07
Subject 7	0.30	0.31	0.05
Subject 8	0.90	0.32	0.08
Subject 9	0.50	0.39	0.47
Subject 10	0.40	0.83	0.39
Average	**0.82 ± 0.47**	**0.42 ± 0.26**	**0.18 ± 0.16**

Some temperature differences were larger than 1.2 C° as shown in table 9 and when we applied pressure-error-correction function, the differences were returned to normal range.

Table 9. The temperature differences bigger than 1.2 C°

	Before (C°)	*After Correction (General) (C°)*	*After Correction (Individual) (C°)*
Toe			
	1.2	0.79	0.26
1st metatarsal			
	1.3	0.67	0.43
3rd metatarsal			
	1.4	0.92	0.04
	1.3	0.60	0.11
	1.2	0.47	0.06
Heel			
	1.7	0.44	0.34
	1.4	0.15	0.04

We also calculated mean absolute error and specificity as shown in table 10 and 11 respectively.

Table 10. Mean absolute error

	Before	*After Correction (General)*	*After Correction (Individual)*
Toe	**0.72**	**0.25**	**0.10**
1st metatarsal	**0.60**	**0.21**	**0.19**
3rd metatarsal	**0.84**	**0.38**	**0.11**
Heel	**0.79**	**0.37**	**0.16**

Table 11. Specificity

	Before (%)	*After Correction (General) (%)*	*After Correction (Individual) (%)*
Toe	90	100	100
1st metatarsal	90	100	100
3rd metatarsal	70	100	100
Heel	80	100	100

CHAPTER 4

DISCUSSIONS

4.1 Pressure effect on temperature

In this study, we proved that as the pressure on plantar foot surface increases, the plantar foot skin temperature decreases. The reason for this can be explained that when the pressure is applied on plantar foot surface, the blood flow gets lower [17]. As the blood flow gets lower, the skin temperature gets lower as well [18, 19]. This applies to all measuring locations as you can see in figure 12(-1, -2) and in figure 13(-1, -2).

4.2 Performance of pressure-error-correction function

As shown in figure 14(-1, -2) and in figure 15(-1, -2), as the pressure on the plantar foot surface increases, the difference between the temperature without pressure and the temperature with increased pressure is getting larger. To make pressure-error-correction function, we used two types of fitting line which are 1st and 2nd degree interpolation. By comparing these two functions, we decided to use 2nd degree interpolation because it has larger R^2 value and also gives less temperature difference between left and right foot. However, R^2 value is still not high enough to be used as general pressure-error-correction function. This is because the amount of temperature changes varies differently among the subjects which are hard to be fitted into the function. Therefore, this means that it will be more accurate if we make pressure-error-correction function individually. Of course we might need more subjects for R^2 value to be high enough to be used, but still it would be better to make individual pressure-error-correction function. When we tested the individual functions on each subjects, they putted more pressure on either left or right foot as shown in figure 16, and there were some temperature differences between left and right foot even though the subjects were normal. Especially, since this study applied the temperature difference of 1.2 C° between left and right foot as early diagnosis of foot ulcer followed by previous research [11], some measuring locations as shown in table 9, where the temperature difference showed more than 1.2 C° difference could be diagnosed as early stage of foot ulcer even though the person is normal. Of course, other measuring locations' temperature differences were still considered to be normal but they could lead to higher risk of getting error in the monitoring result as well. Therefore, when we applied pressure-error-correction function to this data, the differences became smaller as shown in table 5, 6, 7 and 8. As shown in table 10, mean absolute errors were decreased when we applied pressure-error- correction functions and also showed that individual pressure-error-correction functions are better than general pressure-error-correction functions. The specificities also showed that pressure-error-correction function improved the results as shown in table 11. This result proved that by making relationship function between pressure and amount of temperature changes, we can monitor plantar foot skin temperature with removal of pressure effect. This can also be used to the actual diabetic patients with foot ulcer because the difference between left and right foot is already large enough to be diagnosed as foot ulcer and even though there is the pressure applied on the plantar foot, there will still be big differences after the pressure-error-correction function is applied, so there will be less error for the diabetic patients as well. This study will help development in plantar skin temperature monitoring by sensor-embedded insole and be able to diagnose foot ulcer early.

4.3 Limitation

This study has some limitations because we hypothesized that the pressure is the only factor that affects the result. However, there are still other factors such as ambient temperature, humidity and in-shoe conditions that might change the result. This study is conducted in lab environment that the ambient temperature is nearly constant. Most of all, this study is just focused on the person standing on the insole, not on the person with dynamic activities such as walking and running. This will change in-shoe conditions and we are not sure that the pressure effect is different from when the person just stands. However, like how we applied pressure-error-correction function in this study, we can use this function no matter what the standing habit the person has.

APPENDIX

(A) Individual pressure-error-correction functions

$Temp_{fix}$: Temperature after the function is applied

$Temp_{meas}$: Temperature measured from thermistor

P : Pressure value

Toe	***Individual pressure-error-correction function***
Subject 1	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (3\mathrm{E}^{-5} * P^2 - 0.0155 * P - 3\mathrm{E}^{-15})$
Subject 2	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (9\mathrm{E}^{-5} * P^2 - 0.0211 * P - 0.0283)$
Subject 3	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (5\mathrm{E}^{-5} * P^2 - 0.0198 * P + 2\mathrm{E}^{-15})$
Subject 4	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (7\mathrm{E}^{-5} * P^2 - 0.0153 * P + 3\mathrm{E}^{-15})$
Subject 5	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (8\mathrm{E}^{-5} * P^2 - 0.0245 * P - 2\mathrm{E}^{-15})$
Subject 6	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (5\mathrm{E}^{-5} * P^2 - 0.0182 * P + 4\mathrm{E}^{-15})$
Subject 7	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (3\mathrm{E}^{-5} * P^2 - 0.0067 * P - 1\mathrm{E}^{-15})$
Subject 8	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-4} * P^2 - 0.0275 * P + 2\mathrm{E}^{-15})$
Subject 9	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (5\mathrm{E}^{-5} * P^2 - 0.0154 * P + 4\mathrm{E}^{-15})$
Subject 10	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-4} * P^2 - 0.02 * P + 2\mathrm{E}^{-15})$

1st metatarsal	***Individual pressure-error-correction function***
Subject 1	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (3\mathrm{E}^{-5} * P^2 - 0.0146 * P + 4\mathrm{E}^{-15})$
Subject 2	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (-2\mathrm{E}^{-5} * P^2 - 0.0063 * P - 0.0552)$
Subject 3	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * P^2 - 0.0113 * P)$
Subject 4	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * P^2 - 0.0066 * P - 4\mathrm{E}^{-16})$
Subject 5	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (-2\mathrm{E}^{-5} * P^2 - 0.0012 * P)$
Subject 6	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (-4\mathrm{E}^{-5} * P^2 - 0.0021 * P + 9\mathrm{E}^{-16})$
Subject 7	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * P^2 - 0.0099 * P + 4\mathrm{E}^{-16})$
Subject 8	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * P^2 - 0.0056 * P + 3\mathrm{E}^{-15})$
Subject 9	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (4\mathrm{E}^{-5} * P^2 - 0.0134 * P + 3\mathrm{E}^{-15})$
Subject 10	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (5\mathrm{E}^{-5} * P^2 - 0.0185 * P - 2\mathrm{E}^{-15})$

3^{rd} *metatarsal*	*Individual pressure-error-correction function*
Subject 1	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (9\mathrm{E}^{-6} * P^2 - 0.0053 * P - 7\mathrm{E}^{-16})$
Subject 2	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * P^2 - 0.0107 * P - 0.0133)$
Subject 3	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (7\mathrm{E}^{-5} * P^2 - 0.0236 * P + 8\mathrm{E}^{-15})$
Subject 4	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (3\mathrm{E}^{-5} * P^2 - 0.0124 * P - 4\mathrm{E}^{-15})$
Subject 5	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (3\mathrm{E}^{-5} * P^2 - 0.0168 * P + 2\mathrm{E}^{-15})$
Subject 6	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (3\mathrm{E}^{-6} * P^2 - 0.0059 * P - 1\mathrm{E}^{-15})$
Subject 7	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (4\mathrm{E}^{-5} * P^2 - 0.0165 * P + 9\mathrm{E}^{-16})$
Subject 8	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (3\mathrm{E}^{-5} * P^2 - 0.0133 * P + 2\mathrm{E}^{-15})$
Subject 9	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (4\mathrm{E}^{-5} * P^2 - 0.0145 * P + 2\mathrm{E}^{-15})$
Subject 10	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * P^2 - 0.0121 * P - 9\mathrm{E}^{-16})$

Heel	*Individual pressure-error-correction function*
Subject 1	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * P^2 - 0.0076 * P - 9\mathrm{E}^{-16})$
Subject 2	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * P^2 - 0.0105 * P + 0.0052)$
Subject 3	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (1\mathrm{E}^{-5} * P^2 - 0.0046 * P - 2\mathrm{E}^{-16})$
Subject 4	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * P^2 - 0.0064 * P - 2\mathrm{E}^{-15})$
Subject 5	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (-5\mathrm{E}^{-6} * P^2 - 0.0051 * P + 3\mathrm{E}^{-15})$
Subject 6	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (-3\mathrm{E}^{-5} * P^2 - 0.004 * P + 9\mathrm{E}^{-16})$
Subject 7	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (4\mathrm{E}^{-5} * P^2 - 0.0031 * P - 7\mathrm{E}^{-15})$
Subject 8	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (7\mathrm{E}^{-6} * P^2 - 0.006 * P - 2\mathrm{E}^{-15})$
Subject 9	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * P^2 - 0.0097 * P - 2\mathrm{E}^{-15})$
Subject 10	$\mathrm{Temp_{fix}} = \mathrm{Temp_{meas}} - (2\mathrm{E}^{-5} * P^2 - 0.008 * P + 2\mathrm{E}^{-15})$

REFERENCES

1. Diabetes: Facts and Figures [Internet]. [Place unknown]: International Diabetes Federation; 2013 [cited 2013 June 10]. Available from http://www.idf.org/

2. Singh N, Armstrong DG and Lipsky BA. Preventing foot ulcers in patients with diabetes. J Amer Med Assoc [Internet]. 2005 [cited 2013 June 10] Available from The JAMA Network with Full Text: http://jama.jamanetwork.com/article.aspx?articleid=200119

3. Preventing chronic diseases: Investing wisely in health Preventing diabetes and its complications [Internet]. [Place Unknown]: Centers for Disease Control and Prevention; 2008 [cited 2013 June 10]. Available from: http://www.cdc.gov/

4. Veves A, Murray HJ, Young MJ and Boulton AJM. The risk of foot ulceration in diabetic patients with high foot pressure: a prospective study. Diabetologia [Internet]. 1992 [cited 2013 July 14]; 35 (7): 660-663. Avilable from Springer Link: http://link.springer.com/article/10.1007%2FBF00400259

5. Livesley NJ and Chow AW. Infected pressure ulcers in elderly individuals. Aging and Infectious Diseases [Internet]. 2002 December [cited 2013 September 3]; 35(11): 1390-1396. Available from Oxford Journals with Full Text: http://cid.oxfordjournals.org/content/35/11/1390.full

6. Fierheller M and Sibbald RG. A clinical investigation into the relationship between increased periwound skin temperature and local wound infection in patients with chronic leg ulcers. Advances in Skin and Wound Care [Internet]. 2010 August [cited 2014 March 20]; 23(8): 369-379. Available from Wolters Kluer Health: http://ovidsp.tx.ovid.com/sp-3.12.0b/ovidweb.cgi?T=JS&PAGE=fulltext&D=ovft&AN=00129334-201008000-00008&NEWS=N&CSC=Y&CHANNEL=PubMed

7. Archer AG, Roberts VC and Watkins PJ. Blood flow patterns in painful diabetic neuropathy. Diabetologia [Internet]. 1984 [cited 2013 July 14]; 27(6): 563-567. Available from Springer Link: http://link.springer.com/article/10.1007%2FBF00276968

8. Houghton VJ, Bower V and Chant DC. Is an increase in skin temperature predictive of neuropathic foot ulceration inpeople with diabetes? A systematic review and meta-analysis. Journal of Foot and Ankle Research [Internet]. 2013 [cited 2013 September 3]; 6(31). Available from Journal of Foot and Ankle Research with Full Text: http://www.jfootankleres.com/content/6/1/31

9. Petrova NL, Bixton-Thomas M, Moniz C, Bates M, Elias DA and Edmonds ME. Is there a systemic inflammatory response in the acute charcot foot. Diabetes Care [Internet]. 2007 April [cited 2013 August 20]; 30(4): 997-998. Available from Diabetes Care with Full Text: http://care.diabetesjournals.org/content/30/4/997.full

10. Lavery LA, Zamorano RG, Higgins KR, Athanasiou KA, Lanctot DR, Armstrong DG et al. Preventing diabetic foot ulcer recurrence in high-risk patients Use of temperature monitoring as a self-assessment tool. Diabetes Care [Internet]. 2007 Jan [cited 2013 August 20]; 30(1): 14-20. Available from Diabetes Care with Full Text: http://care.diabetesjournals.org/content/30/1/14.full

11. Nishide K, Nagase T, Oba M, Oe M, Ohashi Y, Lizaka S et al. Ultrasonographic and thermographic screening for latent inflammation in diabetic foot callus. Diabetes Research and Clinical Practice [Internet]. 2009 September [cited at 2014 March 12]; 85(3): 304-309 Available from ScienceDirect: http://www.sciencedirect.com/science/article/pii/S0168822709002460

12. Armstrong DG, Holtz-Neiderer K, Wendel C, Mohler MJ, Kimbriel HR and Lavery LA. Skin temperature monitoring reduces the risk for diabetic foot ulceration in high-risk patients. The American Journal of Medicine [Internet]. 2007 December [cited 2013 July 14]; 120(12): 1042-1046. Available from Elsevier Science with Full Text: http://www.sciencedirect.com/science/article/pii/S0002934307007395

13. Benbow SJ, Chan AW, Bowsher DR, Williams G and Macfarlane IA. The prediction of diabetic neuropathic plantar foot ulceration by liquid-crystal contact thermography. Diabetes Care [Internet]. 1994 August [cited 2013 August 20]; 17(8): 835-839. Available from Diabetes Care: http://care.diabetesjournals.org/content/17/8/835.short

14. Roback K, Johansson M and Starkhammer A. Feasibility of a thermographic method for early detection of foot disorders in diabetes. Diabetes Technology and Therapeutics [Internet]. 2009 October [cited 2013 June 12]; 11(10): 663-667. Available from Mary Ann Liebert, Inc.: http://online.liebertpub.com/doi/abs/10.1089/dia.2009.0053?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_dat=cr_pub%3dpubmed

15. Morley RE, Richter EJ, Klaesner JW, Maluf JW and Mueller MJ. In-Shoe Multisensory Data Acquisition System. IEEE Trans Biomed Eng [Internet]. 2001 July [cited 2013 July 2]; 47(7): 815-820. Available from IEEE Xplore: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=930906

16. Maluf KS, Morley RE, Richter EJ, Klaesner JW and Mueller MJ. Monitoring In-Shoe plantar pressures, temperature and humidity: Reliability and Validity of measures from a portable device. Archives of Physical Medicine and Rehabilitation [Internet]. 2001 August [cited 2013 July 2]; 82(8): 1119-1127. Available from ScienceDirect: http://www.sciencedirect.com/science/article/pii/S0003999301922348

17. Fromy B, Abraham P, Bouvet C, Bouhanick B, Fressinaud P and Saumet JL. Early decrease of skin blood flow in response to locally applied pressure in diabetic subjects. Diabetes [Internet]. 2002 April [cited 2013 July 24]; 51(4): 1214-1217. Available from Diabetes with Full Text: http://diabetes.diabetesjournals.org/content/51/4/1214.full

18. Rowell LB. Competition between skin and muscle for blood flow during exercise. In: Ethan Nadel, editor. Problems with Temperature Regulation During Exercise. New York: Academic Press, Inc.; 1977. p. 49-76.

19. Awwad AM, White RJ, Webster MH and Vance JP. The effect of temperature on blood flow in island and free skin flaps: an experimental study. British Journal of Plastic Surgery [Internet]. 1983 July [cited 2014 March 11]; 36(3): 373-382. Available from ScienceDirect: http://www.sciencedirect.com/science/article/pii/S0007122683900644

국문 초록

서론: 발 건강을 모니터링 하는 것은 몸의 종합적인 건강상태를 알려 준다. 특히 발바닥에 가해지는 압력과 피부 온도를 모니터링 함으로서 당뇨로 인한 족부 궤양의 조기 진단이 가능하다. 이러한 이유로 센서가 부착된 깔창을 사용함으로써 일상생활에서도 모니터링을 하는 연구가 진행되었었지만 피부온도를 모니터링 하는 데에 있어서 영향을 주는 요소들로 인하여 특히 양 발의 대응점 (엄지, 1st, 3rd 중족 그리고 뒤꿈치)에서의 차이 (≥1.2 C˚ 차이로 족부 궤양의 조기발견)를 모니터링 하는데 있어서 잘못된 결과를 줄 수 있다. 이 연구에서는 오직 압력만을 오차 요소로 두고 압력이 발바닥 피부온도에 어떠한 영향을 주는지 알아보고 압력으로 인한 오차를 줄이는 방법을 제시하였다.

방법: 실험을 하는 데에 앞서서 서미스터 (thermistor)를 25 도에서 40 도사이에서 온도교정을 하였다. 그리고 이 서미스터를 깔창에 부착하여 이 깔창을 사용하여 발바닥의 관심 부위, 즉 엄지, 1st, 3rd 중족 그리고 뒤꿈치의 피부온도를 측정하였다. 압력에는 압력센서를 이용하여 세 단계의 압력 (무압력, 기준, 집중)을 발바닥의 관심부위에서 측정하였고 각 단계에서 서미스터에서 받은 전압 값을 매트랩을 사용하여 서미스터 교정에서 얻은 식들을 사용하여 온도로 전환하였다. 데이터를 받은 후 압력이 증가할수록 온도가 어떻게 변하는지 경향을

분석하고 또한 압력값과 온도변화량 간의 관계도 분석하여 오차를 줄이는 압력보정함수를 얻을 수 있었다. 그리고 피험자에게 왼발이나 오른발에 다른 발보다 더 큰 압력을 주었을 때 이 함수를 사용하여 과연 얼마나 오차를 줄일 수 있는지도 확인실험을 하였다.

결과: 실험 결과 압력이 증가할수록 피부 온도가 감소하는 것이 보여졌다. 이것은 곧 사람 몸의 다른 부위의 피부온도가 압력의 영향 때문에 생기는 혈류의 감소로 인해 받는 경향과 비슷하다는 것을 보여준다. 또한 실험을 통해 얻은 압력보정함수를 이용하여 피험자에게 적용을 하였을 때 오차가 줄어드는 결과를 보여주었고 이것은 이 방법을 사용하면 오경보 (false alarm)의 확률을 줄일 수 있다는 것을 뜻한다.

고찰: 이 연구는 발바닥에 주어지는 압력으로 인해 피부온도가 줄어드는 것을 보여주었다. 또한 압력보정함수를 제안함으로써 압력으로 인한 피부온도 변화량의 오차를 줄이는 것을 보여주었다. 센서가 부착된 깔창에 이 압력보정함수를 적용하면 사람이 어떠한 서있는 습관에서도 올바른 결과를 낼 수 있다는 것을 보여주었다.

주요어 : 헬스케어, 무구속 측정, 피부온도, 압력보정함수, 족부궤양

학 번 : 2012-23291