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Determination Of The Dynamic Behavior Of Subjects With Diabetic Neuropathy

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DETERMINATION OF THE DYNAMIC BEHAVIOR OF SUBJECTS WITH DIABETIC NEUROPATHY

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DETERMINATION OF THE DYNAMIC BEHAVIOR OF SUBJECTS WITH DIABETIC NEUROPATHY

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Abstract

The diabetic foot is one of the most feared complications of diabetes [3]. Causes of a diabetic foot come from many disorders including diabetic neuropathy, peripheral vascular disease, charcot's neuropathy, foot ulceration, and limb amputation [4]. Statistics have revealed that 8.3 percent of population in the U.S. is affected by diabetes in 2010, i.e., 25.8 million people. About 60 percent to 70 percent of people with diabetes have mild to severe forms of nervous system damage [13]. There is an enormous impact on the physical and mental health of patients who suffer from diabetes.

This research was to determine the dynamic behavior that can provide a quantitative assessment with fuzzy similarity which will help medical doctors by providing quantitative comparison between healthy and diabetic subjects. The ground reaction forces were obtained from an instrumented treadmill from Bertec, muscle activity was obtained using 16 wireless sensors from DELSYS, lower extremity angle measurement (Joint Kinematics) was obtained by LIMA Smart Goniometer designed at LIMA Lab at UTEP, foot sole pressure was obtained using F-scan system by TEKSCAN and finally, a monofilament test was performed using a Semmes-Weinstein monofilament set. With this study the diabetic patients' quality of life (QOL) is improved.

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Chapter 1: Introduction

1.1 Overview of Diabetic Neuropathy

Diabetes is a medical condition caused by high blood sugar. It could be due to the disability of the human body to produce enough insulin, or cells not responding to the insulin which is being produced. According to Centers for Disease Control and Prevention, Diabetes leads to severe complications and early death [12].

Diabetic foot is one of the most feared complications of diabetes [3]. Diabetic Foot does not derivate from a single pathology, it is caused by many disorders including diabetic neuropathy, peripheral vascular disease, Charcot's neuropathy, foot ulceration, and limb amputation [4].

The two major characteristics which result in diabetic neuropathy are: age of the patient and the duration of disease. The lack of glycemic care makes the neuropathy worse.

Neuropathy is a progressive loss of the nerve fibers which affects autonomic and somatic divisions of the nervous systems. There are two branches in sensory-motor neuropathy, they are: painful peripheral neuropathy and painless neuropathy. In the two branches of neuropathy, painless neuropathy is the larger contributor to diabetic foot ulceration and the symptoms affects gait cycle, increases the plantar pressure and deforms the foot structure (cavus foot, hammer toes, etc). It is a fact that, 60-70% of people with diabetes have mild to severe forms of nervous system damage, which reduces the capability of sensing, develops pain in the feet and hands, slows down the digestion, and may result in carpal tunnel syndrome, erectile dysfunction, or any other nerve problems [12]. Excessive pressure on foot causes callus, and if the excessive pressure continues, then it results in the formation of ulcer. Presence of ulceration on foot is a high indicator of loss of sensation and is a consequence of nerve damage. This is preceded by ulcer infection, and amputation.

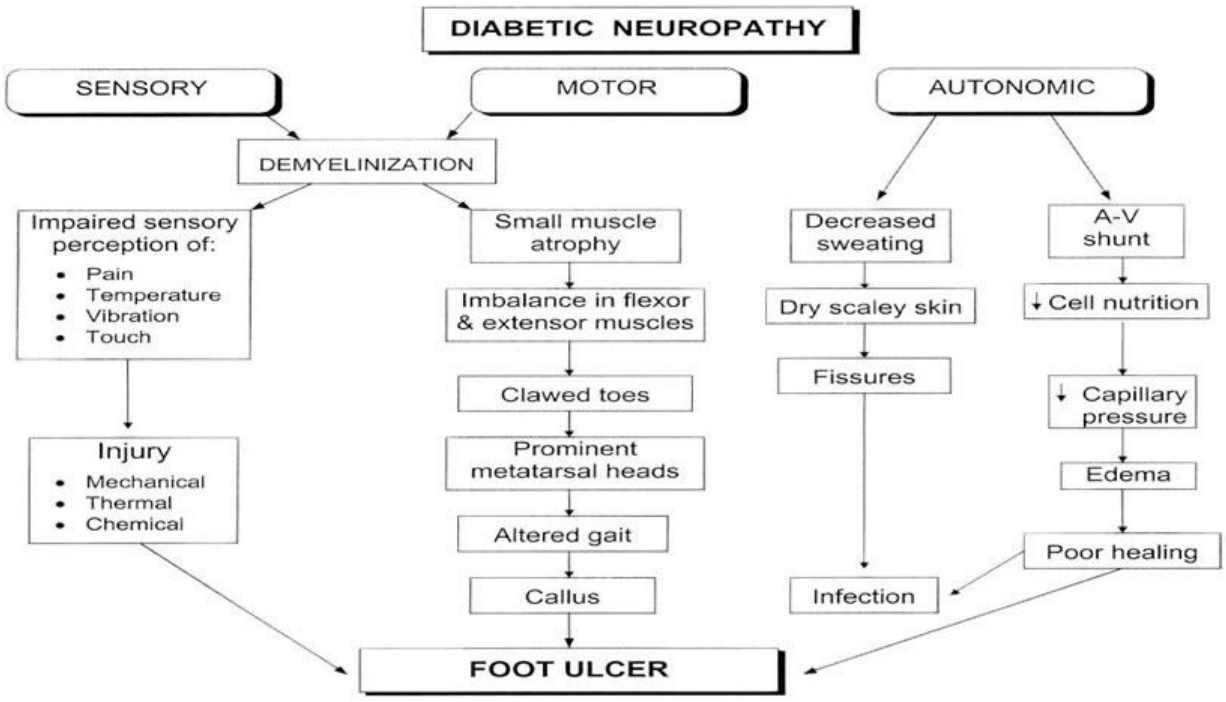


Figure 1.1: Pathway to Ulceration [24].

1.2 Background and Significance

Statistics have revealed that 8.3 percent of the population in the U.S. is affected by diabetes in 2010, i.e., 25.8 million people (As shown on Figure 1.2). About 60 percent to 70 percent of people with diabetes have mild to severe forms of nervous system damage [13]. We can evidently observe the population that suffers from Diabetes Mellitus is increasing.

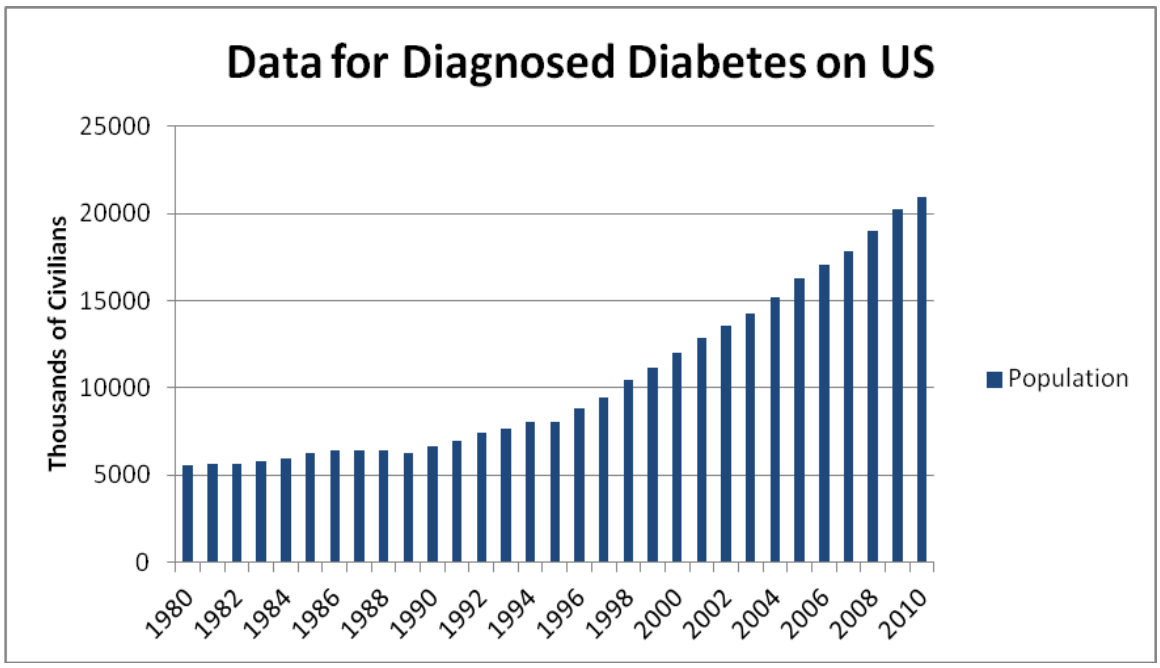


Figure 1.2: Population Diagnosed With Diabetes Mellitus from 1980 to 2010[13].

One out of ten persons in the U.S. suffers from diabetes and was predicted to increase to one out of three persons by the year 2050. In the amputations performed in 2010, 60% of them were lower limb amputations which were caused by diabetes mellitus complications [12]. There is an enormous impact on physical and mental health on patients.

1.3 Specific Aims

This research is to compare healthy subjects' and diabetes mellitus patients' gait analysis during walking. Diabetic foot strongly affects gait patterns, lower extremity muscle activity, joint angles (joint kinematics), kinetics (study of ground reaction forces), and foot pressure.

The specific aims of this research are listed below:

1. To obtain gait pattern through GRFs, sEMG and Goniometer signals for the comparison between the control group and diabetes mellitus patients. In order to accomplish this, the gait cycles will be extracted from the GRF data which is obtained from the instrumented treadmill, in which, this data will be synchronized to help extract the gait cycles for the

sEMG and Goniometer signals. By comparison of data, pattern information should show discrepancies in muscle activity, differences in range of motion in joints, and GRF, for the patients with diabetes.

2. To obtain the average peak foot pressure using F-scan and compare the data between healthy control group and diabetes mellitus patients. This information can be useful to determine, if there is neuropathy on lower limbs.
3. To detect if neuropathy could be found in patients with diabetes mellitus using the monofilament test.
4. To determine dynamic behavior to provide a quantitative assessment with fuzzy similarity which will help medical doctors by providing a quantitative comparison between healthy and diabetic subjects.

1.4 Hypothesis

Because diabetes neuropathy strongly alters the gait cycle, early or delay activation on muscle activity could be present. Due to this alteration, stance and swing phase periods could be affected. A lower range of motion on joint angles for ankle is expected to be present on patients who have developed a neuropathy [1][23].

Chapter 2: State of the Art

The Diabetes Mellitus community has been increasing with the years. Researchers have conducted different studies such as gait analysis, and foot pressure assessments on foot sole to determine severity of Diabetes Neuropathy. These studies include different sensors such as surface Electromyography (sEMG), Ground Reaction Forces, Goniometer, Semmes-Weinstein Monofilament and Kinetics Dynamics.

2.1 Ground Reaction Forces

Ground Reaction Forces are the forces exerted on the X, Y, and Z plane. These planes are also known as the Mediolateral, Anterior Posterior, and Vertical planes which are analyzed. These forces can be measure with different instrument like force plates, insoles, and an instrumented treadmill. Researchers have demonstrated that *"patients with diabetes have a higher peak on horizontal braking force walking with shoes compared to barefoot". "The diabetic individuals may be adopting a strategy to increase the sensitive inputs by increasing the force when the contact their heel to the floor*" [22]. In other study, researchers have found that diabetes mellitus patients, who have suffered ulceration in the past, show a lower second GRF [23].

2.2 Electromyography

Carine H. and their research group have found that the peroneal and tibial muscle tends to suffer from weakness in patients with Diabetic Neuropathy and Diabetic Ulcer history when compared with subjects with no diabetes mellitus history or with diabetes history without neuropathy [4]. Also I.C.N. Sacco *"has shown that diabetic patients presented important delays in the activation of the tibialis anterior bilaterally and vastus lateralis during gait in treadmill. Because of these delays, Sacco and Co. have interpreted that mechanisms of mechanical loads and shocks attenuation could be collapsed"* [7][22][23].

2.3 Goniometer

The mechanical goniometers are used in the clinics, and the range of motion (ROM) of the joint can be evaluated. Results presented by Muller on 1994 showed that diabetic patients have less ankle mobility, ankle power, velocity, and stride length during walking. *"Angle range motion on this study the patient were positioned on prone position on a treatment table with an standard goniometer with the scale mark in 2 degree increments*" [1][23]. A standard goniometer limits the measurement to one axis and this subjective angle measurement cannot obtain the ROM from the dynamic locomotion. Figure 3.1 displaying dorsiflexion and plantar flexion on subtalar joint.

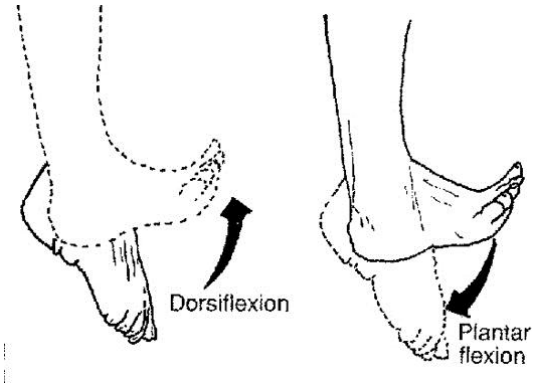


Figure 2.1: Displaying Dorsiflexion and Plantar Flexion of Subtalar Joint.

2.4 F-scan

"In order to prevent ulcers, causes for skin stress on foot sole are due to Diabetic Neuropathy measurements of foot pressure which is useful. Variability on gait parameters can be increased due to stride step force and stride length"[14][15]. A study where the F-scan was used has shown that *"patients with previous amputation of the great toe have increased their pressure on their pressures points. The first metatarsal pressure point was increased by approximately one third compared with a no amputation group. The lesser metatarsals have increased to double according to the no amputation group, and lesser for toes where pressure was a little bit greater than the double of the no amputation group"* [25].

2.5 Semmes-Weinstein Monofilament

Semmes-Weinstein monofilaments are nylon monofilaments that are precisely calibrated. A study conducted with monofilaments concluded that Semmes-Weinstein monofilament tests are reliable, and low cost test. Pressure sensation is usually assessed with a 10g nylon monofilament to identify people at increased risk of ulceration [3]. Another study included a control group(CG), diabetes group with no ulceration (DG), diabetes group with previous ulceration(DU), and diabetes group with neuropathy(DN) which said that the *"DU performed worse on sensory testing perception, in which sensory neuropathy contributes more to the etiology of diabetic foot ulceration than foot deformity"* [4]. On the other hand, researchers have found that *"the accuracy of monofilaments to produce a buckling force of 10 grams varies among manufacturers. Bailey Instruments and Owen Mumford filaments were the most accurate with a 100 percent buckling within ±1.0 g of 10 g. Only 70 percent of Semmes-Weinstein monofilaments buckled within ±1.0 g of 10 g"* [26].

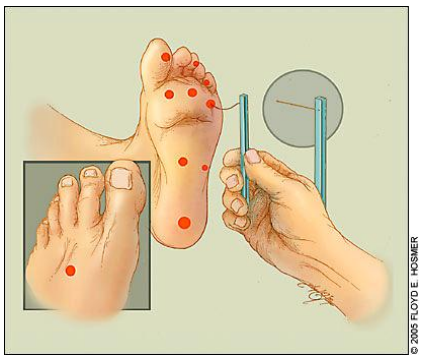


Figure 2.2: Assessment of monofilament test on different pressure point areas.[16]

2.6 Vibration Perception Threshold

Vibration perception threshold (VPT) is increasingly used as a measure of large nerve fiber function in studies of patients with diabetes and in other neurological disorders.

Medical researchers and scientist have been using this assessment with different devices; Vibratron II, and Biothensiometer. Vibratron II produces vibrations with amplitude ranging from 0.005-200 microns, which is expressed as 0.1 to 20 vibration units. Figure 3.3 shows Vibratron II. Vibration is

also commonly used to test perception sensation. Using a 128Hz tuning fork, *"There is evidence to suggest that the tunning fork is less predictive of foot ulceration compared to the monofilament"[3]. There also results from other study showing that patients with a VPT les that 15 V had a cumulative incidence of foot ulceration of 2.9 percent compared with a 19.8 percent in patients with VPT greater than 25V" [27].*

Figure 2.3: Vibratron II from Physitemp Instruments, Inc.

Chapter 3: Experimental Design

This experiment has been designed to collect data from five different sensors and correlated to identify diabetic neuropathy and its severity. These results are intended to show diabetic patient's conditions with quantitative results regarding the diabetic foot. To accomplish this objective, the experiment has been designed as shown in figure 3.1.

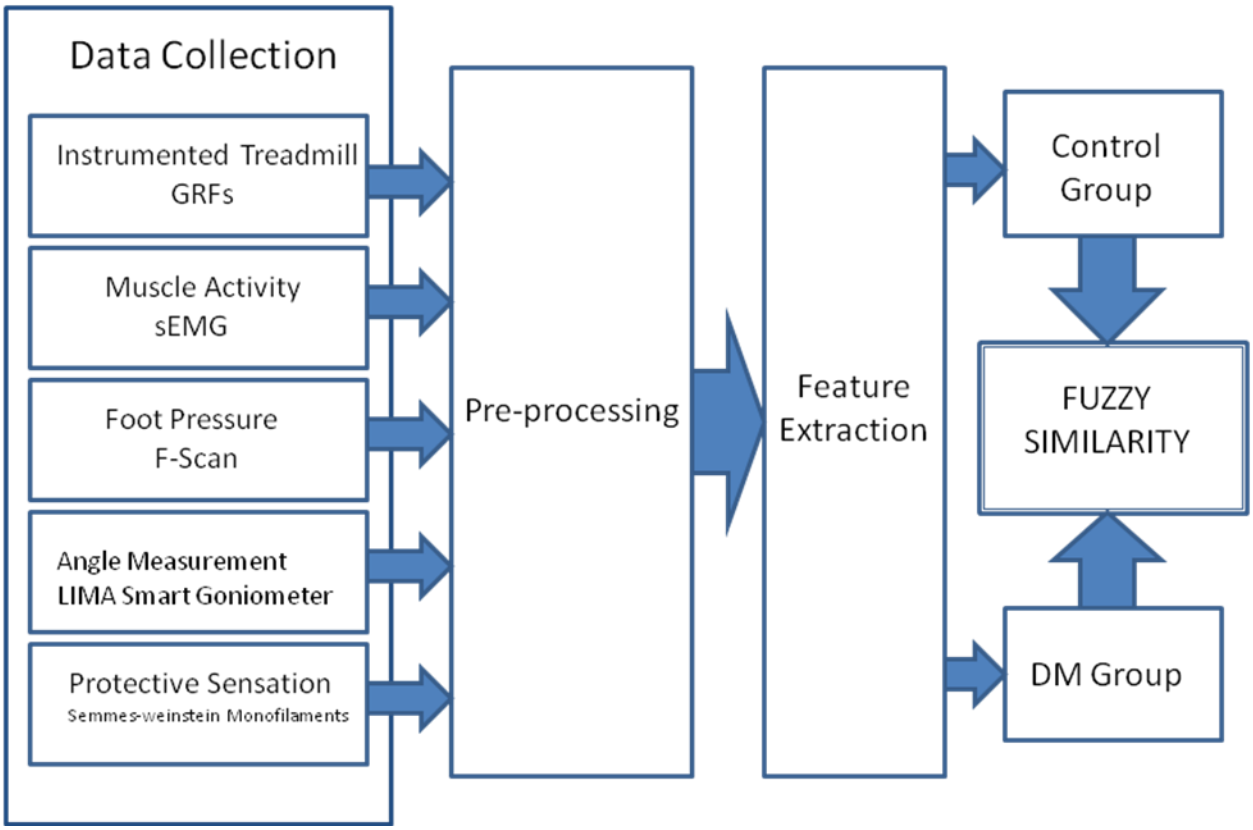


Figure 3.1: Experimental Design

In Figure 3.1, the instrumented treadmill is from BERTEC® which measures ground reaction forces in X, Y, and Z axes. The surface electromyography (EMG) from Delsys® used to monitor 16 muscles on lower extremity. The 16 muscles are: Soleus (Sol), Tibialis Anterior (TA), Gastrocnemius Lateralis (LG), Vastus Lateralis (VL), Rectus Femoris (RF), Biceps Femoris (BF), Gluteus Medius (Gmed), and Erector Spinae (ES). The F-scan from TEKSCAN® is able to measure pressure from the

right and left foot, it is an ultra-thin insole. Preceding the F-scan, we have the LIMA Smart Goniometer developed in the LIMA Lab in 2012, This sensor is capable to obtain joint kinematics of the ankle, knee, and hip in real time. Semmes-Weinstein monofilaments from BASELINE® are nylon monofilaments that are able to assess foot pressure on a subjective test.

Chapter 4: Experimental Procedure

Before this experiment was executed, all volunteers are asked to read and the informed consent form which is approved by Institutional Review Broad (IRB). The informational consent states clearly the points, such as the confidentiality and authorization statement. Once subjects sign the consent form, we proceed with the experiment.

Each subject needs to wear comfortable shorts. The EMG and Goniometer sensors are placed accordingly. Subjects are made to wear their own shoes and ultra-thin insole sensors from TEKSCAN® were trimmed to fit each patient's shoe. Once the sensors are placed, they are calibrated.

4.1 Materials

4.1.1 Instrumental Treadmill from BERTEC

The dual belt instrumental treadmill from Bertec® has two independent force plates that measure the ground reaction forces on the X, Y, and Z axes, also known as the mediolateral, anterior posterior, and vertical planes. This measurement is done at a sampling ratio of 100 Hz. Accurate measurement of ground reaction forces will provide important information for the study of the gait analysis.

Figure 4.1: Instrumented Treadmill, BERTEC® USA.

4.1.2 Trigno Delsys Wireless sEMG

Each sensor includes both EMG and accelerometer sensors. Muscle activity is monitored using 16 EMG channels and accelerations are acquired using 48 accelerometers. The sampling rate of the sensor can be set either at 2000 Hz or 4000 Hz and is compatible with the EMGworks® sofware.

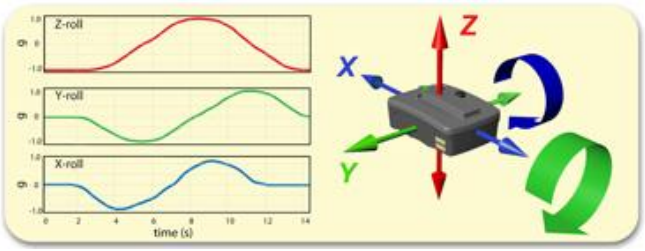


Figure 4.2 Delsys Trigno Wireless sEMG displaying acceleration orientation

4.1.3 LIMA Smart Goniometer (Developed by LIMA 2012)

Electronic Dynamic Goniometer designed in LIMA Lab which was able to obtain trunk, head, hip, knee, and ankle joint kinematics in real time.

4.1.4 F-scan from TEKSCAN

Ground reaction forces can be measured with force plates, and insoles. In this case, the F-scan system from TEKSCAN is able to detect and records foot pressure where different spots on the foot can be extracted. This system consists of a scanning electronics, software, and patented thin-film sensor that quantifies contact pressure. F-scan system can record events up to 750Hz, and it can be easily changed from the software [17].

Figure 4.3: F-Scan system

4.1.4 Semmes-Weinstein Monofilaments

Nylon Semmes-Weinstein monofilaments are from BASELINE Evaluation Instruments. It is utilized to perform monofilament test on healthy subjects and diabetic patients. The set of Semmes-Weinstein monofilaments includes 0.07grams force, 0.4 grams force, 2.0 grams force, 4.0 grams force, 10 grams force and 300 grams force. For this research, only the 10 gram monofilament and 300 gram monofilament were used.

Figure 4.4: Monofilament set from BASELINE Evaluation Instruments.

4.2 Participants

4.2.1 Healthy (Control Group) Subject

A healthy control group was integrated by twelve males and eight females. All volunteers were without any motor impairment. Twelve male healthy subjects were within 19-38 years old and the eight female healthy subjects were within the ages of 20-40 years old. Anthropometric data from the control group is presented in the following tables 4.1 and 4.2.

Table 4.1: Anthropometric Data for Male Healthy Subjects

Male Subjects	Age	Weight (Kg)	Height (cm)	BMI %
MH01	32	90	192	24.41
MH02	38	88	174	29.07
MH03	23	60.5	167	21.69
MH04	24	65.1	178	20.55
MH05	31	84.3	171	28.83
MH06	26	76.3	175	24.91
MH07	26	77.9	168	27.60
MH08	19	81.4	185	23.78
MH09	22	70	163	26.35
MH10	24	83	178	26.20
MH11	25	81.1	173	27.10
MH12	20	61.7	167	22.12

Table 4.2: Anthropometric Data for Female Healthy Subjects

Female Subjects	Age	Weight (Kg)	Height (cm)	BMI %
FH01	25	53.1	155	22.10
FH02	20	64.5	170	22.32
FH03	27	63.3	168	22.43
FH04	20	40.8	162	15.55
FH05	25	54.8	155	22.81
FH06	23	55.9	159	22.11
FH07	20	57.8	155	24.06
FH08	40	62	165	22.77

Similarities were found in the anthropometric information for all healthy subjects. All the healthy subjects anthropometric data were averaged. The resulting information is presented in table 4.3:

Table 4.3: Average Anthropometric Data for Control Group (n=20)

	Control Group (N=20)			
	Age	**Weight (Kg)**	**Height (cm)**	**BMI %**
AVG(Std)	24.21(4.49)	67.26(12.94)	167.68(8.45)	23.76(3.264)

4.2.3 Patients (Diabetes Mellitus Patients)

The diabetes mellitus group consists of two males and five females. Male diabetic patients, PM01 and PM02 were 44 years and 52 years in age respectively. The five female diabetic patients' age ranged from 26-60 years. All participants volunteered for this research and had no previous ulceration history. Anthropometric data for the diabetic group for both male and female are displayed in the following table 4.4.

Table 4.4: Anthropometric Data from Diabetes Mellitus Control Group

Subjects	Age	Weight	Height (cm)	BMI %	Year Of being Diagnosed	Monofilament >2 areas failed (10gr)
MP01	44	97.4	179	30.39855186	8	No
MP02	52	91.1	164	33.87120761	6	Yes
FP01	60	95.5	155	39.75026015	22	Yes
FP02	56	69.9	154	29.47377298	2	Yes
FP03	47	62.3	146	29.22687183	3	Yes
FP04	26	100.7	161	38.84880985	4	No
FP05	34	141.3	168	50.06377551	4	No

4.3 Software Preparation

F-scan Mobile software version 5.27 from TEKSCAN was used in this research to obtain the pressures of the left and right foot. To set-up this software, it is necessary to know personal subject information, for example, full name, body weight, date of birth, and gender. All this information is required by the software because it will generate a patient's database. Body weight is needed for calibration of the software. On the other hand, LABView® was programmed to record the ground reaction forces (X, Y, and Z axes) and kinematics dynamic (joint angles from the ankle, knee and hip). Finally, the sEMG Works Acquisition 4.0v was used to collect the EMG information from wireless sensors. All the sensors were software triggered using LABView® software and a triggering box.

4.4 Hardware Preparation (Sensor Placement)

The EMG sensors were placed on following muscles: the soleus (Sol) which is located over the inner posterior side of the leg, the tibialis anterior (TA) which is located between the knee and ankle, at lateral to the tibia bone, the gastrocnemius lateralis (LG) which is located on upper half of the posterior aspect of the calf, the vastus lateralis (VL) which is located in the lower end of the thigh, approximated 6 centimeters above the kneecap, the rectus femoris (RF) which is located on the thigh between the hip bone and knee, the biceps femoris (BF) which is located half way between the ischial tuberosity and the

lateral epicondyle of the tibia, the gluteus medius (Gmed) which is located three centimeters towards the spin, going from the hip bone, and finally, the erector spinae (ES) which is located on bilateral Longissimus 1[18][19]. Gyroscopes from the LIMA Smart Goniometer are placed on the following locations: on the outside of foot which is 1.5 centimeters approximately from the ankle, on the shank located between knee and ankle, on the thigh between knee and hip, and the hip itself. Gyroscope sensor placement needs to be performed carefully due to the fact that the sensors need to be aligned. Figure 4.5 shows the sensor placements.

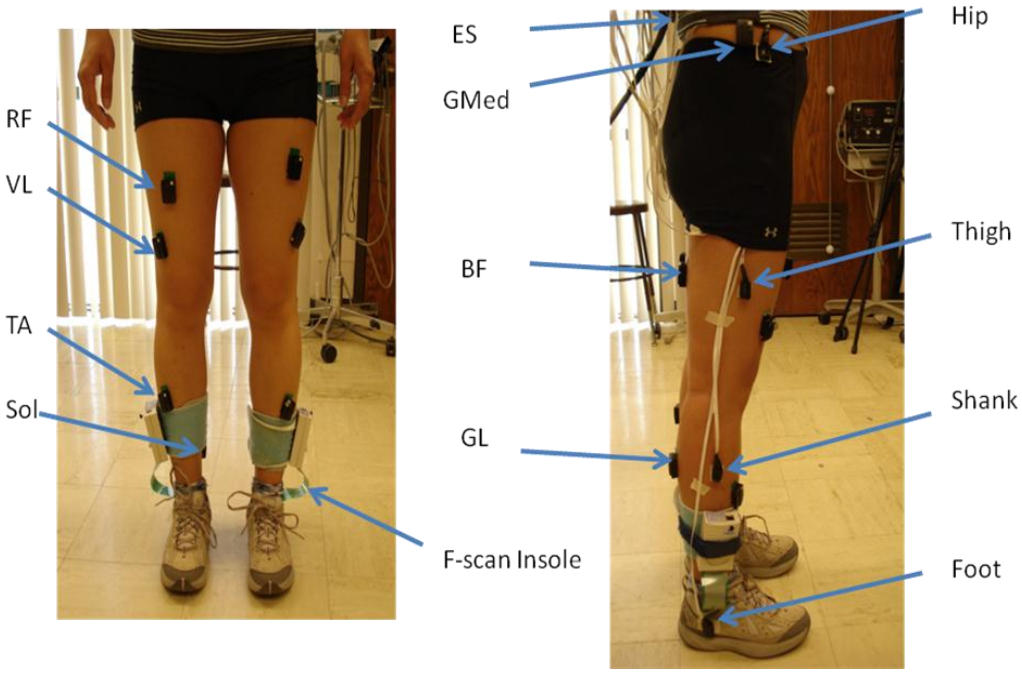


Figure 4.5: Sensor Placement

4.5 Trials

The process of the experiments constitutes two trials. The first trial incorporated walking on an instrumented treadmill at a self-selected speed, and the second trial incorporated over ground walking at the participants' natural walking speed.

4.5.1 Treadmill

Each subject performed a treadmill trial at a self-selected speed (natural walking speed) for a period of 180 seconds. Before recording data, each subject got familiar to the instrumented treadmill for a few seconds to reach their natural walking speed. Once the natural walking speed was reached, the data is recorded for 180 seconds.

4.5.2 Over ground

Five over ground trials were performed for each subject on a walkway delimited to 5 meters. During the over ground trials, EMG, F-scan, and Goniometer's sensors remained in the same place that were placed at the beginning of the experiment to collect data.

Chapter 5: Data Processing

5.1 Ground Reaction Forces

Due to the vibration of the treadmill, the noise is introduced to the ground reaction forces. A low pass second order Butterworth filter with 20Hz needs to be applied to reduce the noise.

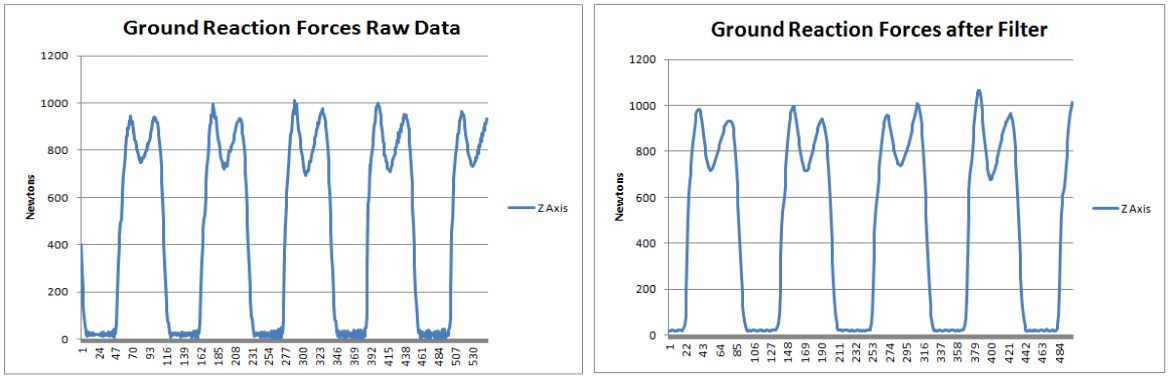


Figure 5.1: Ground Reaction Forces Raw Data and Ground Reaction Forces Data After Filter from one of the volunteers.

5.2 sEMG

Electromyography information was filtered to obtain a clean signal. The sEMG data was third order Band pass filtered between 20-200Hz, this frequency is applied because the Power Spectrum Density is more concentrated in this range (Figure 5.4). After filtering, a full-wave rectification was applied to obtain the absolute value for EMG data. Finally, a second order Butterworth filter is applied with a cutoff frequency of 6Hz. This process is known as a linear envelope [18].

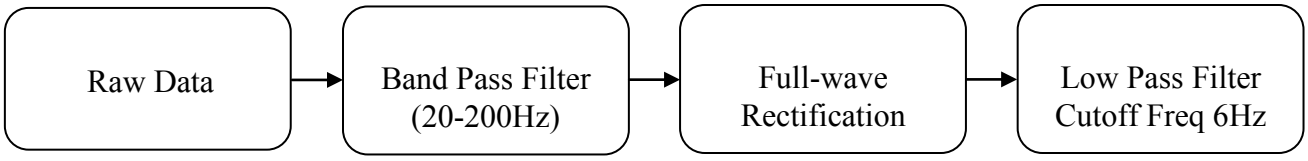
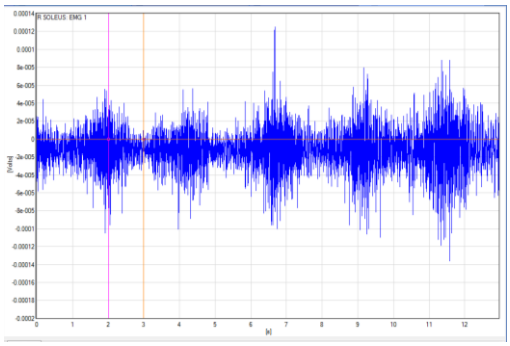
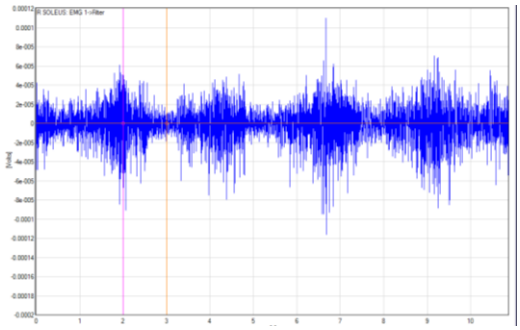


Figure 5.2: Process of Linear Envelope



(a)



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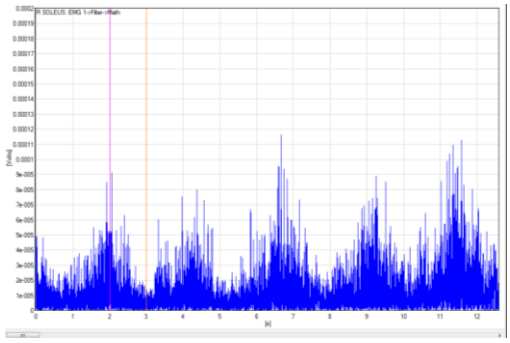

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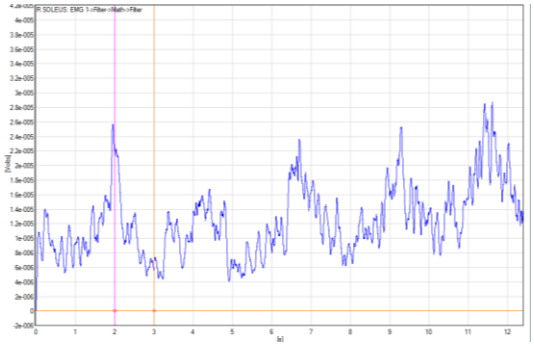

(d)

Figure 5.3: (a) Raw Data. (b) Band Pass Filter. (c) Full-wave Rectification. (d) Linear Envelope

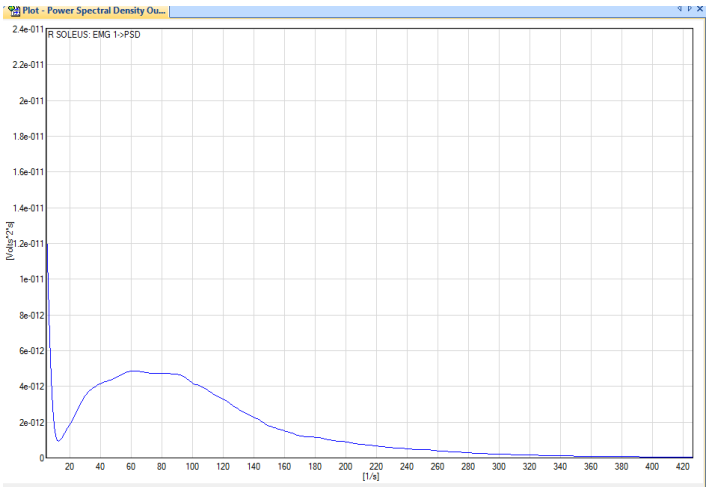

Figure 5.4: Power Spectrum Density

5.3 F-scan

In order to eliminate noise provided from the F-scan information a second order Butterworth filter with a cutoff frequency of 7Hz is applied. Most of the noise is produced by the mechanical parts, bends of the insole, and other sources. Over a period of time, the management of the insole can provide some difficulty obtaining data in which replacement of the insole is required to obtain the highest quality data [20].

5.4 Goniometer

Because of the nature of the data from the LIMA Smart Goniometer, it is very simple to condition the data obtained. The signal from LIMA Smart Goniometer is a Low pass filtered with a frequency of 7Hz to eliminate noise.

5.5 Feature Extraction

The method utilized to extract stride information is presented inside this section, as well as how the control group was created. For this research, the ground reaction forces on the Z axis were used in order to detect and extract strides. Detection of strides is performed by identifying the start point, known as the heel strike, and proceeding to detect the next heel strike to finally find the beginning and end of each stride. A threshold is used to determine when the heel strike and toe off occur during a gait cycle. This information will provide the gait cycle parameters such as stride time, stance phase time, swing

phase time, and double support time. Figure 5.5 illustrates the vertical ground reaction force in a full gait cycle.

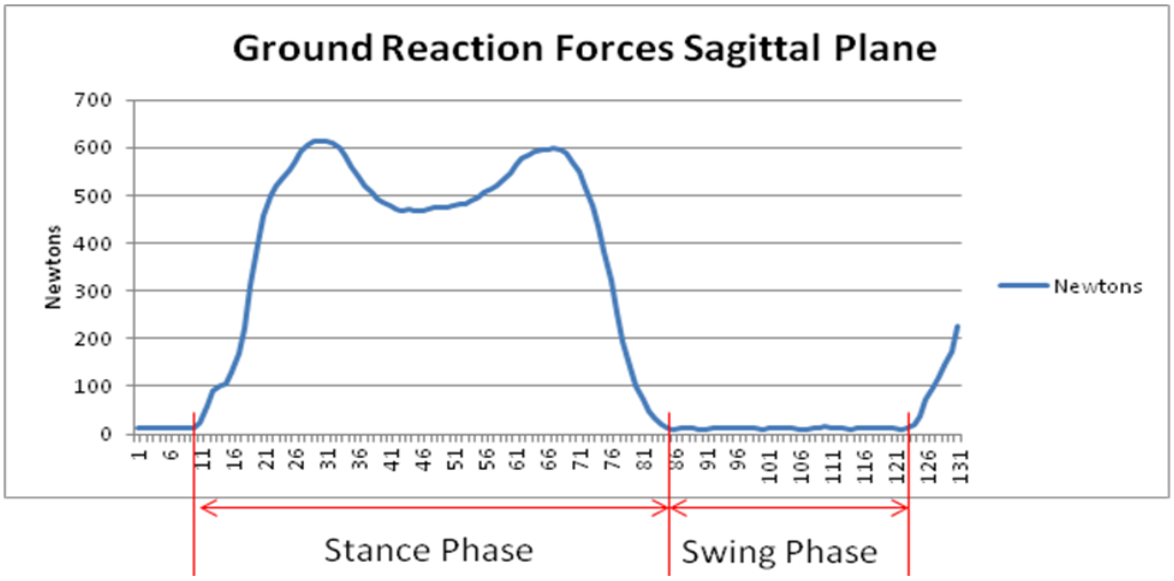

Figure 5.5: Ground Reaction Forces on Sagittal plane with Stance Phase and Swing Phase Delimitation

Because all systems were triggered at the same time for data collection, the GRF information obtained helped determine the strides times projected on the EMG and Joint Kinematics information. The vertical ground reaction force, which is the ground reaction force on the Z axis, is used to obtain the stride times, where each stride starts and finishes, and then applied to all the systems. Once all strides were extracted from the GRFs, EMG and Joint Kinematics, averaging of all strides is performed for each system.

The method we used to extract stride information for GRFs, EMG and Joint Kinematics gave results shown below in Figure 5.6. The graph displays the average GRFs of the control group represented by the blue line including +/- standard deviation represented in red.

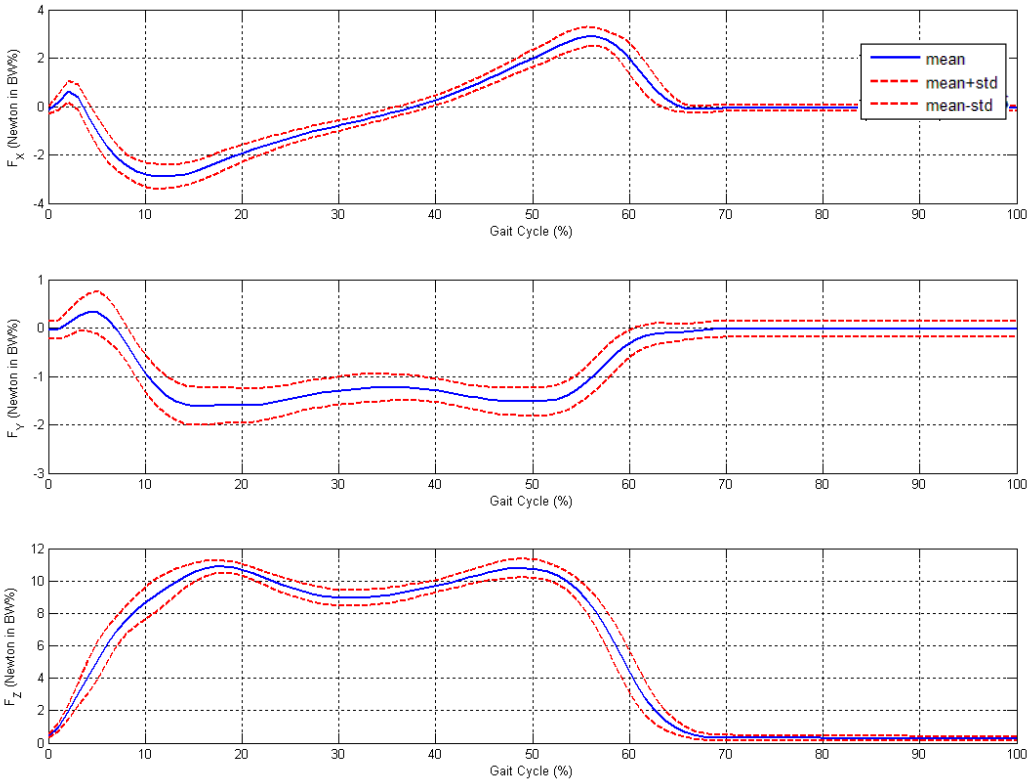

Fig. 5.6 Ground Reaction Forces of Control Group with +/- Standard Deviation

In order to create a control group with the EMG information, the strides were extracted, using the ground reaction forces of the Z axis as a reference, and averaged. Once the information was completed, there are two methods to present EMG information. The first method is to present EMG information by normalizing by the maximum value. This method will show results within ranging from 0-1 in amplitude. On the other hand, there is another method to show the results of the EMG data. This method is known as normalizing by obtaining the mean value. With this method, we can differentiate between the control group and patient data based off amplitude, and delay or early activation. This analysis is been done due to the fact that the objective of my research is to compare the amplitude of the control group against the patient information. As a result, a control group for the EMG information was normalized by the mean value. The results can be seen in Figure 5.7.

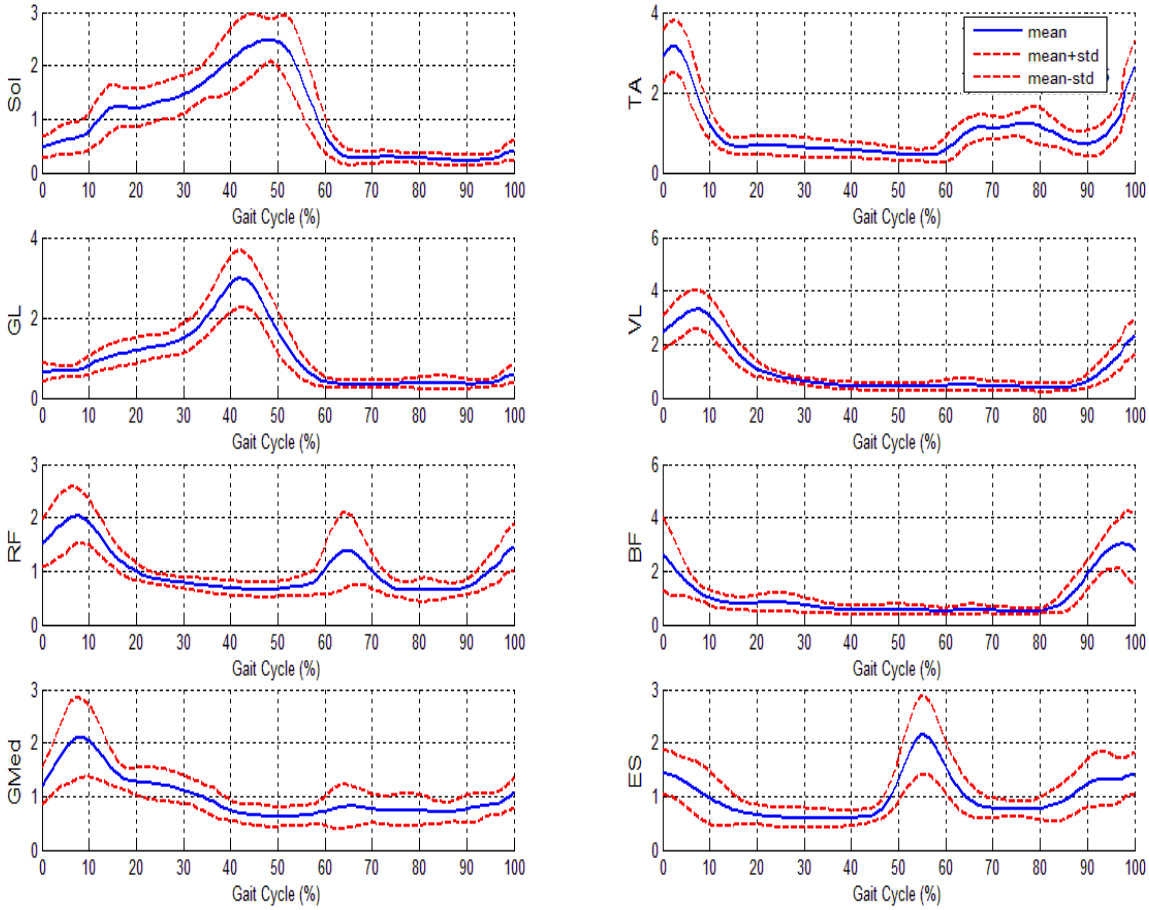

Figure 5.7: EMG Control Group

For the control group, as seen on Figure 5.7, the muscles are presented as the following: Soleous(Sol), Tibialis Anterior (TA), Lateral Gastrocnemious(GL), Vastus Lateralis(VL), Rectus Femoris (RF), Bicep Femoris (BF), Gluteus Medius (GMed), and Spinae Erectus(ES). The blue line is an average of all the healthy subjects including +/- standard deviation represented in red.

Regarding the joint kinematics data, after the conditioning process has been passed, averaging of all strides must be performed (previously extracted with GRFs as mention before). This information has not been normalized. This decision was made because the amplitude is going to be analyzed, therefore, the actual range of motion needs to be presented directly from the subject's data. Results for the joint kinematics of the ankle, knee, and hip are displayed in Figure 5.8.

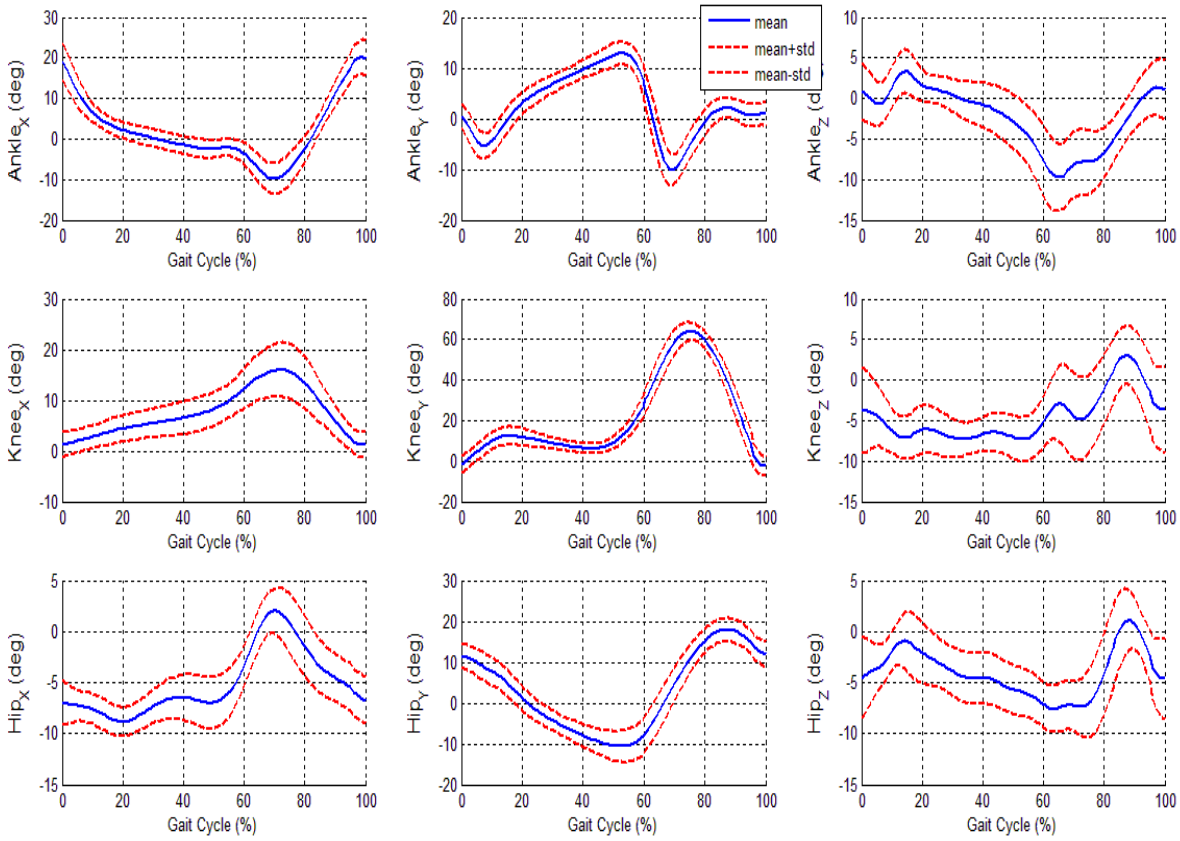

Figure 5.8: Joint Kinematics for Control Group

In Figure 5.8, the control group information including Ankle, Knee and Hip from top of the graph to the bottom respectively. The X, Y and Z axes are presented from Left to Right for the same joints.

After filtering F-scan information, a control group was created for both trials, treadmill trial and over ground trial. The trials recorded the pressures of the foot sole. The information was presented on a graph which included the big toe max peak pressure, first metatarsal max peak pressure, third metatarsal max peak pressure, and heel max peak pressure. In order to analyze this data, max peak point pressures were extracted for both trials. After extracting max point pressures, the mean was obtained.

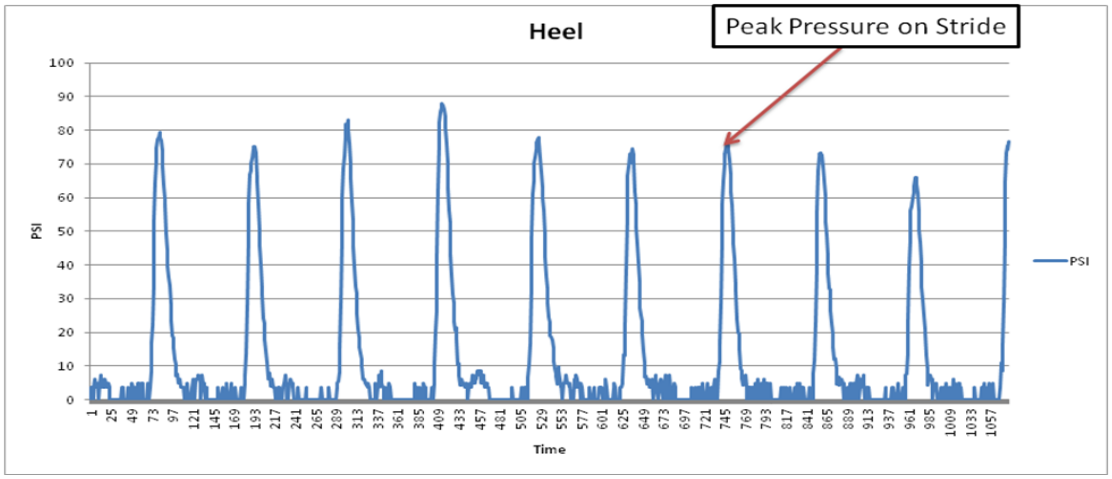

Figure 5.9: F-scan Information Showing Max Peak Pressure Point

This analysis concluded that healthy subjects had similar max peak point pressures, which resulted in the decision to average all of them. As a final result, figure 5.10 shows the average max point pressures of the big toe, first metatarsal, third metatarsal, and heel for the treadmill and over ground trials of the control group [21].

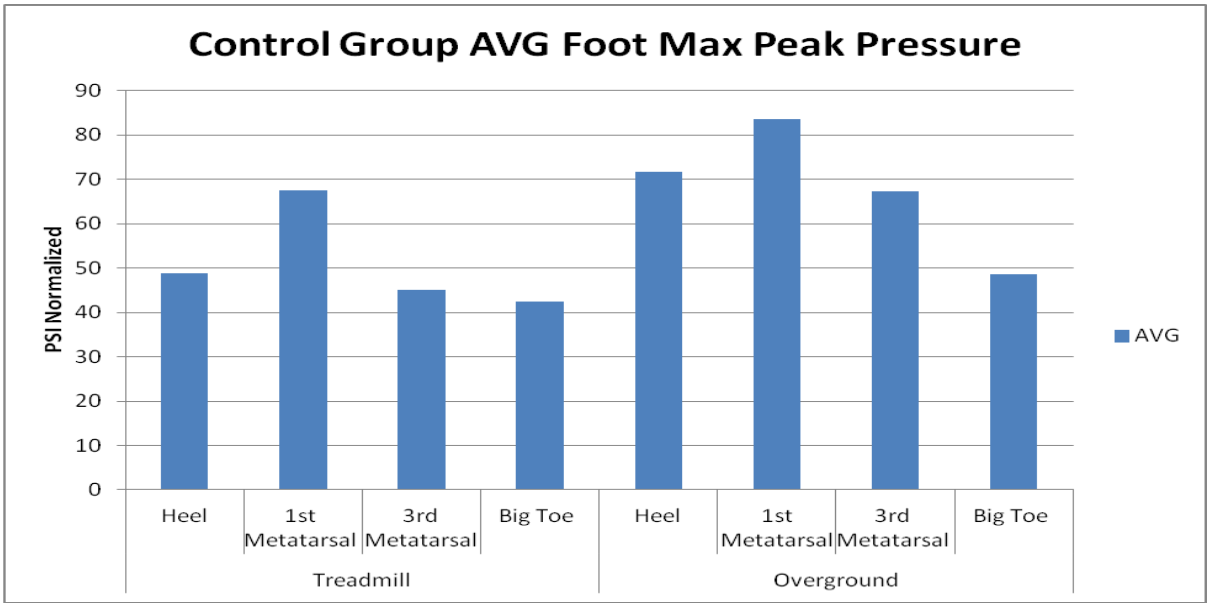

Figure 5.10: F-scan Control Group on Treadmill and Over Ground Information

A monofilament test was performed on all subjects. The test was instructed using Semmes-Weinstein monofilaments. As a protective sensation reference, a 10 gram monofilament was utilized [3][21]. The assessment was performed by the following procedures. A 10 gram monofilament was placed at a 90º angle on the tested surface known as the foot sole. Continuing, force was applied to the monofilament against the foot sole until it bends. The subject was given a diagram, shown in figure 5.11, which showed the areas of the foot sole that would be tested for pressure. Once the test was performed, pressure from the monofilament was removed and the subject was asked if he/she felt something in that specific area. Tested areas were randomly chosen. These areas were the big toe, first metatarsal, third metatarsal, fifth metatarsal, and heel. This test was performed twice with a one shaft test (no pressure test). If subjects fail more than two areas, the procedure was performed again with another monofilament which is to be greater than 10 grams. In this case, we would use a 300 gram monofilament. This research concluded that all healthy subjects that were tested with a monofilament passed the test with the 10 gram monofilament. Because of these results, we used these monofilament test results as a reference.

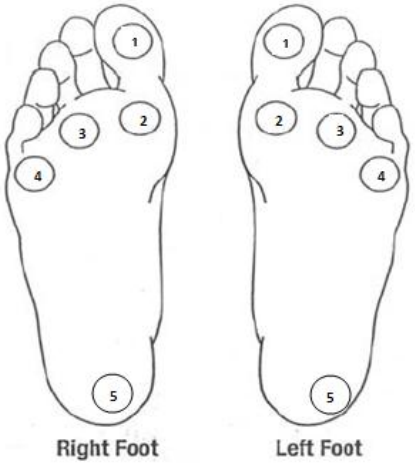

Figure 5.11: Monofilament Pressure point areas

To complete the purpose of this research, fuzzy similarity analysis was done to provide objective results from the GRFs, EMG, and joint kinematics information. Fuzzy similarity represents the grade of similarity between the control group and the diabetic patient, where μRef is known as the control group

and μDM Patient is the diabetes mellitus patient. Fuzzy similarity was calculated using the following formula:

$$\mu_{\mathrm{Ref}\times DmPatient} = \frac{\min\left[\mu_{\mathrm{Ref}}(Xi,Yj), \mu_{DMPatient}(X'i,Y'j)\right]}{\max\left[\mu_{\mathrm{Ref}}(Xi,Yj), \mu_{DMPatient}(X'i,Y'j)\right]} = Similarity$$

The fuzzy similarity of this research has been compared according to the seven phases of the gait cycle. These seven phases are known as the loading response, mid-stance, terminal stance, pre-swing, initial swing, mid-swing, and terminal swing. The initial contact is known to be from 0-2% of the gait cycle which is when the foot touches the floor. The loading response is known as the first phase which is from 0-10% of the gait cycle. Here, the initial contact is made until the other foot's toe-off is performed. The second phase is known as the mid-stance and is from 10-30% of the gait cycle. This phase starts when the other foot's toe off is performed until the body weight is aligned over the forefoot. The third phase is called the terminal stance and is from 30-50% of the gait cycle. The terminal stance starts from the end of the mid-stance until the opposite foot contact is made. The pre-swing is known as the fourth phase which lasts approximately from 50-60% of the gait cycle. The fifth phase is known as the initial swing and is approximately 60-70% of the gait cycle. The initial swing is performed from the toe off until the maximum knee flexion occurs. The sixth phase is known as the mid-swing which is approximately 70-85% of the gait cycle. The mid-swing occurs when the knee is flexed at the maximum level until the tibia is in vertical position. The seventh phase is called the terminal swing and it is approximately 85-100% of the gait cycle [18]. This phase starts when the tibia is in a vertical position until the foot contact is performed. The seven phases of the gait cycle described are the phases that are taken into consideration for the fuzzy similarity analysis.

This fuzzy similarity analysis has been done to give quantitative results of the comparisons between a control group and diabetic patients. As an example, fuzzy similarity results are shown in figure 5.12.

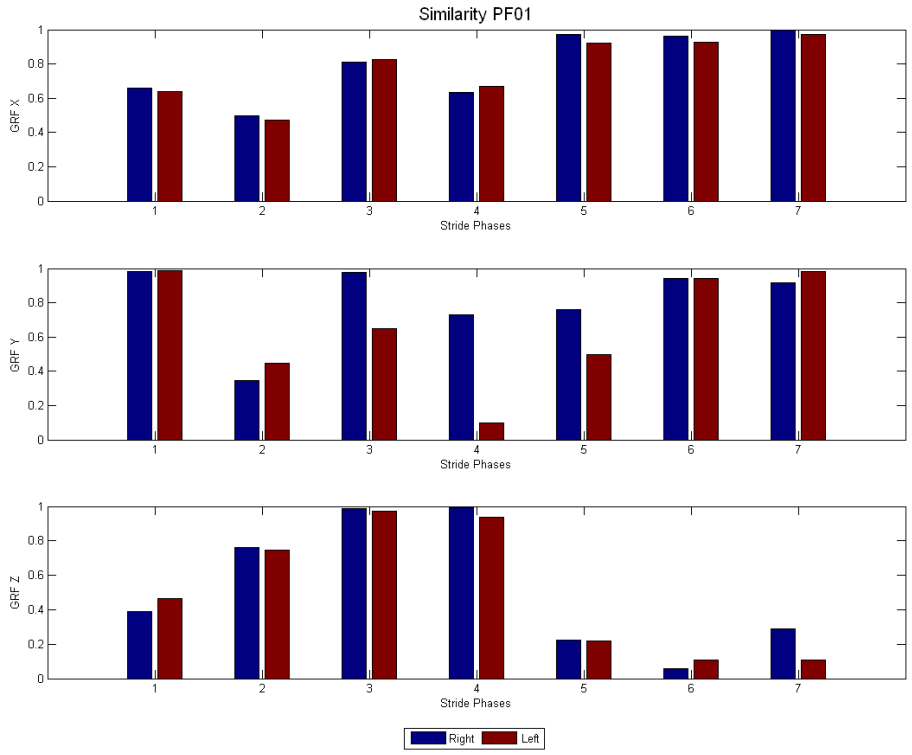

Figure 5.12: Fuzzy Similarity Results of Seven Phases of the Gait Cycle for PF01. The right foot is represented in blue and the left foot is represent in red

Chapter 6: Results

In this chapter, case studies will be presented. Each patient is to be analyzed individually by comparing the control group based on GRFs, EMG and joint angle kinematics. Monofilaments test that were performed on patients will also be observed individually. This decision was made based on previous test done on the control group. Results of the monofilament tests showed that all healthy subjects passed the monofilament test with a 10 gram monofilament. This research found that a 10 gram monofilament is sufficient enough to perform test on diabetic patients to detect diabetic neuropathy.

6.1 Case Study 1

6.1.1 General Information (PF01)

Patient female 01, identified as PF01, is 60 years-old women with a height of 155 centimeters and a body weight of 95.5 kilograms. This patient has been diagnosed with diabetes mellitus for 22 years. Self-selected speed for this patient was 0.4 meters per second on an instrumented treadmill. By a physical inspection, no callus was found on sole area. A lower speed performed on the instrumented treadmill trial was noticed compared to the average speed of the control group, giving a noticeable difference of the vertical ground reaction force. We can evidently see that the vertical ground reaction force "M" shape has a tendency to become a "N" shape, along with a delay in the stance phase. The stance phase was found between 0% to around 80% of the gait cycle, when the normal stance phase is approximately between 0% to 60% or 70%. Results can be viewed in figure 6.1 below.

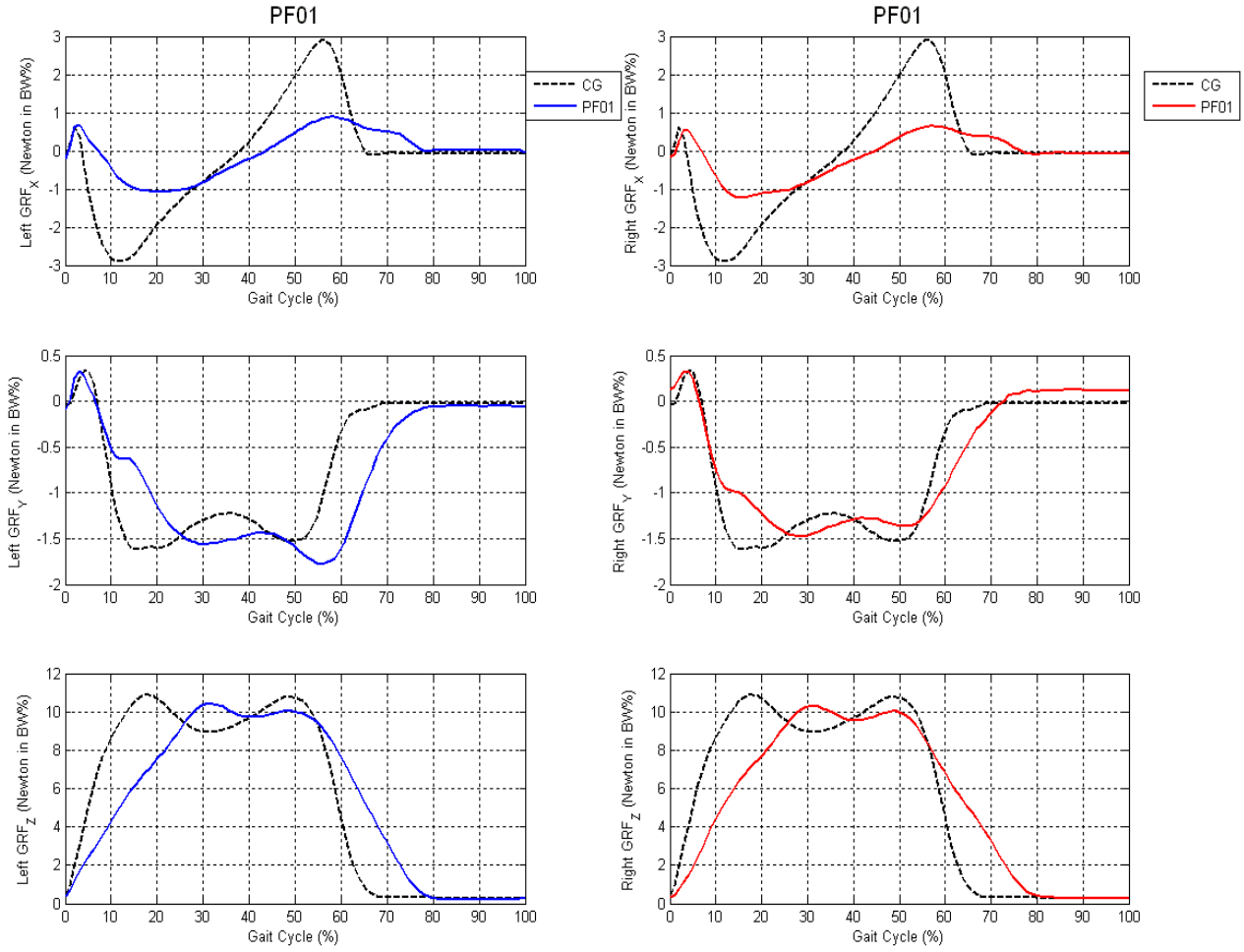

Figure 6.1: Ground Reaction Forces of Patient Female 01 Compared to Control Group

Fuzzy similarity results from the ground reaction forces is provided in figure 6.2, showing the quantitative results. These results are fuzzy similarities of the control group ground reaction forces against the PF01 ground reaction force. The ground reaction force results of PF01 that are closest to magnitude 1 conclude that the grade of similarity to the control group is bigger. Fuzzy similarity results can be viewed in figure 6.2.

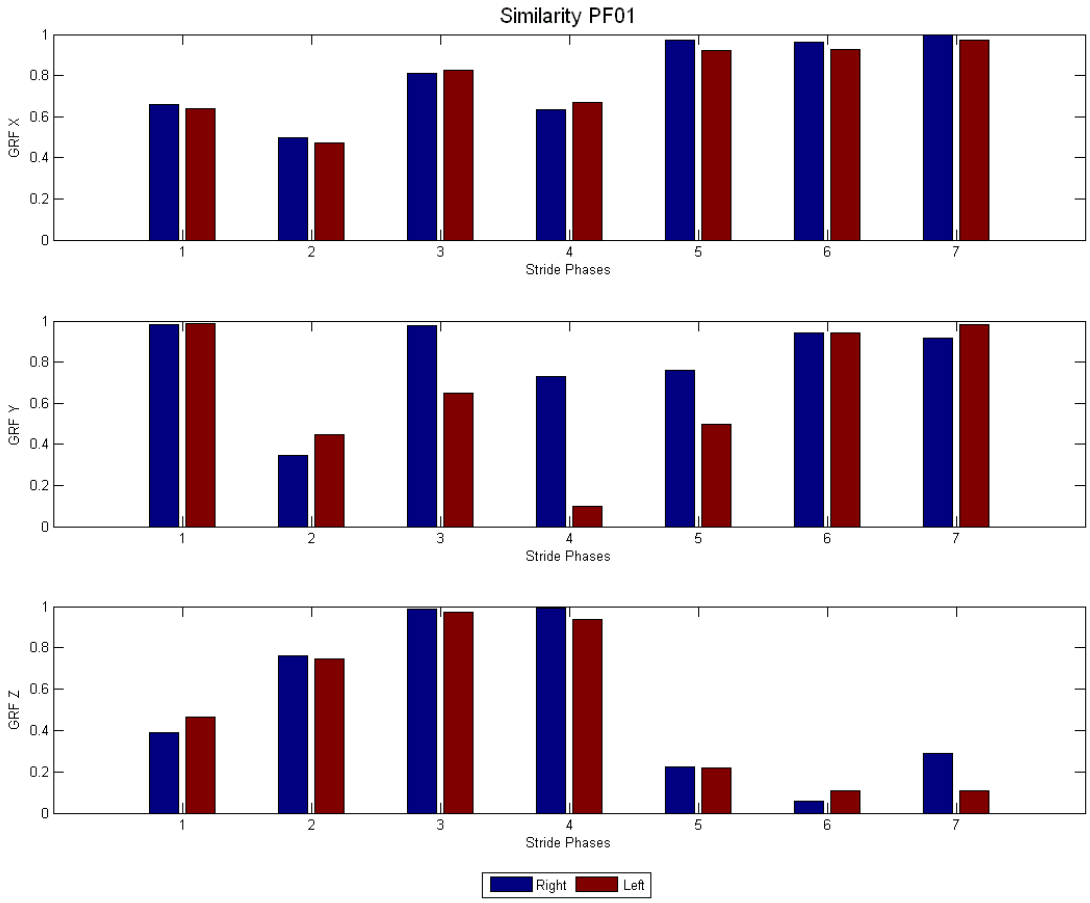

Figure 6.2 Fuzzy Similarity Results for Ground Reaction Forces of Patient Female 01. The right lower limb is represented in blue and the left lower limb is represented in red.

Joint kinematics for PF01 has shown that there is a decreased range of motion for subtalar joint and for the knee joint as well, which both were on sagittal planes and 99 percent of the relevant information is concentrated. An observed delay in kinetics was found that resulted from the low speed of the treadmill that was comfortable to the patient. Figure 6.3 displays the range of motion of the ankle, knee, and hip on the X, Y, and Z axes. The red color will represent the right lower limb while the blue color represents the left lower limb. The black color represents the control group.

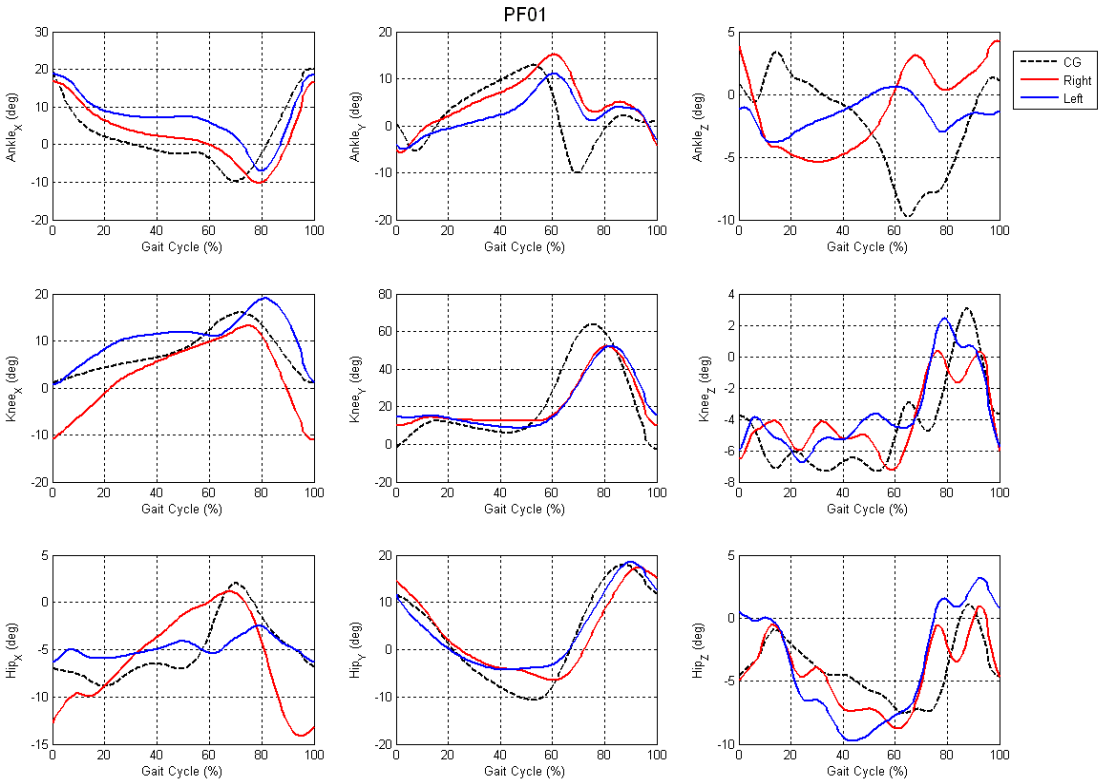

Figure 6.3: Kinetics for PF01. The right lower limb is represented in red, and left lower limb is represented in blue. The control group is represented in black for comparison

In order to provide a quantitative result, fuzzy similarities have been provided in figures 6.4, 6.5, and 6.6. Each joint has been provided with a fuzzy similarity graph that shows the proper joint on the X, Y, and Z axes.

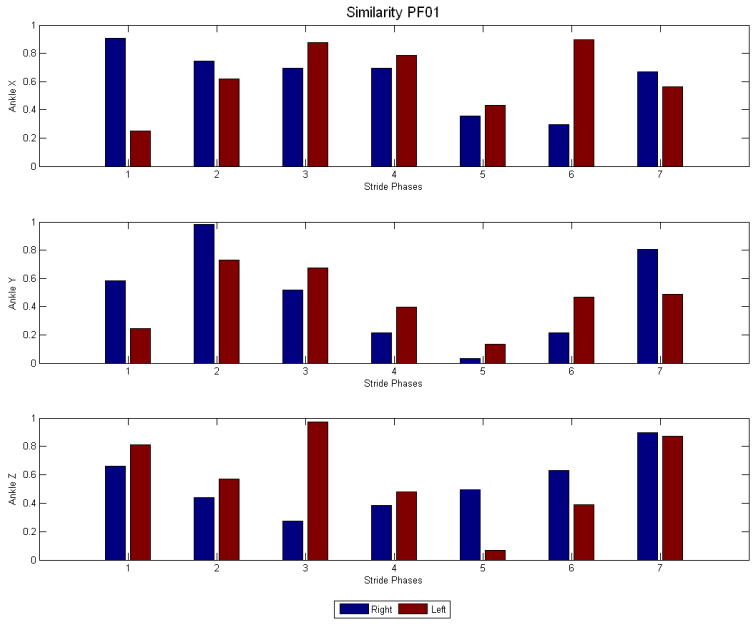

Figure 6.4: Fuzzy Similarity Results from Subtalar Joint of PF01 on X, Y, and Z axes

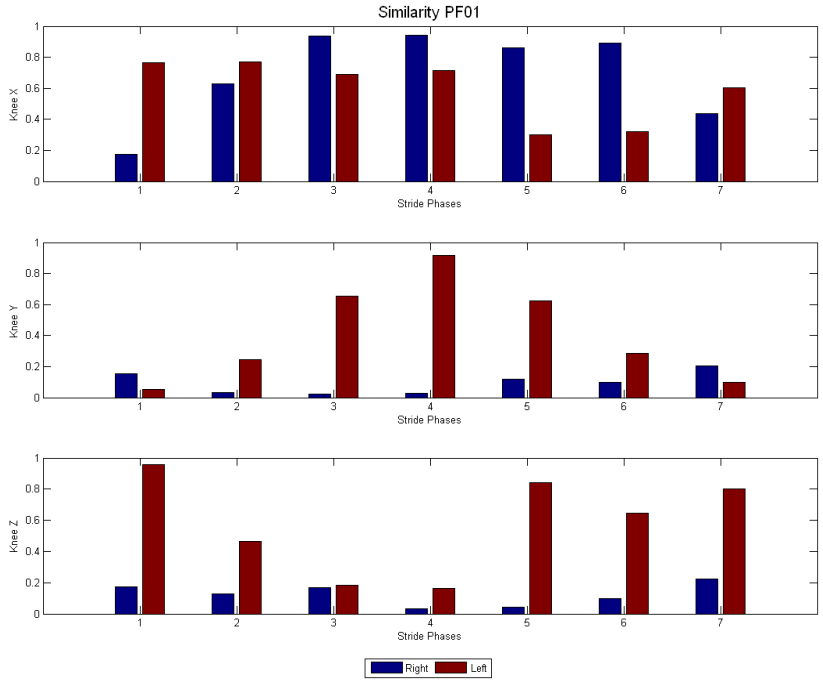

Figure 6.5: Fuzzy Similarity Results from Knee Joint of PF01 X, Y, and Z axes

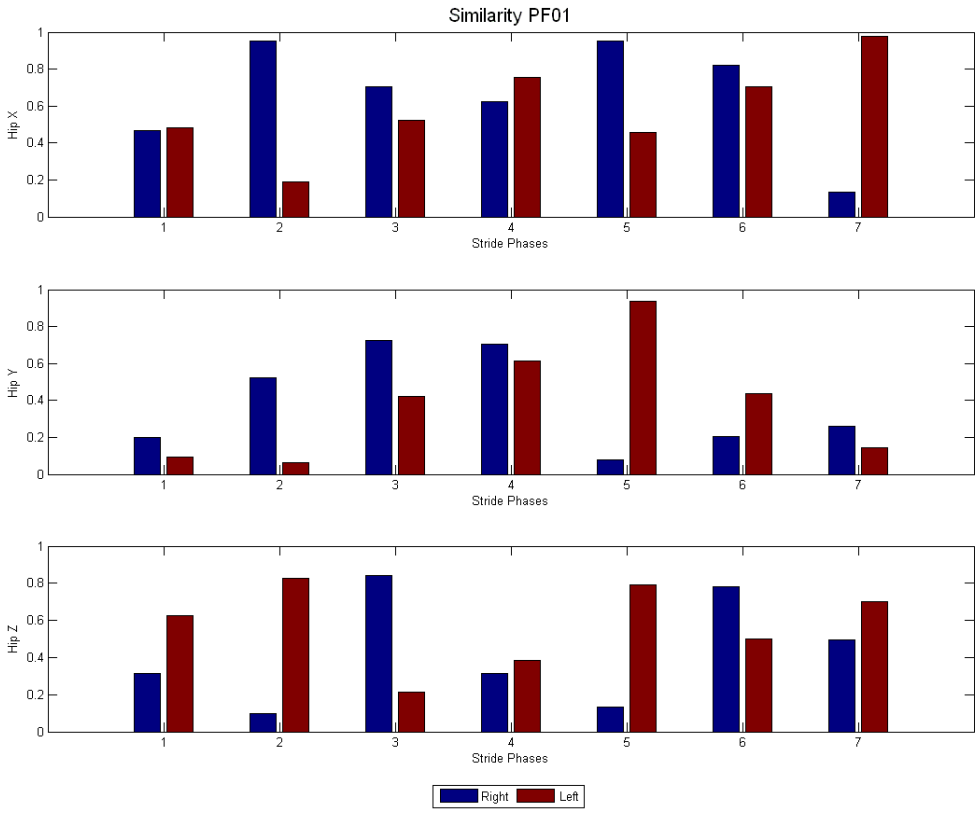

Figure 6.6: Fuzzy Similarity Results from Hip Joint of PF01 X, Y, and Z axes

There is evident from the F-scan results that diabetic neuropathy does not develop at the same time on both feet. We can clearly see that there is higher pressure shown on the right foot compared to the left foot. At the same time, there is higher pressure shown compared to the control group. Figures 6.7 and 6.8 display the following results; The pressures from the heel that are averaged from the treadmill (AVG TD) trial of the control group, and the pressure of the heel of the over ground (AVG OG) trial of the control group. After these results, we can also observe pressures of the female patient 01 on the treadmill (PF01 TD), and last we can see the information for female patient 01 of the over ground trial (PF01 OG). This format will continue the same for the first metatarsal, third metatarsal, and big toe.

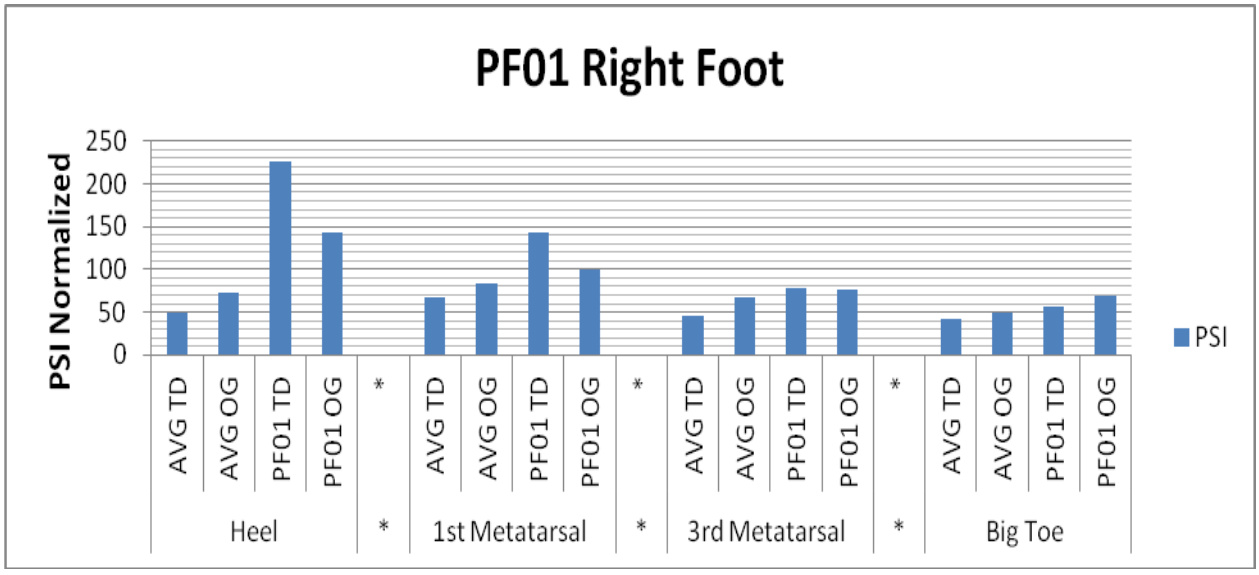

Figure 6.7: F-scan Results from PF01 Right Foot on Four Pressure Points Compared with Control Group

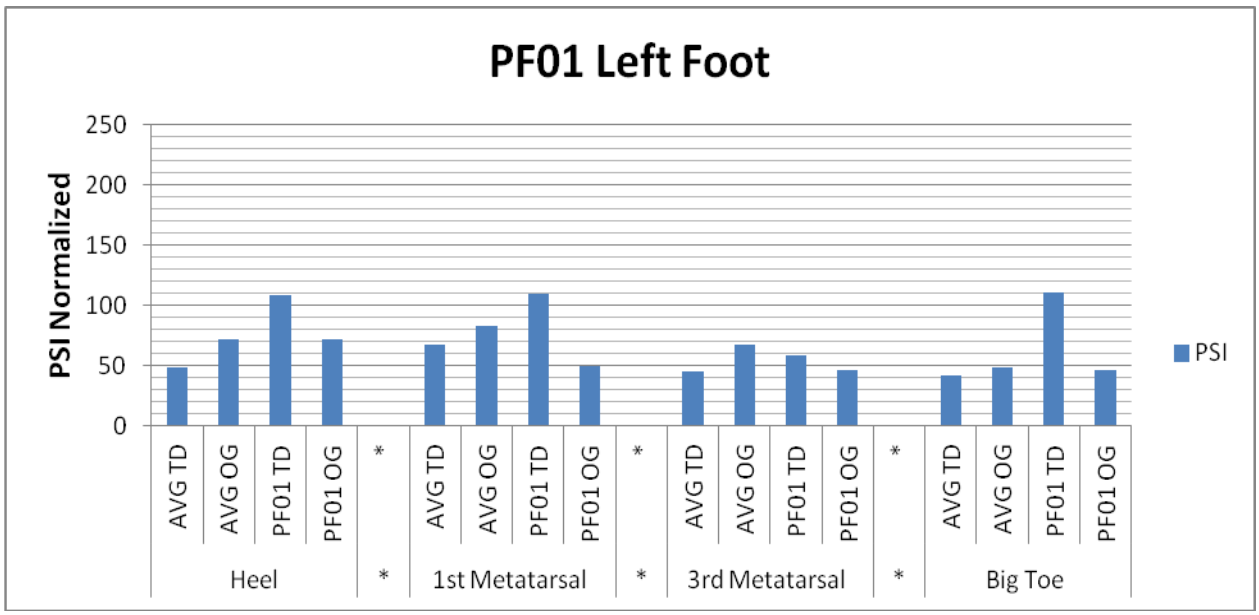

Figure 6.8: F-scan Results from PF01 Left Foot on Four Pressure Points Compared with Control Group

Patient female 01 passed the monofilament test with a 10gr monofilament on all five pressure point areas. Her results can be viewed in table 6.1. These areas include the big toe, first metatarsal, third metatarsal, fifth metatarsal, and heel.

Table 6.1: Results from Monofilament test of Female Patient 01. P=Pass, or Fail

Fail 10gr Monofilament Test on more > 2 areas

	Heel		1st Metatarsal		3rd Metatarsal		5th Metatarsal		Big Toe	
	R	L	R	L	R	L	R	L	R	L
PF01	P	P	P	P	P	P	P	P	P	P

6.2 Case Study 2

6.2.1 General Information (PF02)

Patient female 02, identified as PF02, is 56 years-old with a height of 154 centimeters and a body weight of 69.9 kilograms. This patient has been diagnosed with diabetes mellitus for 2 years. By a physical inspection, no callus was found on sole area. A lower speed was performed on instrumented treadmill trial compared to the control group (self-selected speed for this patient was 0.5 m/s) and there was a noticeable difference in the vertical ground reaction force. The vertical ground reaction force "M" shape tends to become a "N" shape, along with a small delay on stance phase that can be noticed on the Z axis ground reaction forces on both the right and left foot. Figure 6.9 displays the results of the ground reaction forces of the left foot (blue) and right foot (red).

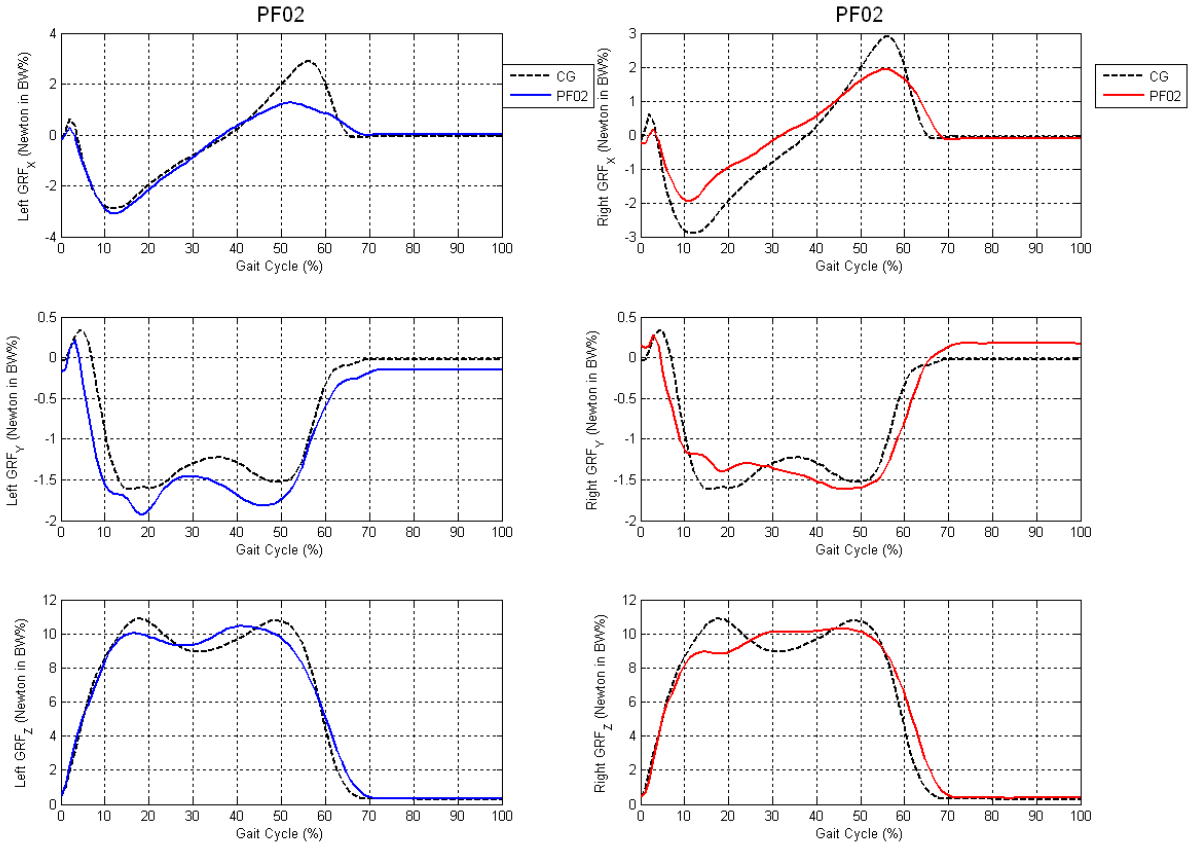

Figure 6.9: Result for Ground Reaction Forces on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

As a consequence, quantitative results can be shown in figure 7.10 by using the fuzzy similarity between the control group and female patient 02. The ground reaction force results of PF02 that are closest to magnitude 1 conclude that the grade of similarity to the control group is bigger. Fuzzy similarity results can be viewed in figure 6.10.

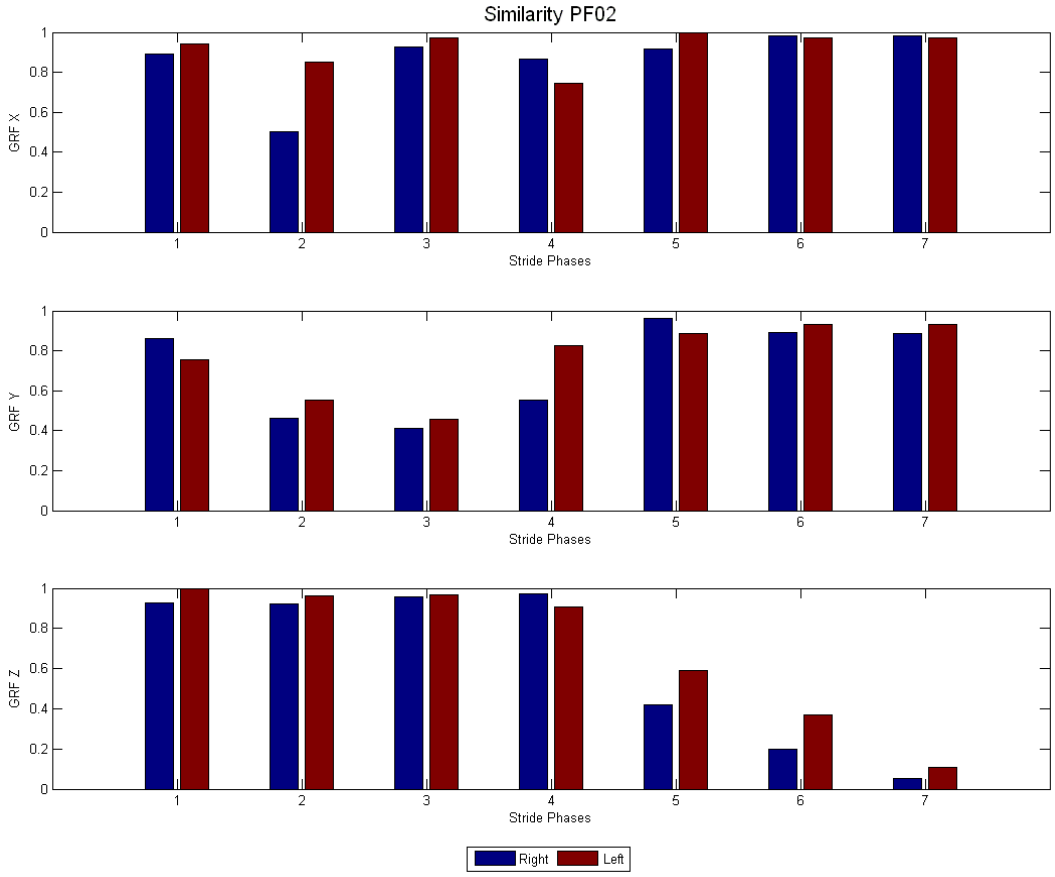

Figure 6.10: Result for Fuzzy Similarity for Ground Reaction Forces of Control Group against PF02, where the left foot is represented in red and right foot is represented in blue

By analyzing the EMG information, we have noticed that there is an early activation on tibialis anterior, and as consequence a delay on grastrocnemious lateralis and vastus lateralis activation is present. Figure 6.10 evidently shows previous statement.

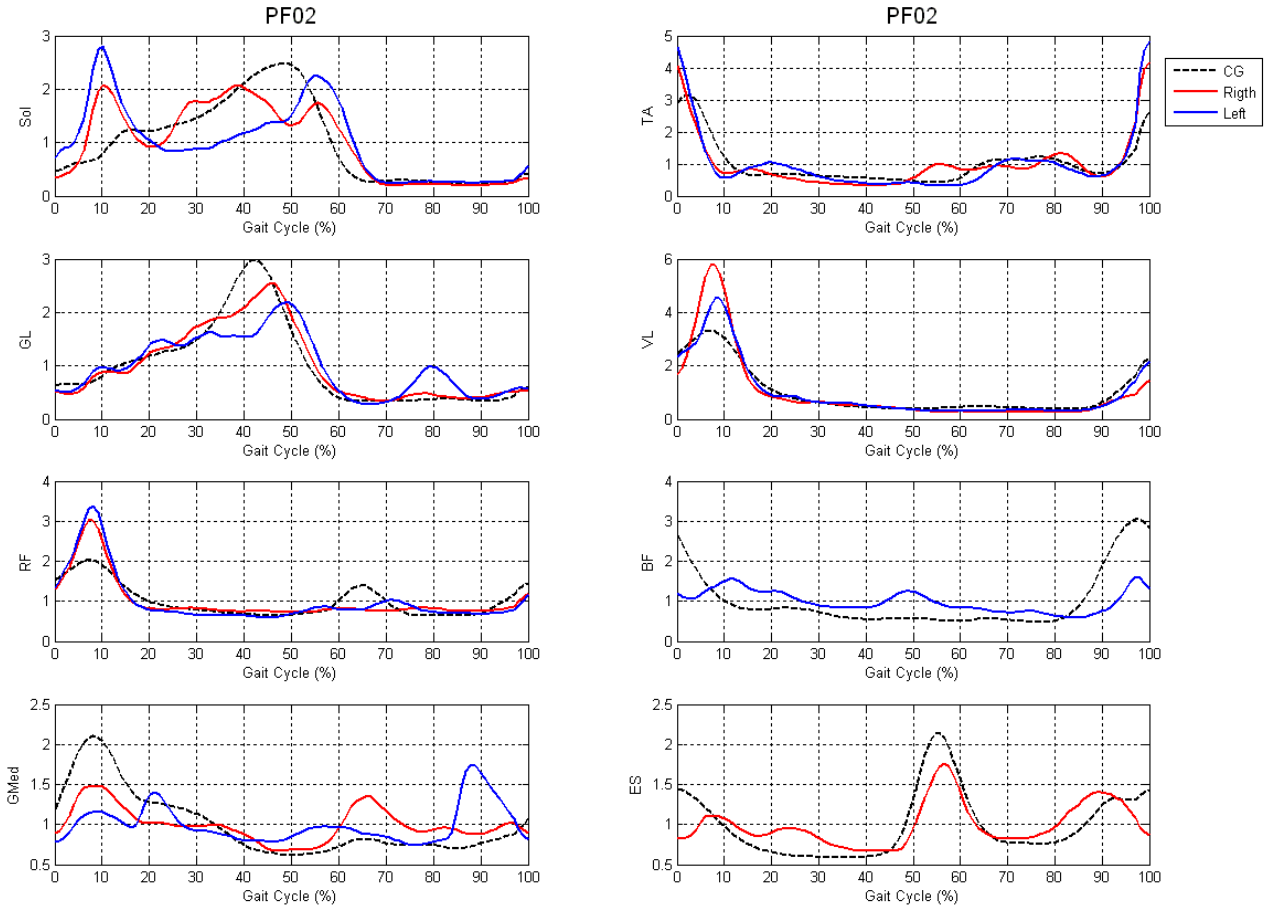

Figure 6.11: Result for EMG on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

This information has been processed with fuzzy similarity to obtain quantitative results. Quantitative results are presented on figure 6.12.

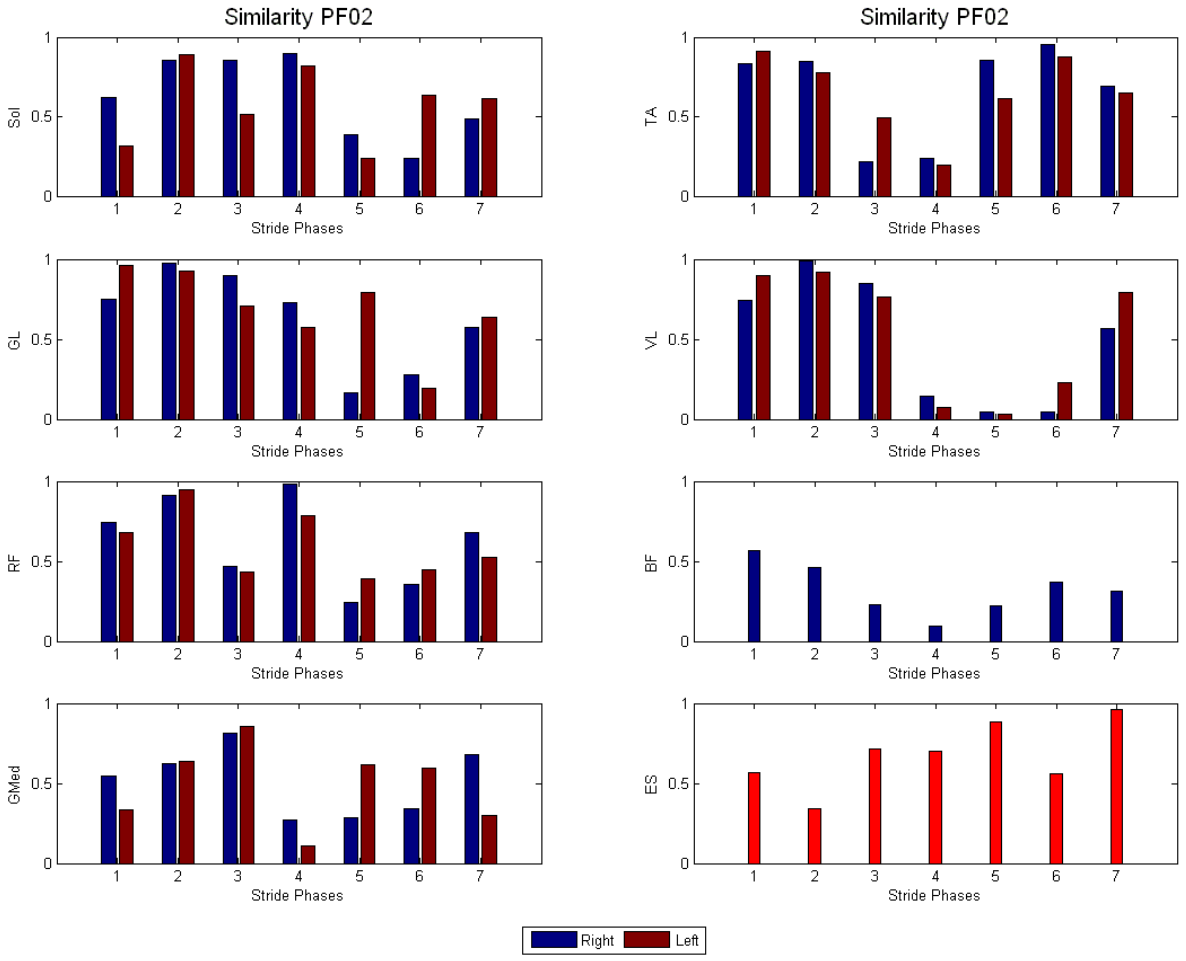

Figure 6.12: Result for Fuzzy Similarity for EMG of Control Group against PF02, where the left foot is represented in red and right foot is represented in blue

Joint kinematics for PF02 has shown that there is a decreased angle range motion for subtalar joint and for the knee joint as well, which both were on sagittal planes and 99 percent of the relevant information is concentrated. An observed on PF01, delay in joint kinematics was found that resulted from the low speed of the treadmill that was comfortable to the patient. Figure 6.13 displays the angle motion of the ankle, knee, and hip on the X, Y, and Z axes. The red color will represent the right lower limb while the blue color represents the left lower limb. The black color represents the control group.

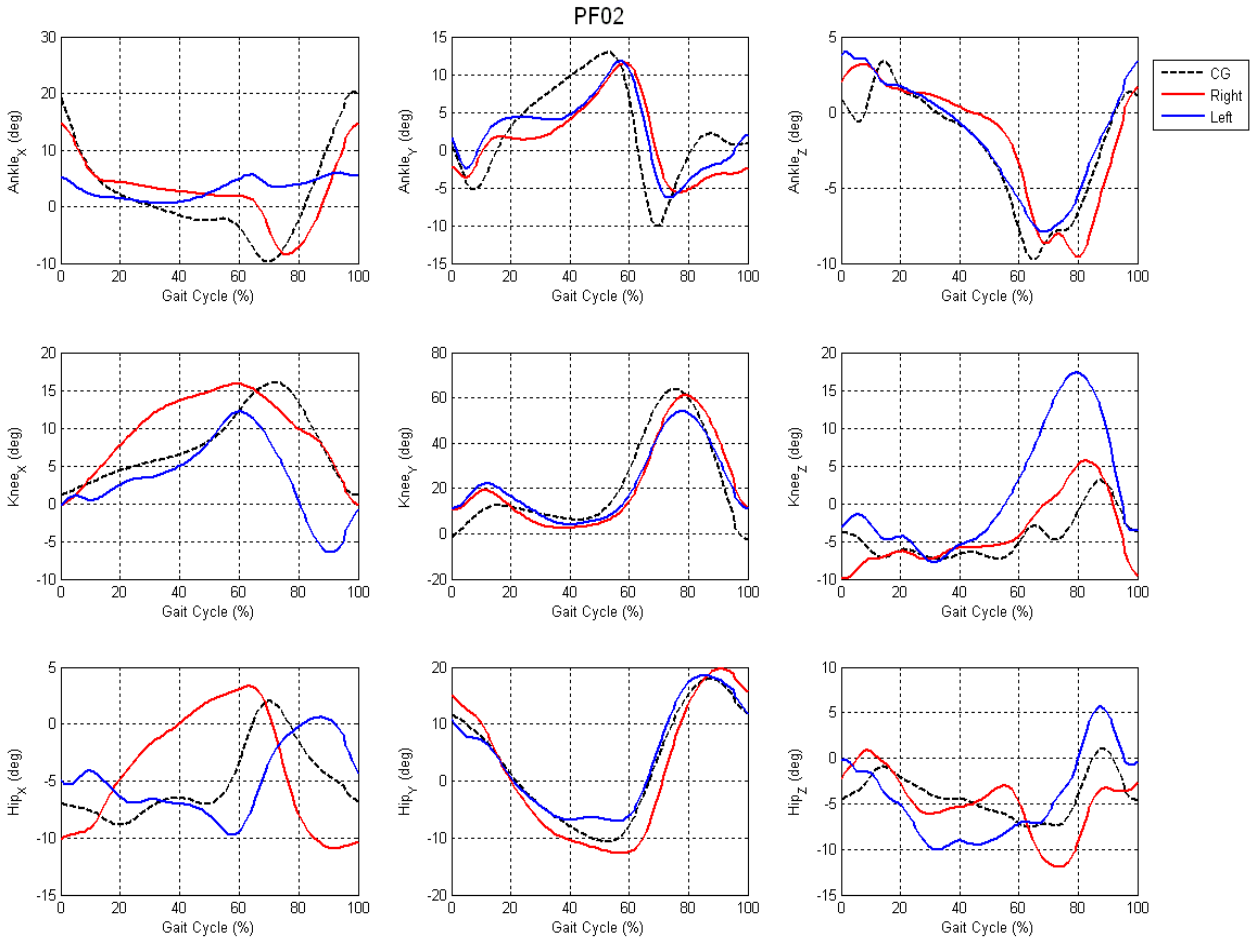

Figure 6.13: Kinetics for PF02. The right lower limb is represented in red, and left lower limb is represented in blue. The control group is represented in black for comparison

Fuzzy similarity results are presented on figures 6.14, 6.15 and 6.16. The lack of similarity on sagittal plane for ankle, knee, and hip is displayed.

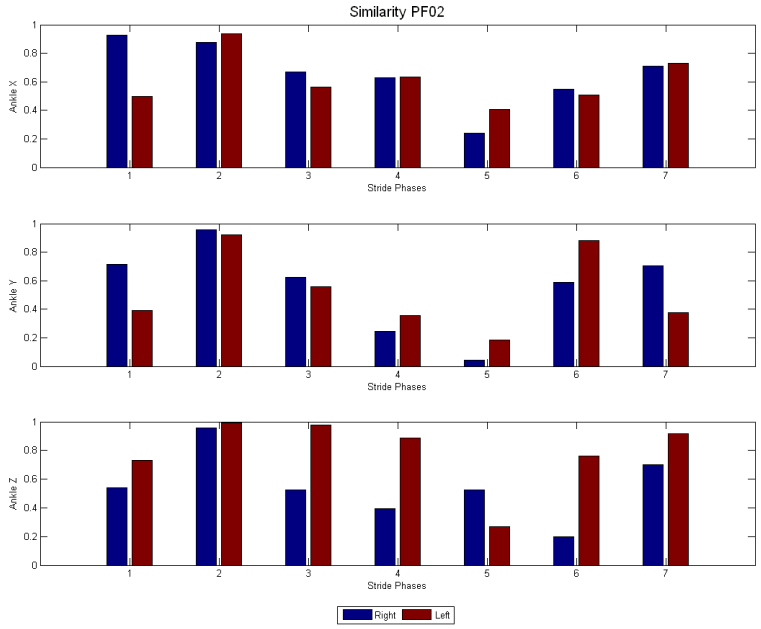

Figure 6.14: Fuzzy Similarity Results from Subtalar Joint of PF02 on X, Y, and Z axes

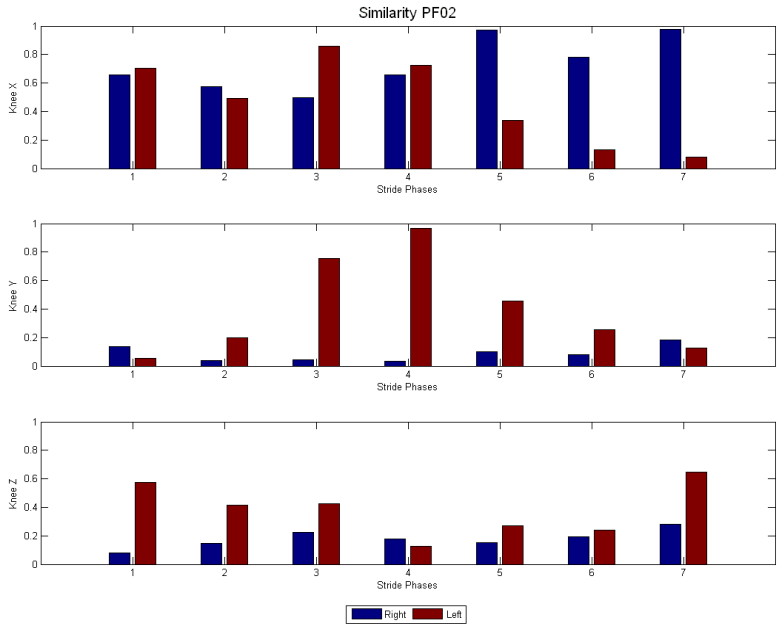

Figure 6.15: Fuzzy Similarity Results from Knee of PF02 on X, Y, and Z axes

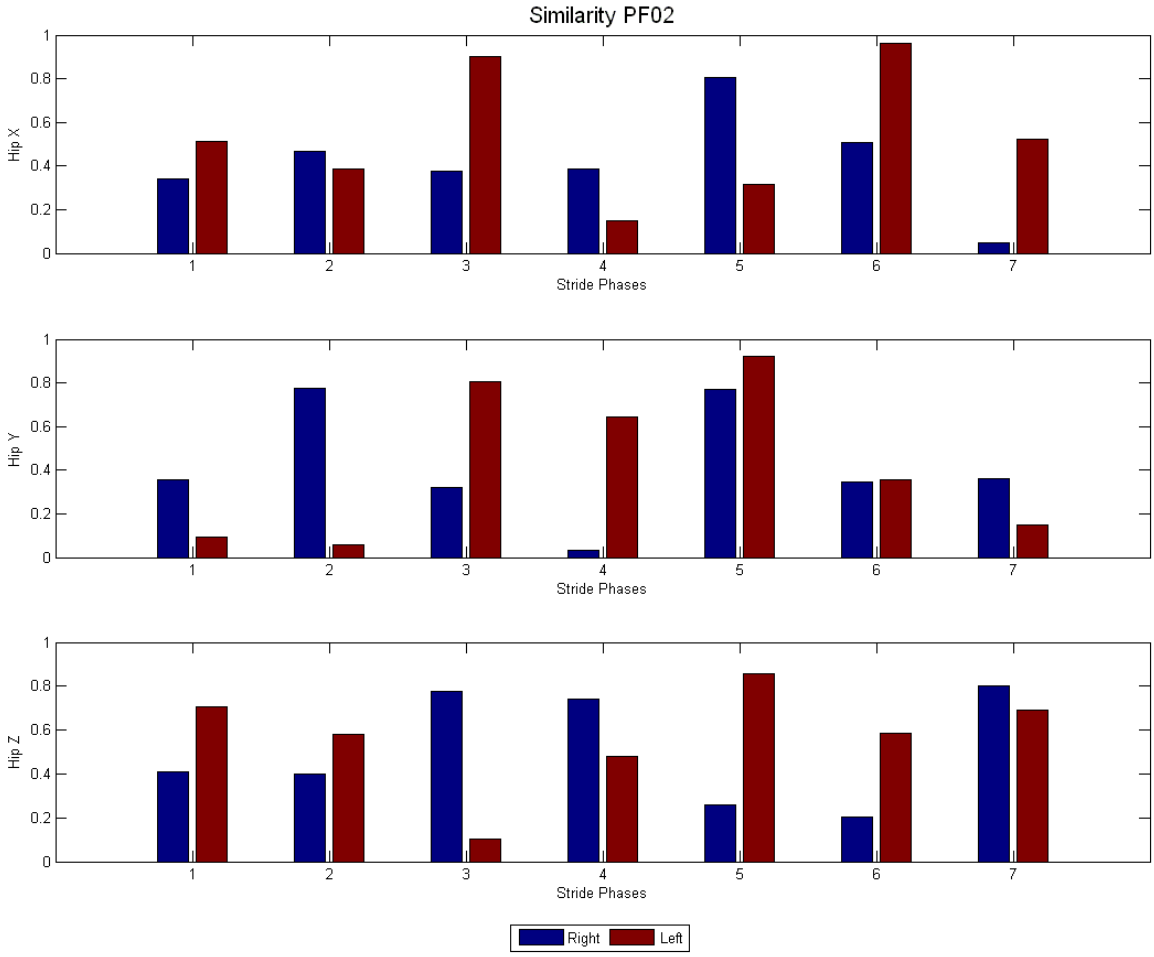

Figure 6.16: Fuzzy Similarity Results from Hip of PF02 on X, Y, and Z axes

The F-scan results show that diabetic neuropathy does not develop at the same time on both feet. We can observe that there is higher pressure shown on the left foot compared to the right foot. At the same time, there is higher pressure on left foot compared to the control group. Figures 6.17 and 6.18 display from left to right the following results; The pressures from the heel that are averaged from the treadmill (AVG TD) trial of the control group, and the pressure of the heel of the over ground (AVG OG) trial of the control group. After these results, we can also observe pressures of the female patient 02 on the treadmill (PF02 TD), and last we can see the information for female patient 02 of the over ground trial (PF02 OG). This format will continue the same for the first metatarsal, third metatarsal, and big toe.

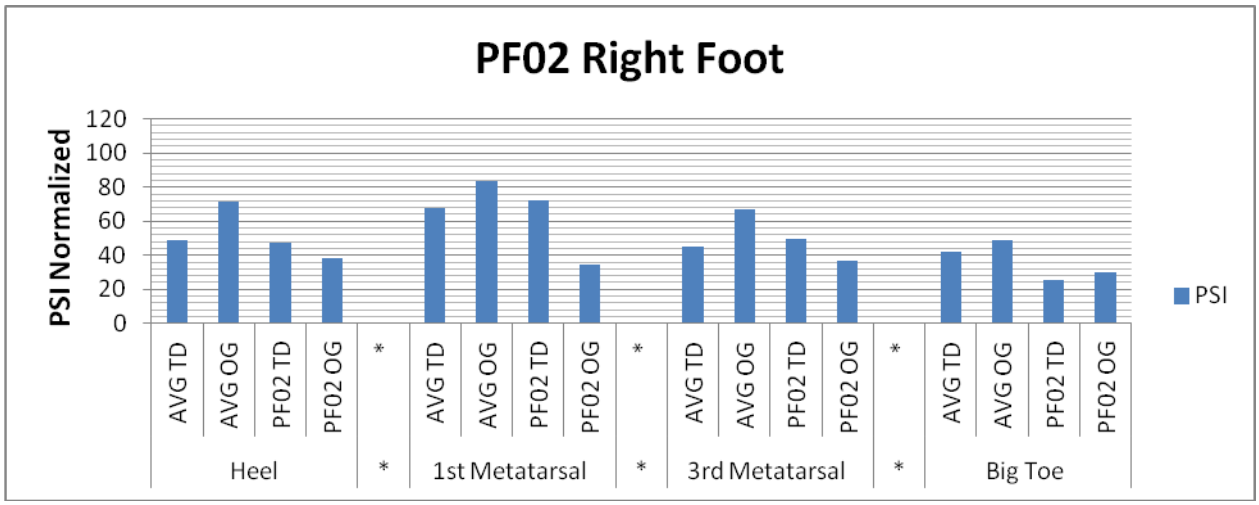

Figure 6.17: F-scan Results from PF02 Right Foot on Four Pressure Points Compared with Control Group

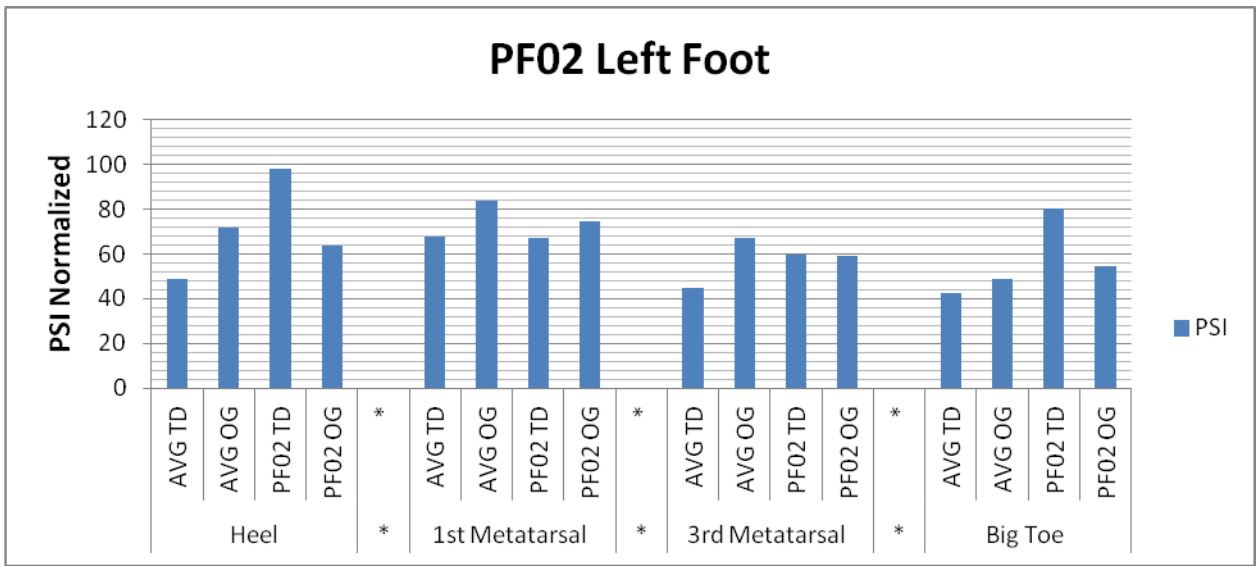

Figure 6.18: F-scan Results from PF02 Left Foot on Four Pressure Points Compared with Control Group

The 10 gram monofilament test was assessed during this experiment and showed that PF02 failed on four areas for left foot. The right foot of PF02 failed only on the fifth metatarsal pressure area. As seen on table 6.2, the results from the 10 gram monofilament test are presented. Because PF02 failed the 10 gram monofilament test, PF02 was a candidate to be tested with a higher pressure monofilament.

Table 6.2: Results from Monofilament test of Female Patient 02. P=Pass, or Fail

Fail 10gr Monofilament Test on more > 2 areas

	Heel		1st Metatarsal		3rd Metatarsal		5th Metatarsal		Big Toe	
	R	**L**	**R**	**L**	**R**	**L**	**R**	**L**	**R**	**L**
PF02	p	fail	p	Fail	p	Fail	Fail	Fail	P	P

6.3 Case Study 3

6.3.1 General Information (PF03)

Female patient 03, identified as PF03, is 47 years-old with a height of 146 centimeters and a body weight of 62.3 kilograms. This patient has been diagnosed with diabetes mellitus for 3 years. By a physical inspection, no callus was found on sole area. A speed was performed on instrumented treadmill trial is similar to the control group (self-selected speed for this patient was 0.85 m/s) and there was no noticeable difference in the vertical ground reaction force. Figure 6.19 displays the results of the ground reaction forces of the left foot(blue) and right foot (red).

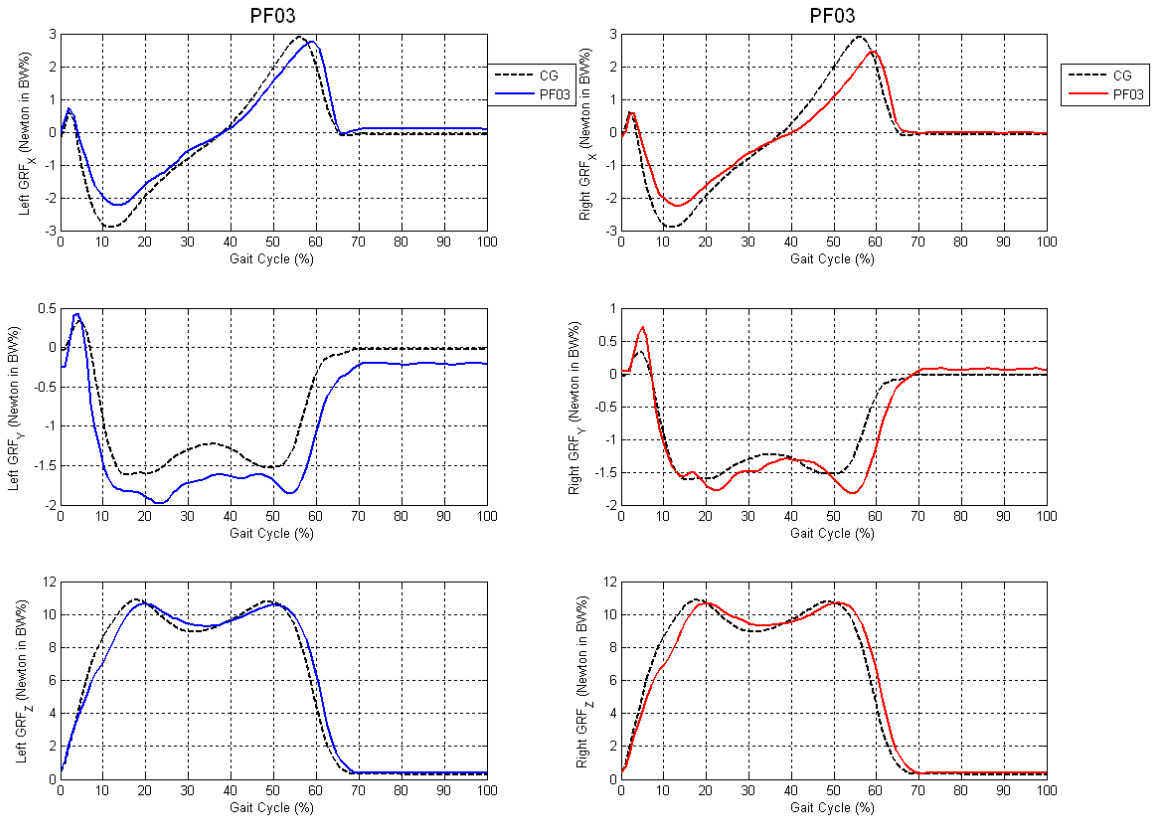

Figure 6.19: Result for Ground Reaction Forces on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

Quantitative results can be shown in figure 6.20 by using the fuzzy similarity between the control group and female patient 03. The ground reaction force results of PF03 were closest to magnitude 1 conclude that the grade of similarity to the control group is bigger. Fuzzy similarity results can be viewed in figure 6.20.

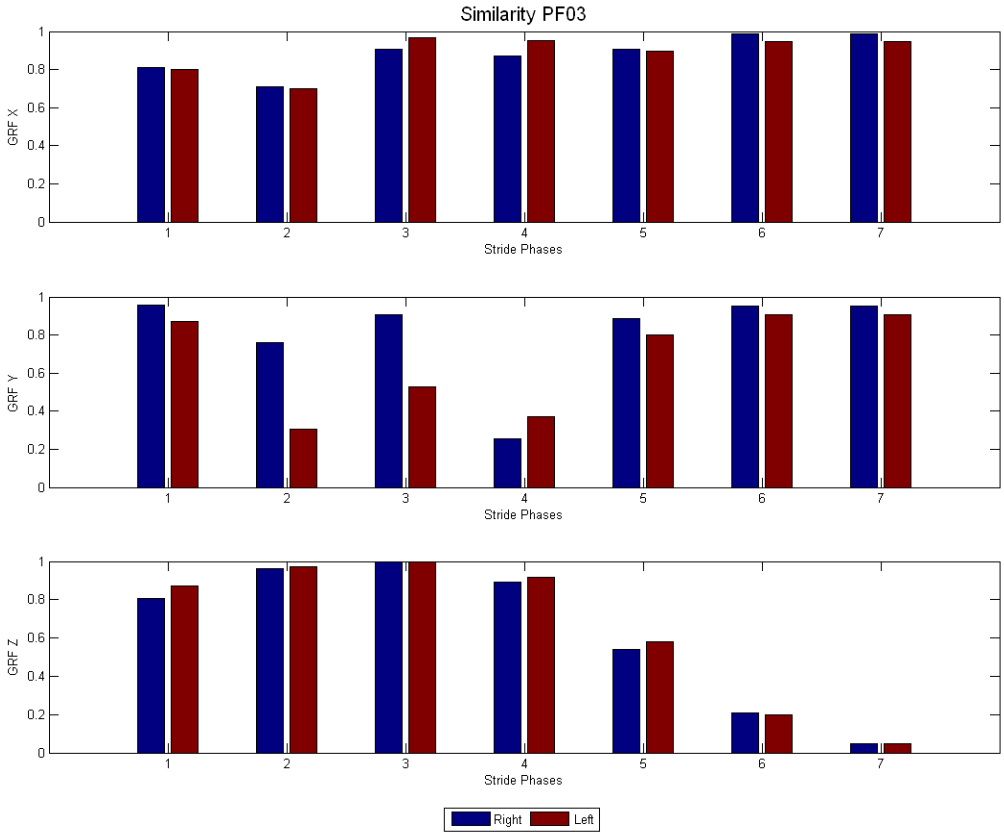

Figure 6.20: Result for Fuzzy Similarity for Ground Reaction Forces of Control Group against PF03, where the left foot is represented in red and right foot is represented in blue

By analyzing the EMG information, we have noticed that there is an early activation on soleous, tibialis anterior, and lateral grastocnemious. PF03 has also presented muscle weakness on soleous for right and left foot. On Figure 6.21 results for the EMG on left foot (Blue) and right foot (Red) compared with control group (Black).

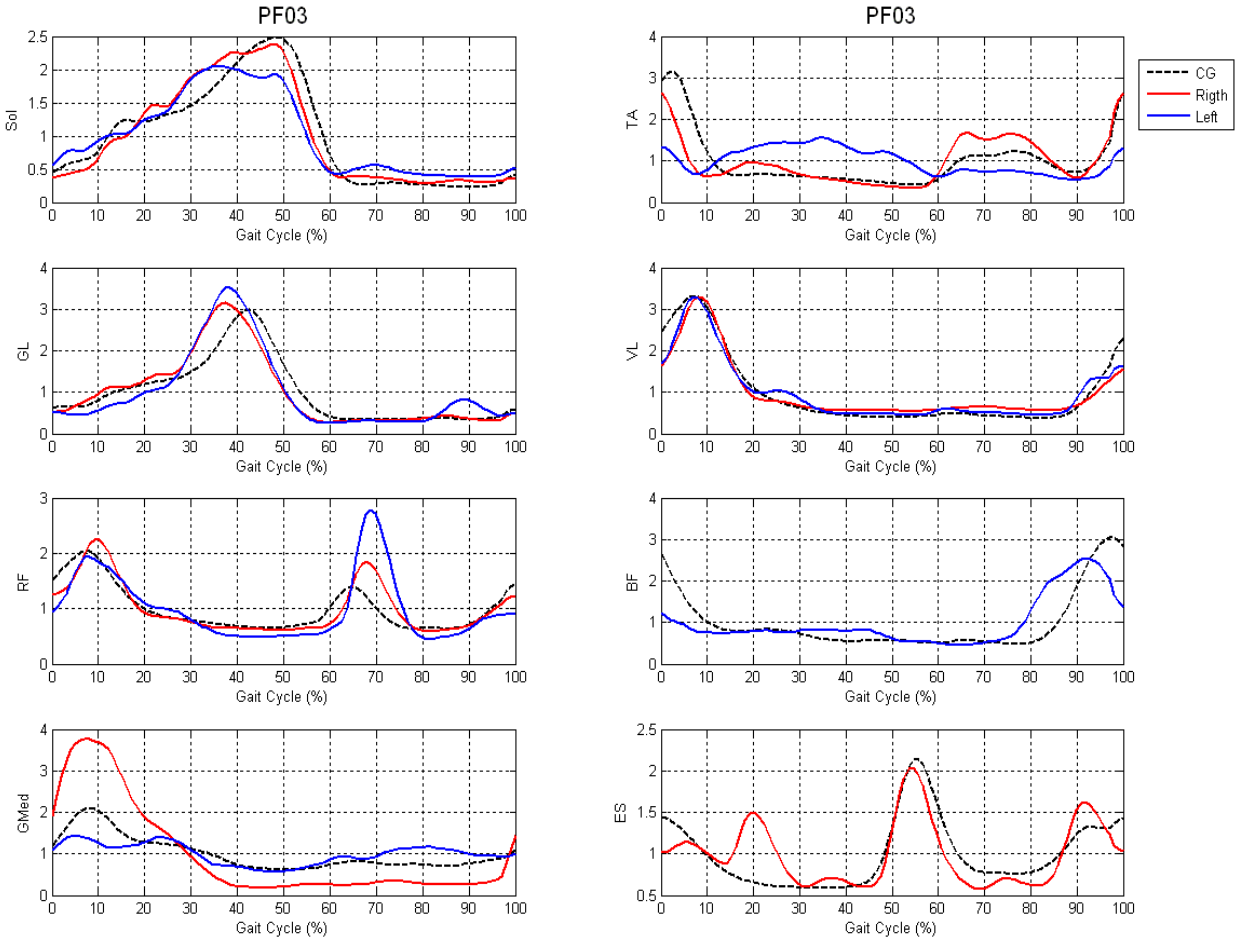

Figure 6.21: Result for EMG on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

Fuzzy similarity results are also presented for this patient analysis. This is to present quantitative results on the EMG information.

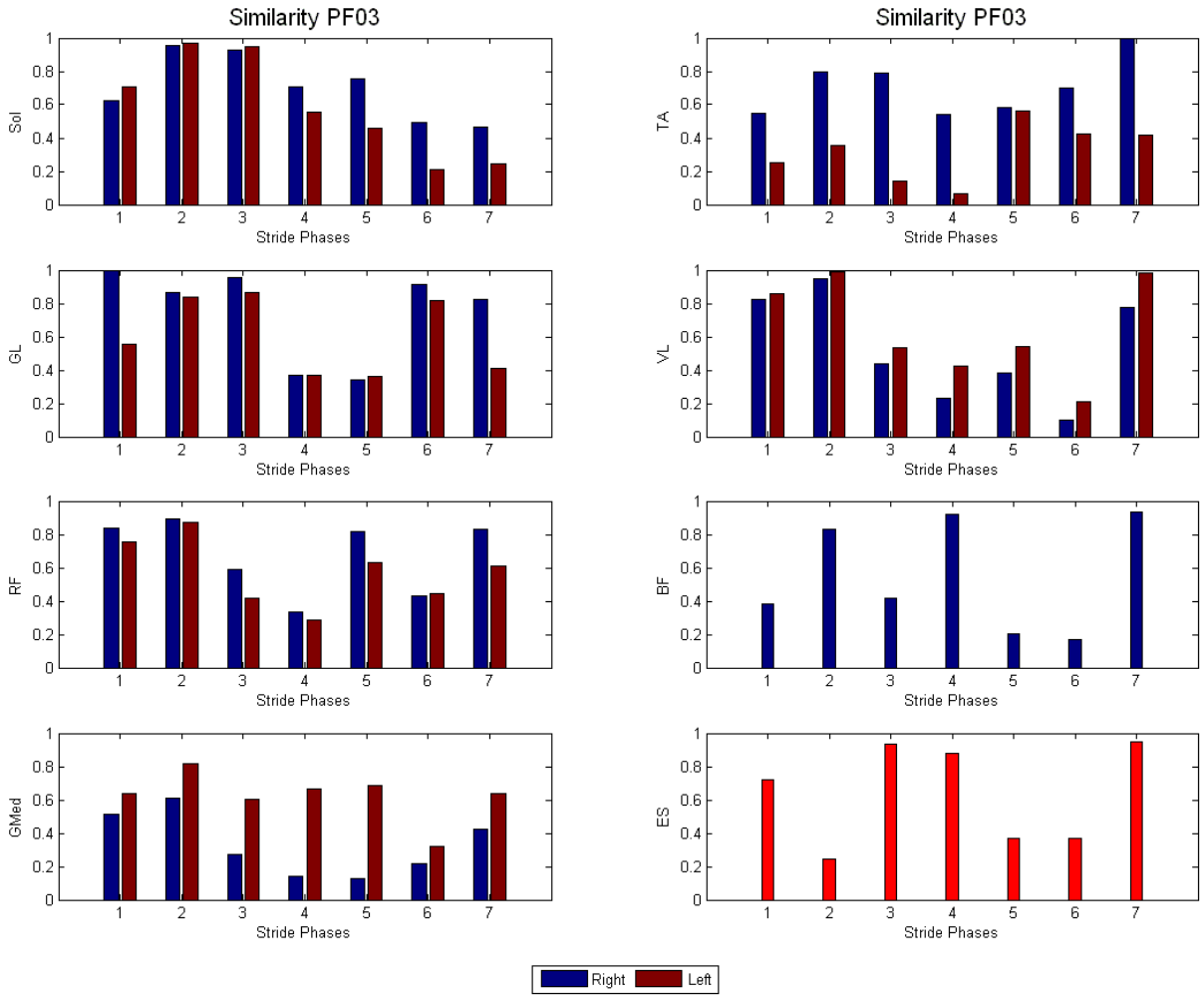

Figure 6.22: Result for Fuzzy Similarity for EMG of Control Group against PF03, where the left foot is represented in red and right foot is represented in blue

Joint kinematics for PF03 has shown that there is a decreased angle in range of motion for subtalar joint on right foot, which is the same lower limb which presented muscle weakness on soleus. Figure 6.23 displays the range of motion of the ankle, knee, and hip on the X, Y, and Z axes. The red color represents the right lower limb while the blue color represents the left lower limb. The black color represents the control group.

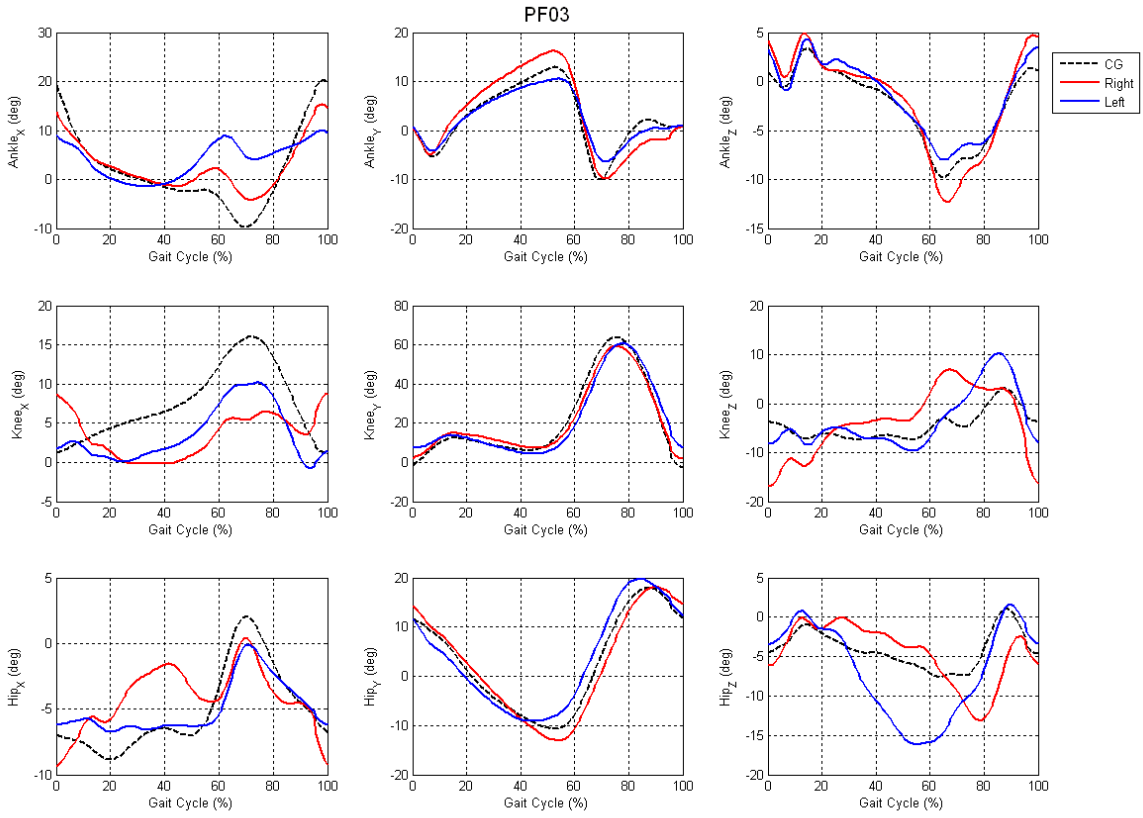

Figure 6.23: Kinetics for PF03. The right lower limb is represented in red, and left lower limb is represented in blue. The control group is represented in black for comparison

Fuzzy similarity is presented on figures 6.24, 6.25 and 6.26. The lack of similarity on sagittal plane for ankle and knee is displayed.

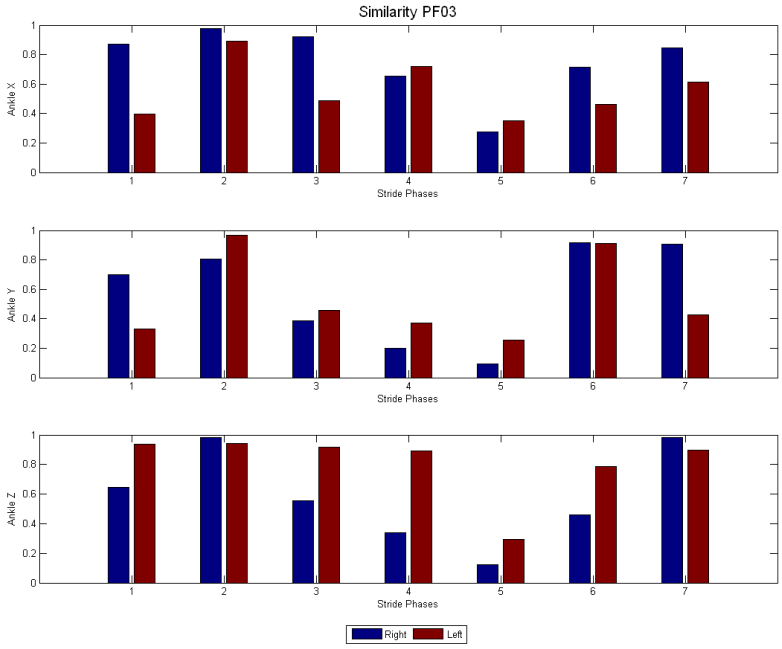

Figure 6.24: Fuzzy Similarity Results from Subtalar Joint of PF03 on X, Y, and Z axes

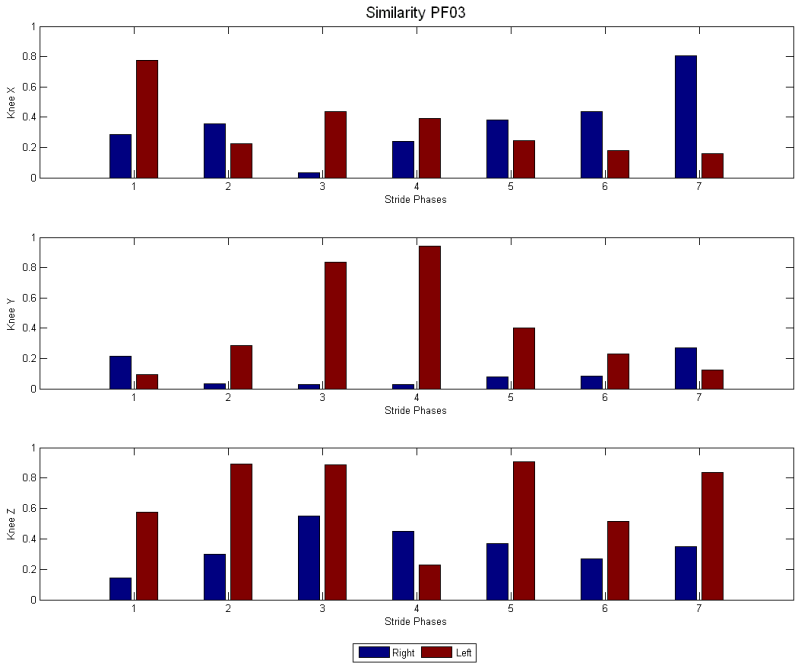

Figure 6.25: Fuzzy Similarity Results from Knee of PF03 on X, Y, and Z axes

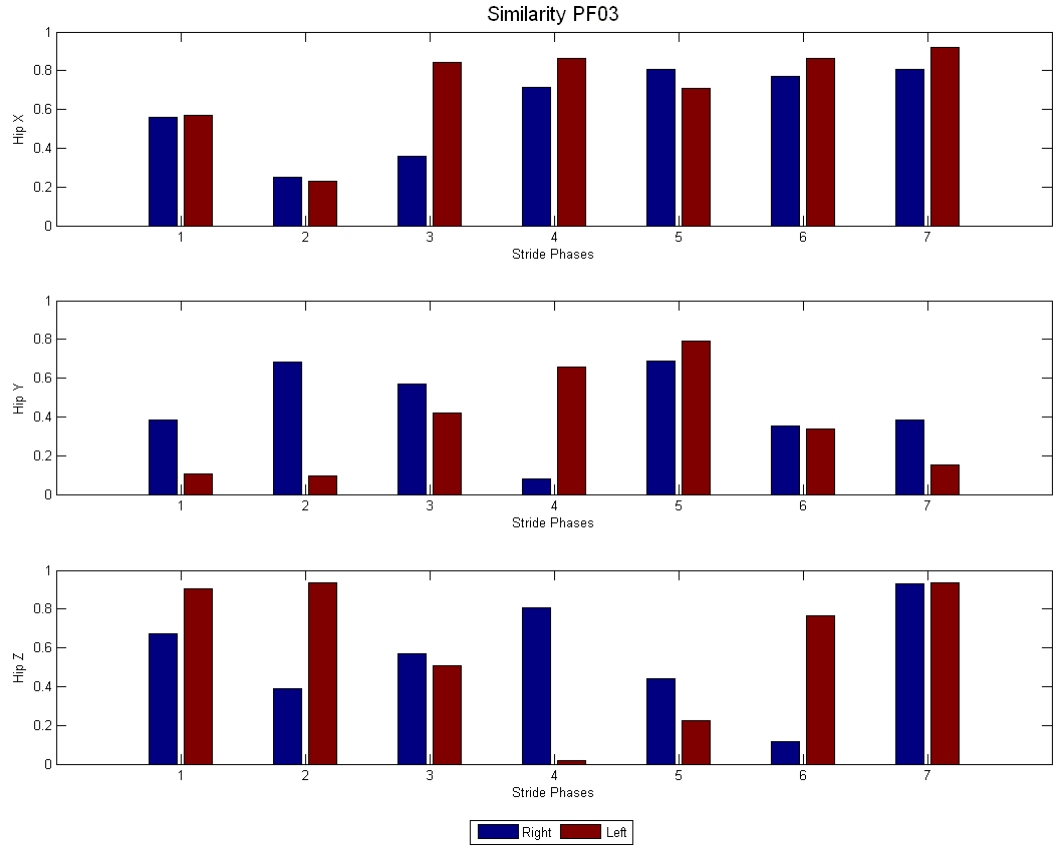

Figure 6.26: Fuzzy Similarity Results from Hip of PF03 on X, Y, and Z axes

The F-scan results show that diabetic neuropathy does not develop at the same time on both feet. We can observe that there is higher pressure shown on the left foot. Higher pressure on left foot is presented on first metatarsal and third metatarsal for treadmill trial. Figures 6.27 and 6.28 display from left to right the following results; The pressures from the heel that are averaged from the treadmill (AVG TD) trial of the control group, and the pressure of the heel of the over ground (AVG OG) trial of the control group. After these results, we can also observe pressures of the female patient 03 on the treadmill (PF03 TD), and last we can see the information for female patient 03 of the over ground trial (PF03 OG). This format will continue the same for the first metatarsal, third metatarsal, and big toe.

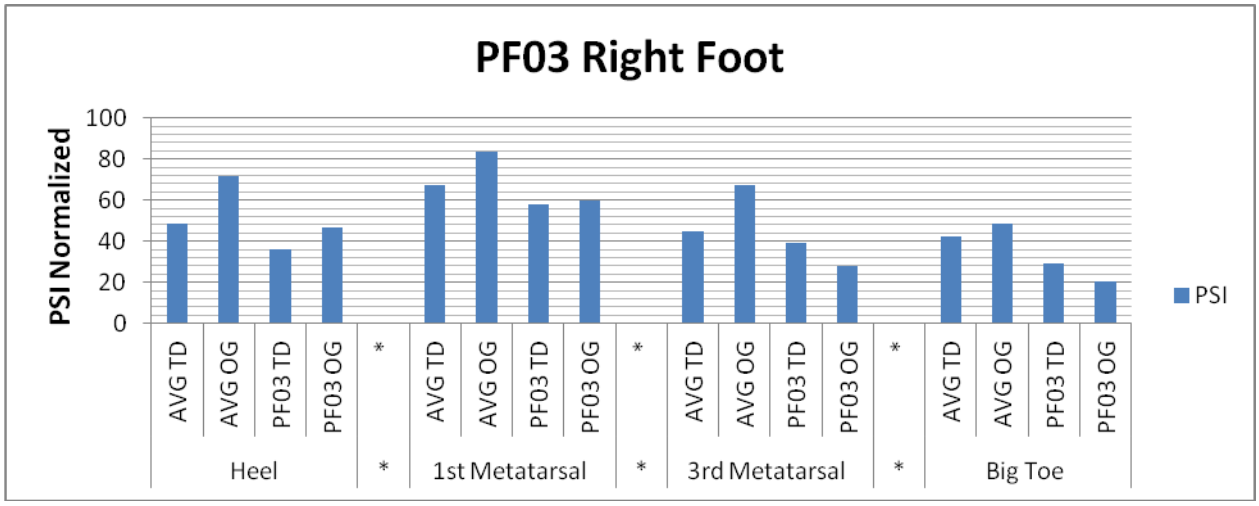

Figure 6.27: F-scan Results from PF03 Right Foot on Four Pressure Points Compared with Control Group

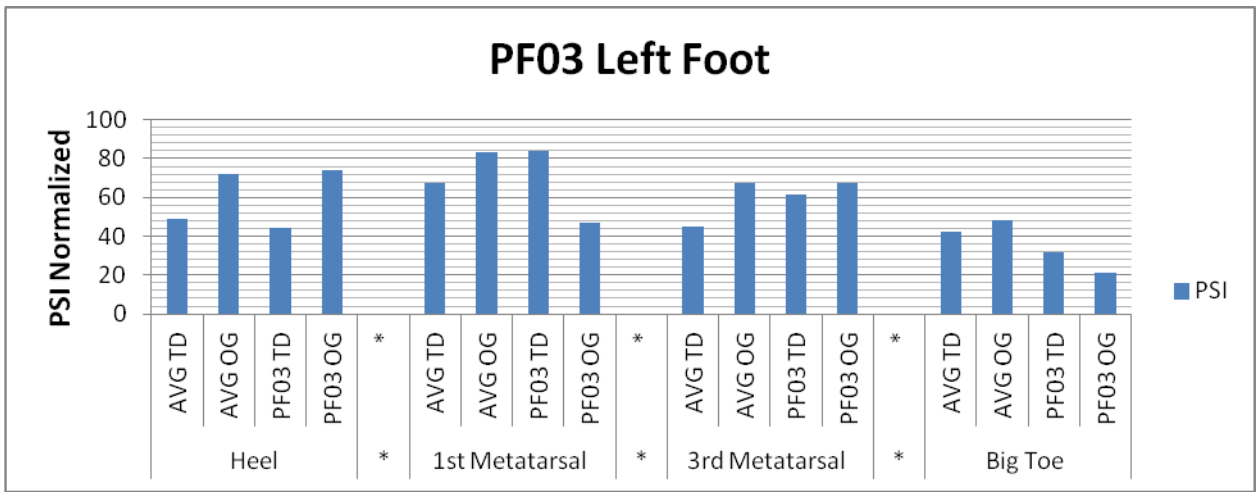

Figure 6.28: F-scan Results from PF03 Left Foot on Four Pressure Points Compared with Control Group

The 10 gram monofilament test was assessed during this experiment and showed that PF03 failed on four areas for left foot. The right foot of PF03 failed only on the fifth metatarsal pressure area. As seen on table 6.3, the results from the 10 gram monofilament test are presented. Because PF03 failed the 10 gram monofilament test, PF03 was a candidate to be tested with a higher pressure monofilament.

Table 6.3: Results from Monofilament test of Female Patient 03. P=Pass, or Fail

Fail 10gr Monofilament Test on more > 2 areas

	Heel		1st Metatarsal		3rd Metatarsal		5th Metatarsal		Big Toe	
	R	L	R	L	R	L	R	L	R	L
PF03	P	P	fail	P	fail	P	P	P	P	P

6.4 Case Study 4

6.4.1 General Information (PF04)

Female patient 04, identified as PF04, is 26 years-old with a height of 161 centimeters and a body weight of 100.7 kilograms. This patient has been diagnosed with diabetes mellitus for 4 years. By a physical inspection, no callus was found on sole area. A speed was performed on instrumented treadmill trial is similar to the control group (self-selected speed for this patient was 0.85 m/s, same as PF03) and the noticeable difference in the ground reaction forces is the delay presented on three axes. Figure 7.29 displays the results of the ground reaction forces of the left foot (blue) and right foot (red).

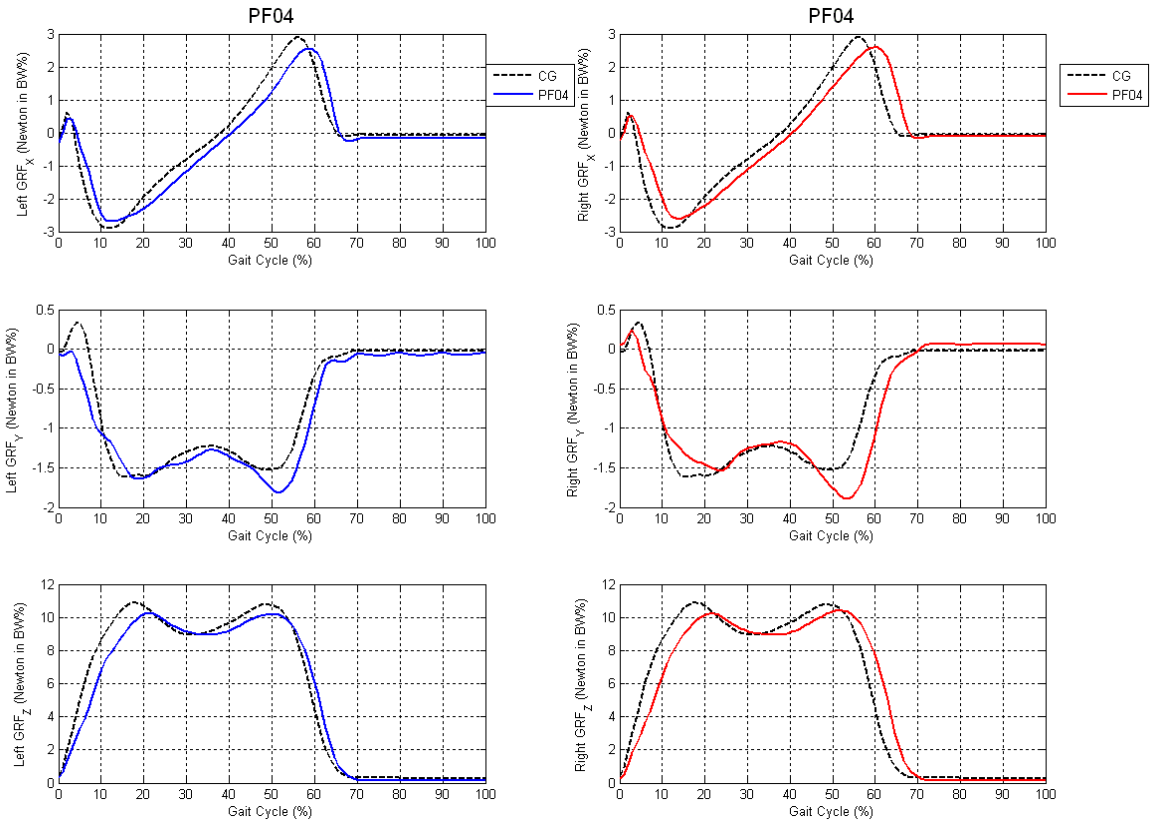

Figure 6.29: Result for Ground Reaction Forces on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

Quantitative results can be shown in figure 6.30 by using the fuzzy similarity between the control group and female patient 04. The ground reaction force results of PF04 that are closest to magnitude 1 conclude that the grade of similarity to the control group is bigger. Fuzzy similarity results can be viewed in figure 6.30.

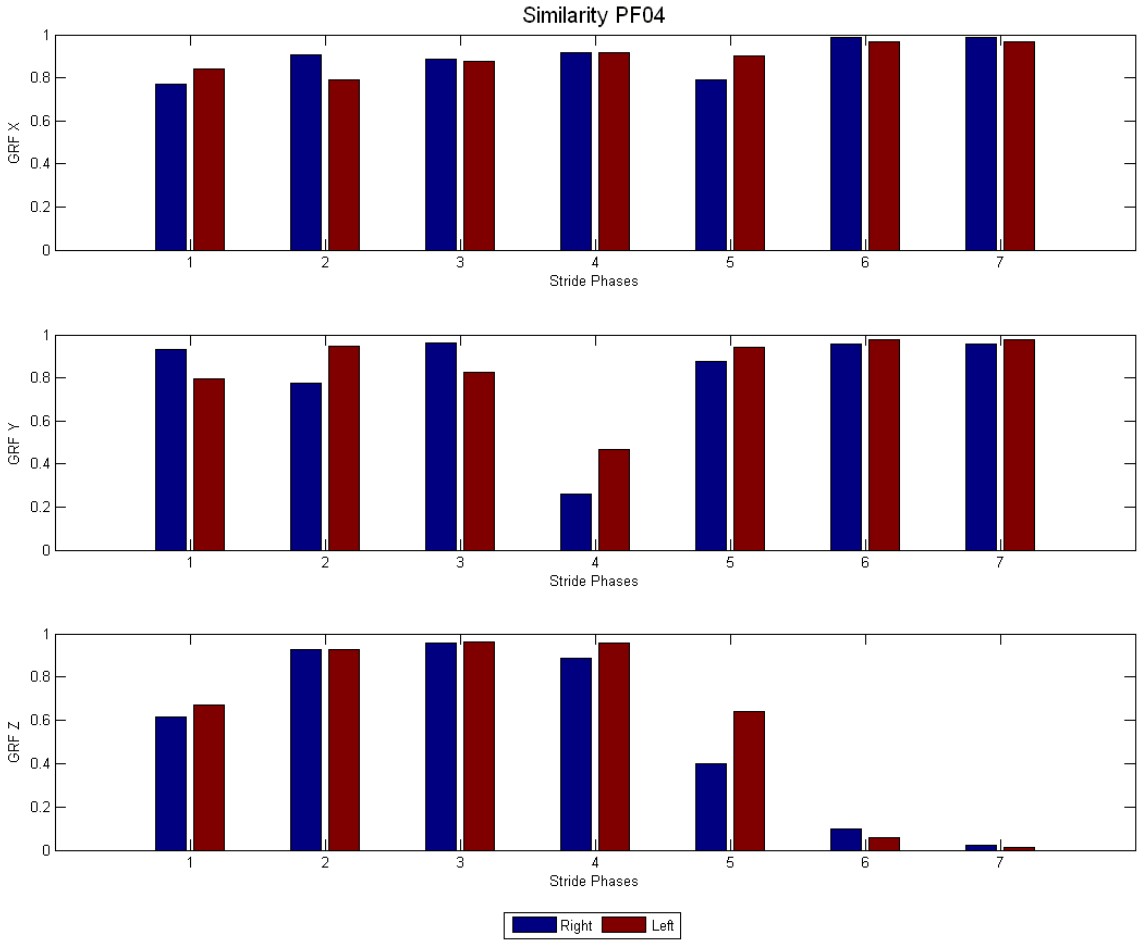

Figure 6.30: Result for Fuzzy Similarity for Ground Reaction Forces of Control Group against PF04, where the left foot is represented in red and right foot is represented in blue

By analyzing the EMG information, we have noticed that there is an early activation on soleous, tibialis anterior, and lateral grastocnemious. PF04 has also presented muscle weakness on soleous and vastus lateralis for right and left foot. On Figure 6.31 results for the EMG on left foot (Blue) and right foot (Red) compared with control group (Black).

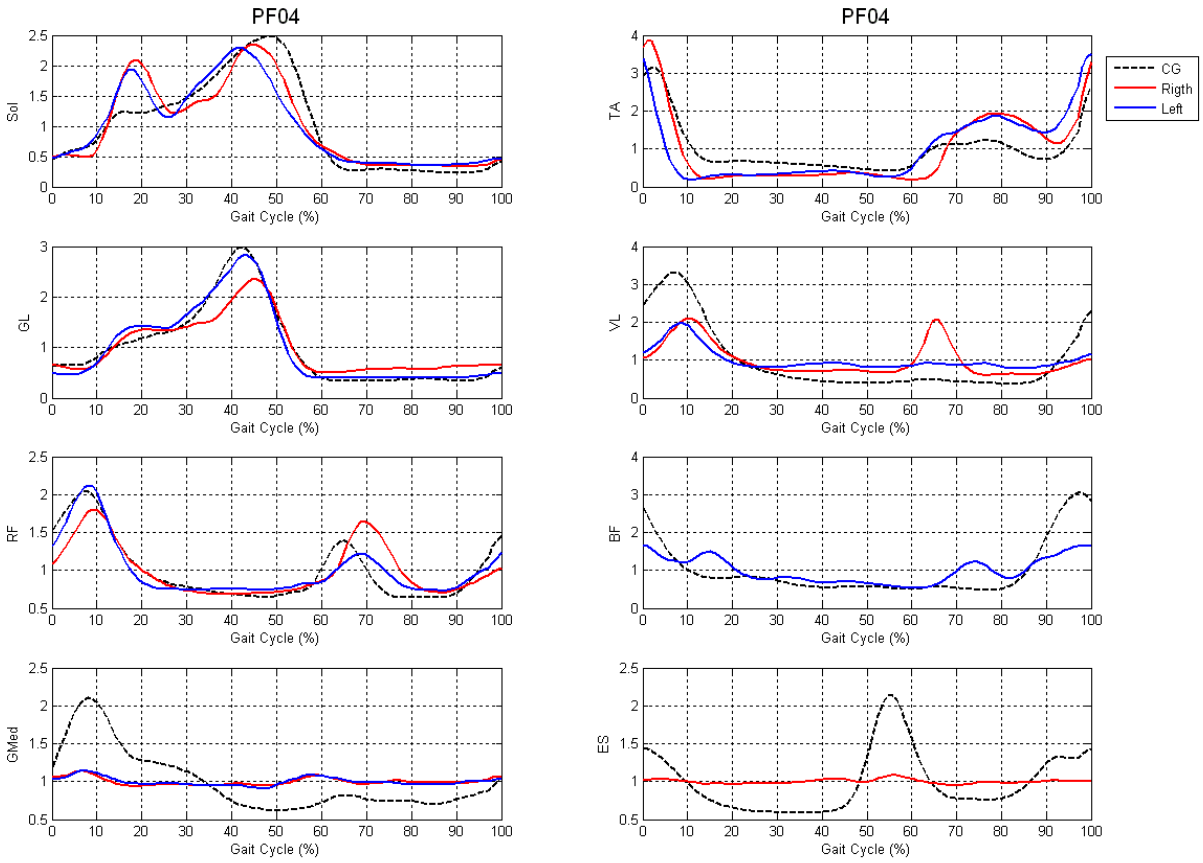

Figure 6.31: Result for EMG on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

This information has been processed with fuzzy similarity to obtain quantitative results. Quantitative results are presented on figure 6.32.

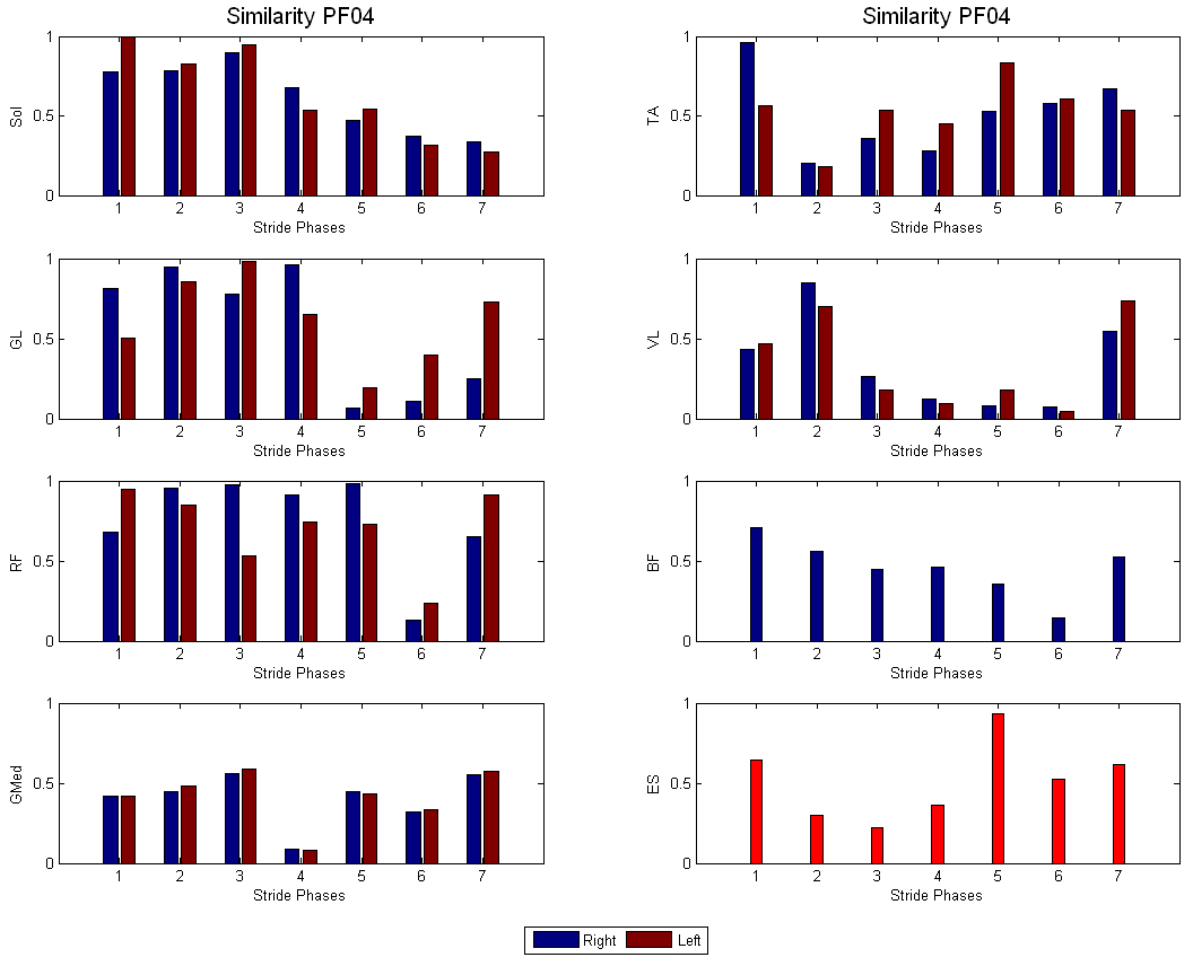

Figure 6.32: Result for Fuzzy Similarity for EMG of Control Group against PF04, where the left foot is represented in red and right foot is represented in blue

Joint kinematics for PF04 has shown that there is a decreased angle in range of motion for the knee joint on left lower limb in sagittal plane, where 99% of the relevant information is concentrated. Figure 6.33 displays the range of motion of the ankle, knee, and hip on the X, Y, and Z axes. The red color represents the right lower limb while the blue color represents the left lower limb. The black color represents the control group.

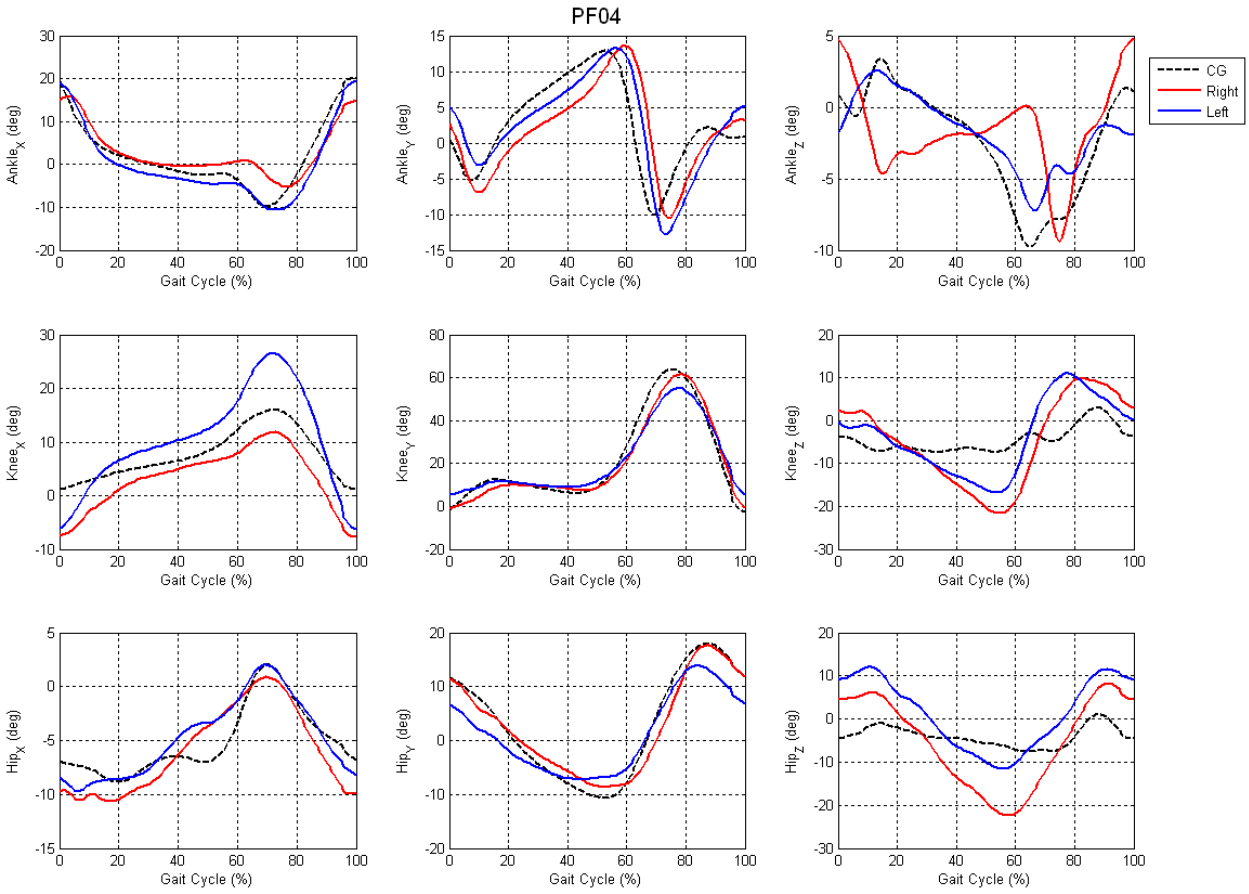

Figure 6.33: Kinetics for PF04. The right lower limb is represented in red, and left lower limb is represented in blue. The control group is represented in black for comparison

Fuzzy similarity is presented on figures 6.34, 6.35 and 6.36. The lack of similarity on sagittal plane for ankle and knee is displayed.

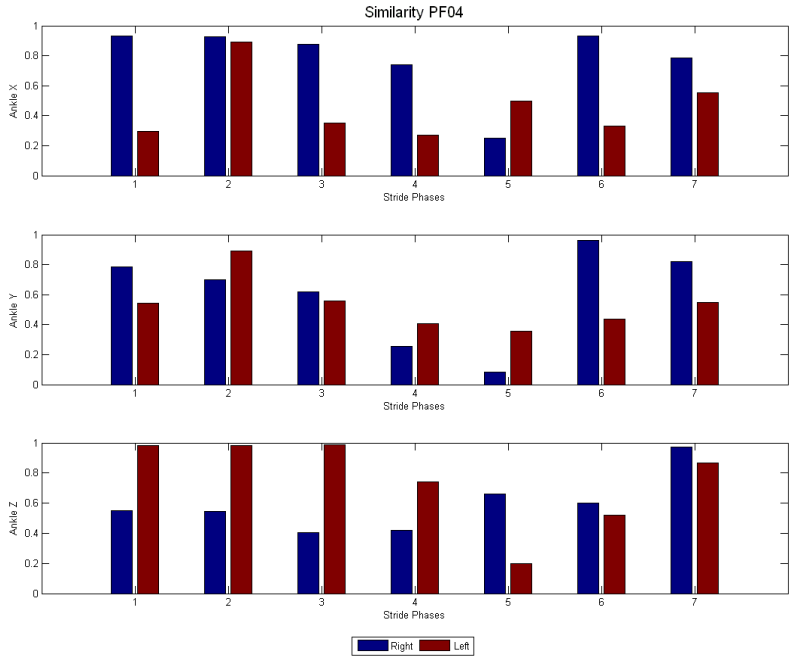

Figure 6.34: Fuzzy Similarity Results from Subtalar Joint of PF04 on X, Y, and Z axes

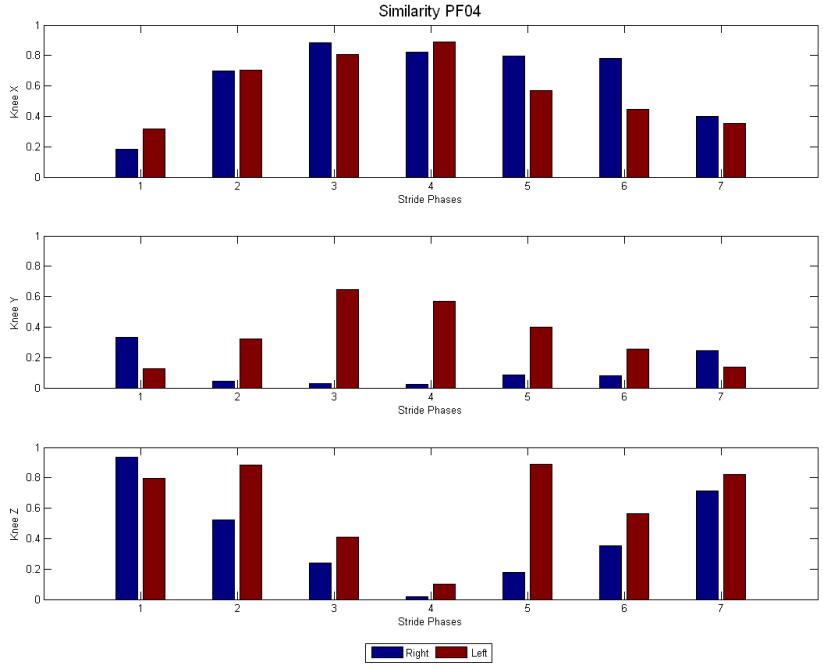

Figure 6.35: Fuzzy Similarity Results from Knee of PF04 on X, Y, and Z axes

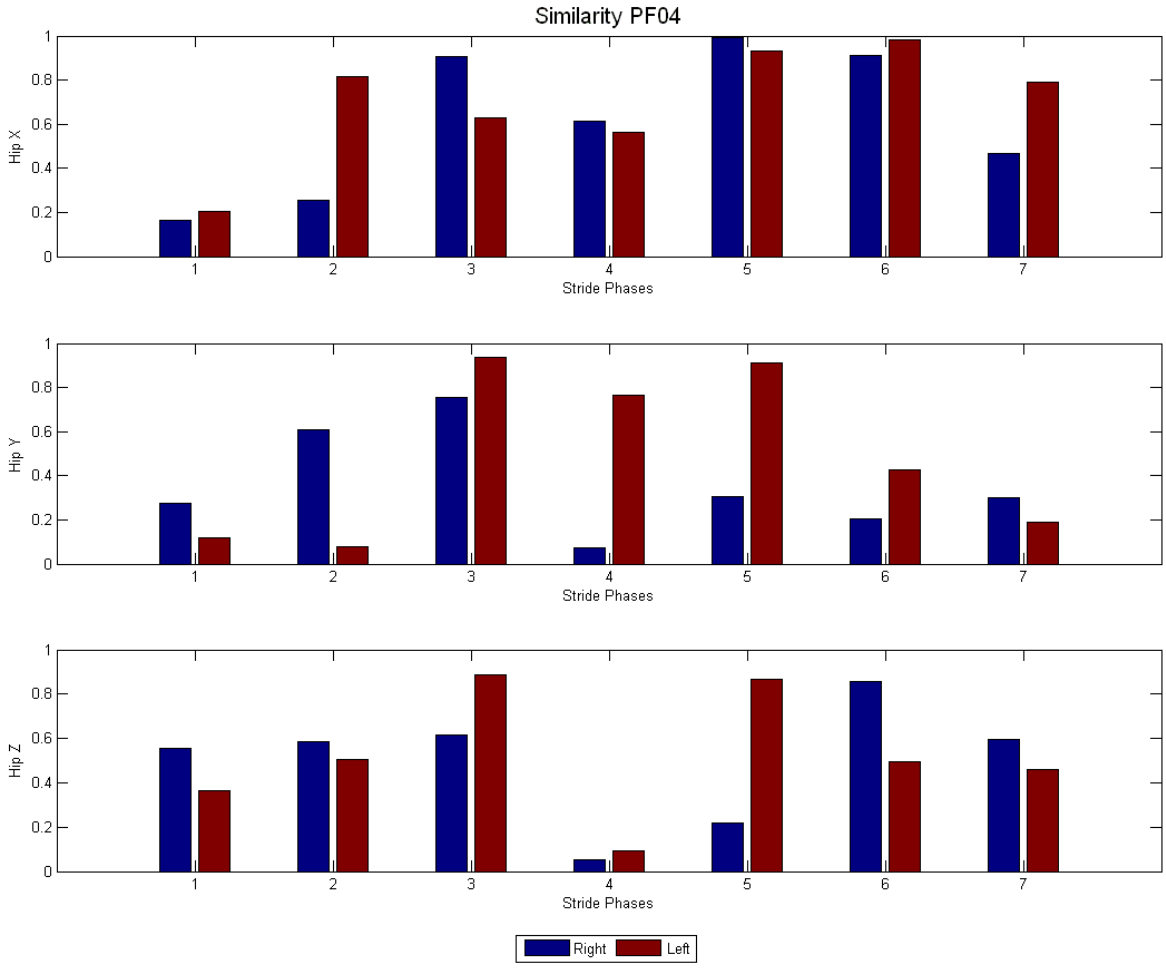

Figure 6.36: Fuzzy Similarity Results from Hip of PF04 on X, Y, and Z axes

The F-scan results show that diabetic neuropathy does not develop at the same time on both feet. We can observe that there is higher pressure shown on the left foot. Higher pressure on left foot is presented on first metatarsal and third metatarsal for treadmill trial. Figures 6.37 and 6.38 display from left to right the following results; The pressures from the heel that are averaged from the treadmill (AVG TD) trial of the control group, and the pressure of the heel of the over ground (AVG OG) trial of the control group. After these results, we can also observe pressures of the female patient 04 on the treadmill (PF04 TD), and last we can see the information for female patient 04 of the over ground trial (PF04 OG). This format will continue the same for the first metatarsal, third metatarsal, and big toe.

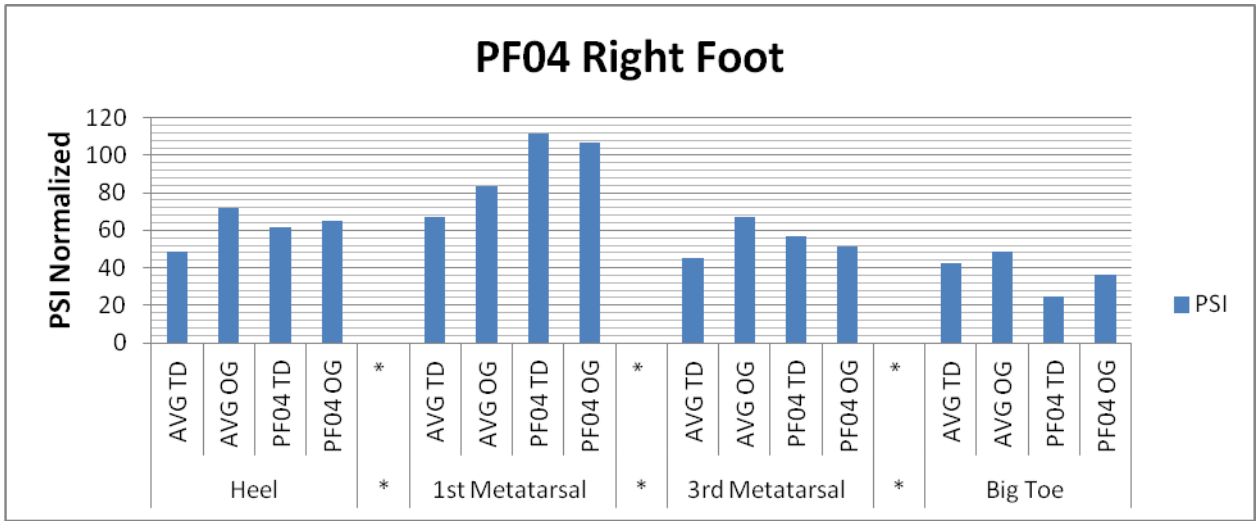

Figure 6.37: F-scan Results from PF04 Right Foot on Four Pressure Points Compared with Control Group

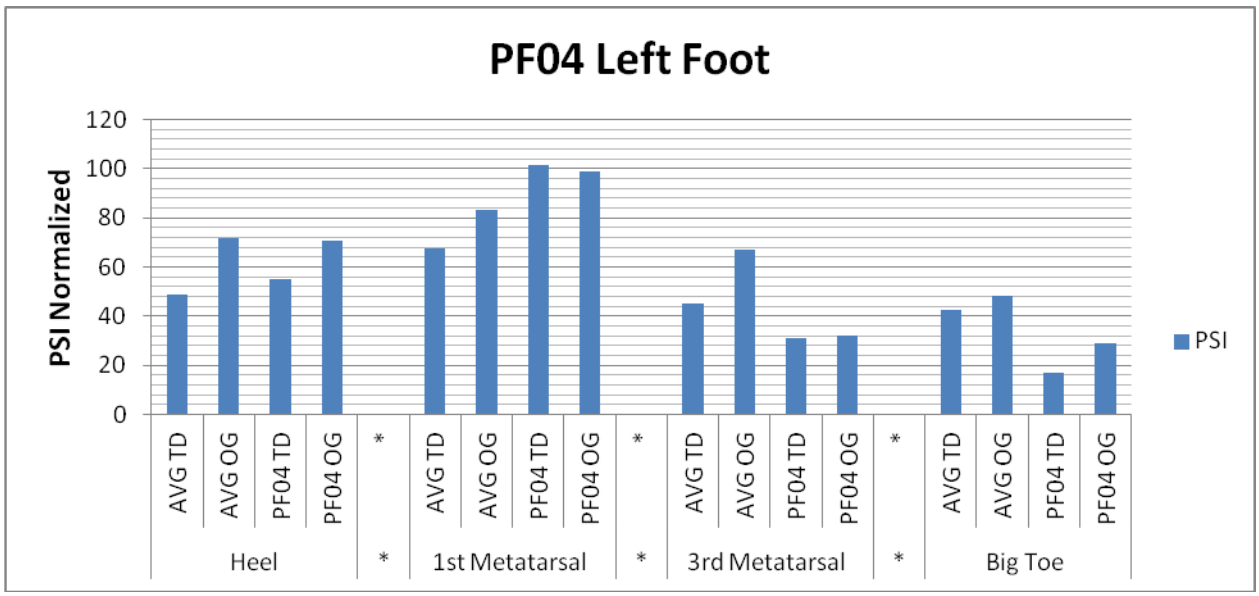

Figure 6.38: F-scan Results from PF04 Left Foot on Four Pressure Points Compared with Control Group

As seen on table 6.4, the results from the 10 gram monofilament test are presented. The 10 gram monofilament test was assessed during this experiment has showed that PF04 passed.

Table 6.4: Results from Monofilament test of Female Patient 04. P=Pass, or Fail

Fail 10gr Monofilament Test on more > 2 areas

	Heel		1st Metatarsal		3rd Metatarsal		5th Metatarsal		Big Toe	
	R	L	R	L	R	L	R	L	R	L
PF04	P	P	P	P	P	P	P	P	P	P

6.5 Case Study 5

6.5.1 General Information (PF05)

Female patient 05, identified as PF05, is 34 years-old with a height of 168 centimeters and a body weight of 141.3 kilograms. This patient has been diagnosed with diabetes mellitus for 4 years. By a physical inspection, no callus was found on sole area. A speed was performed on instrumented treadmill trial is similar to the control group (self-selected speed for this patient was 0.7 m/s). The vertical ground reaction force "M" shape tends to become a "N" shape, along with a small delay on stance phase that can be noticed on the X, Y, and Z axes ground reaction forces on both the right and left foot. The Figure 6.39 displays the results of the ground reaction forces of the left foot (blue) and right foot (red).

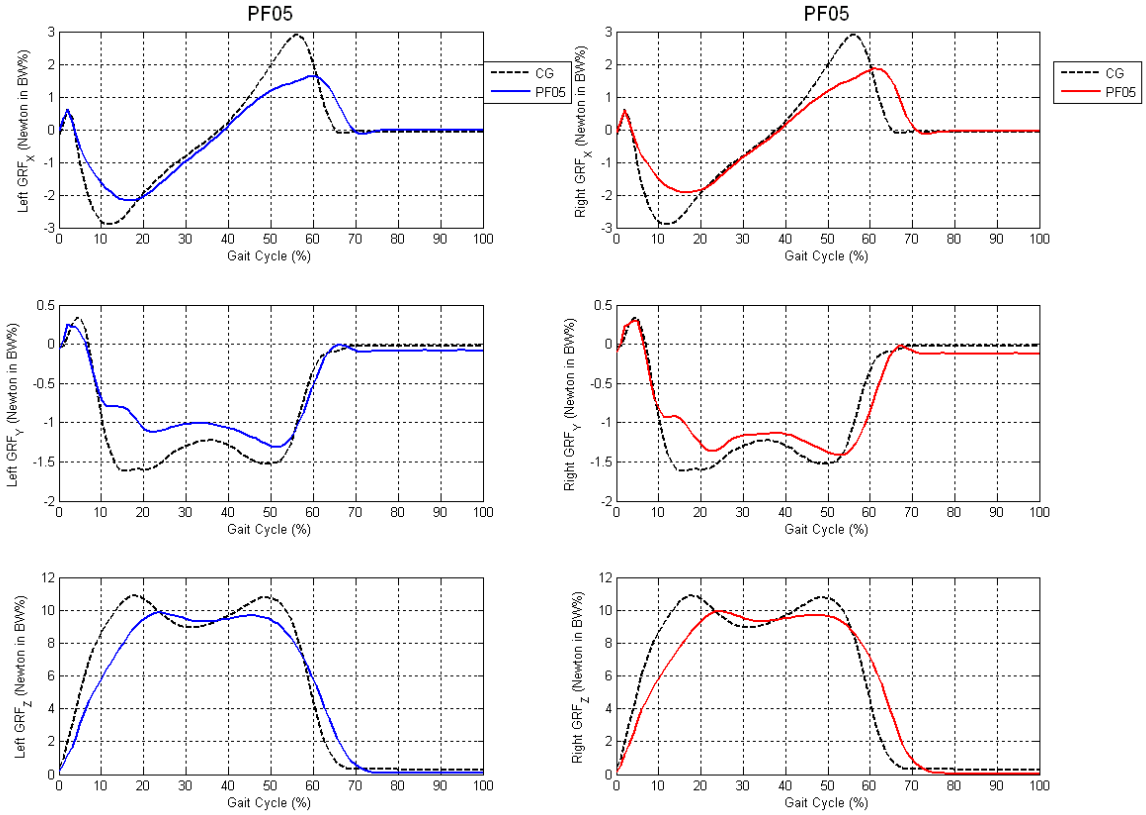

Figure 6.39: Result for Ground Reaction Forces on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

Quantitative results from the ground reaction forces can be shown in figure 6.40 by using the fuzzy similarity between the control group and female patient 05. The ground reaction force results of PF05 that are closest to magnitude 1 conclude that the grade of similarity to the control group is bigger. Fuzzy similarity results can be viewed in figure 6.40.

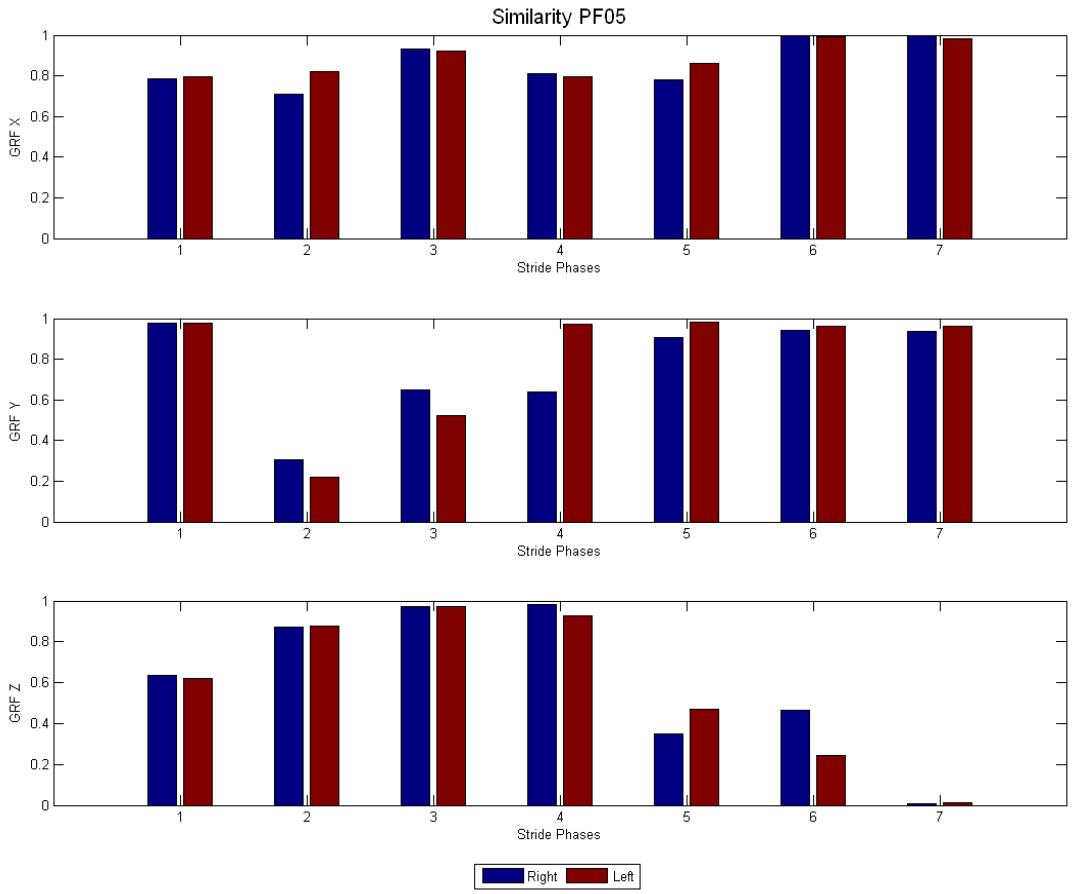

Figure 6.40: Result for Fuzzy Similarity for Ground Reaction Forces of Control Group against PF05, where the left foot is represented in red and right foot is represented in blue

By analyzing the EMG information, we have noticed that muscle weakness is present on tibialis anterior, lateral grastocnemious, vastus lateralis, and recuts femoris for right and left foot. PF05 has also presented delay on right soleous and an early activation for lateral gastrocnemious. On Figure 6.41 results for the EMG on left foot (Blue) and right foot (Red) compared with control group (Black).

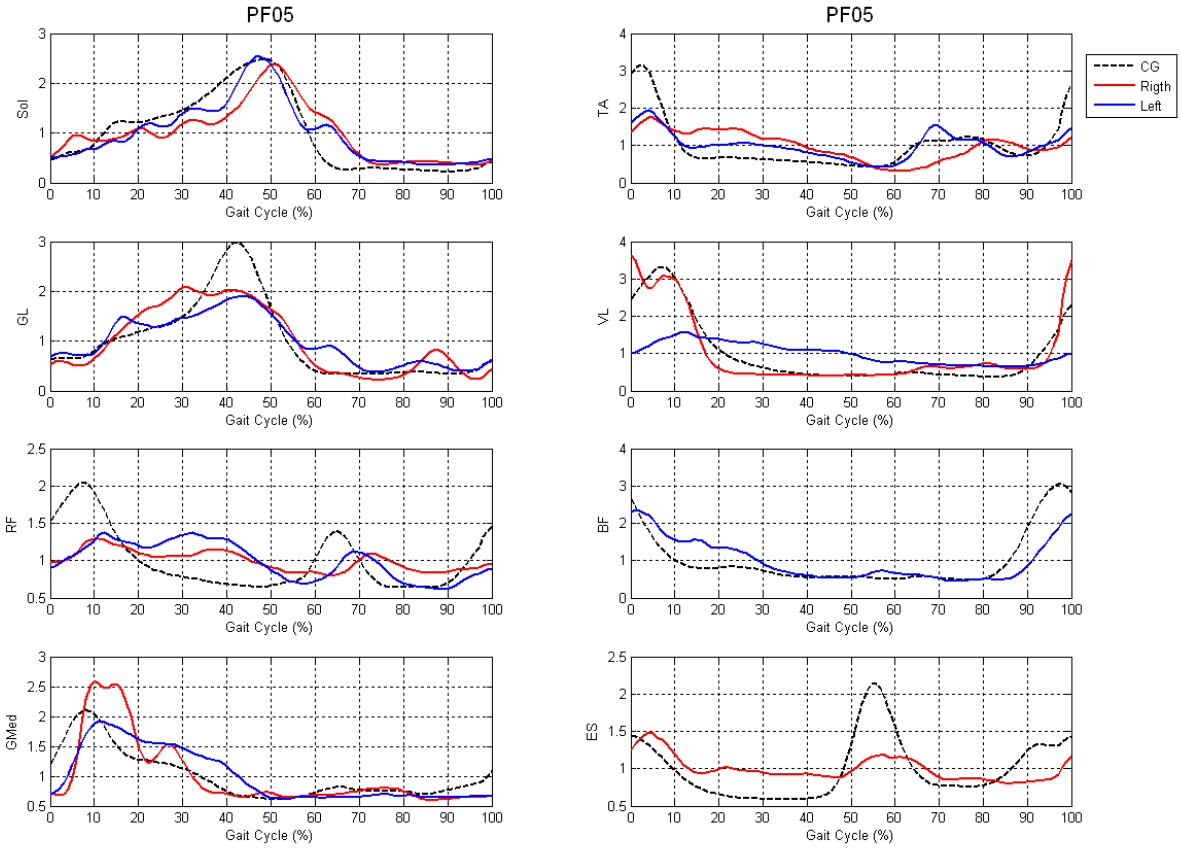

Figure 6.41: Result for EMG on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

This information has been processed with fuzzy similarity to obtain quantitative results. Quantitative results are presented on figure 6.42.

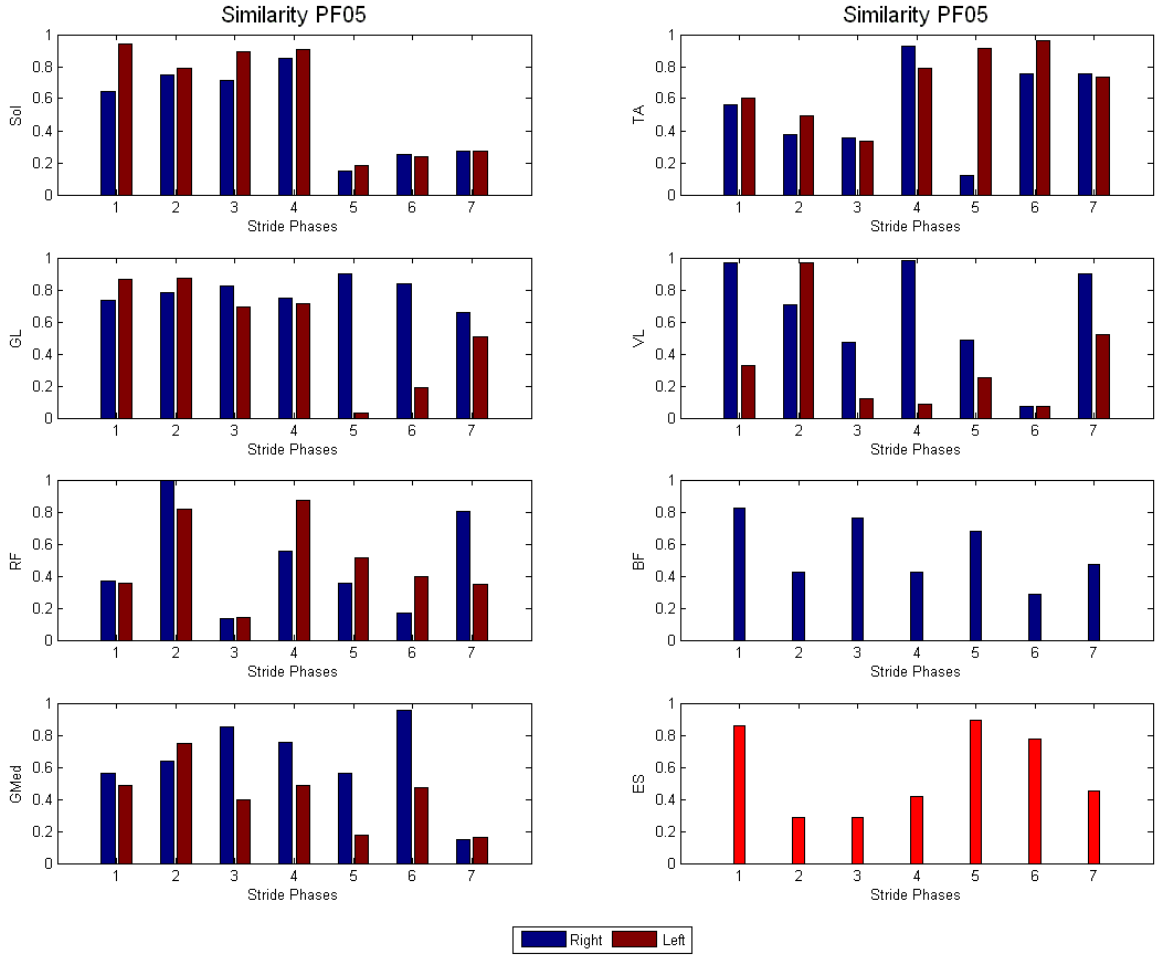

Figure 6.42: Result for Fuzzy Similarity for EMG of Control Group against PF05, where the left foot is represented in red and right foot is represented in blue

Joint kinematics for PF05 has shown that there is a decreased angle in range of motion for subtalar joint on right foot, which is the same lower limb which presented the most muscle weakness on tibialis atnerior and lateral gatrocnemious. Figure 6.43 displays the range of motion of the ankle, knee, and hip on the X, Y, and Z axes. The red color represents the right lower limb while the blue color represents the left lower limb. The black color represents the control group.

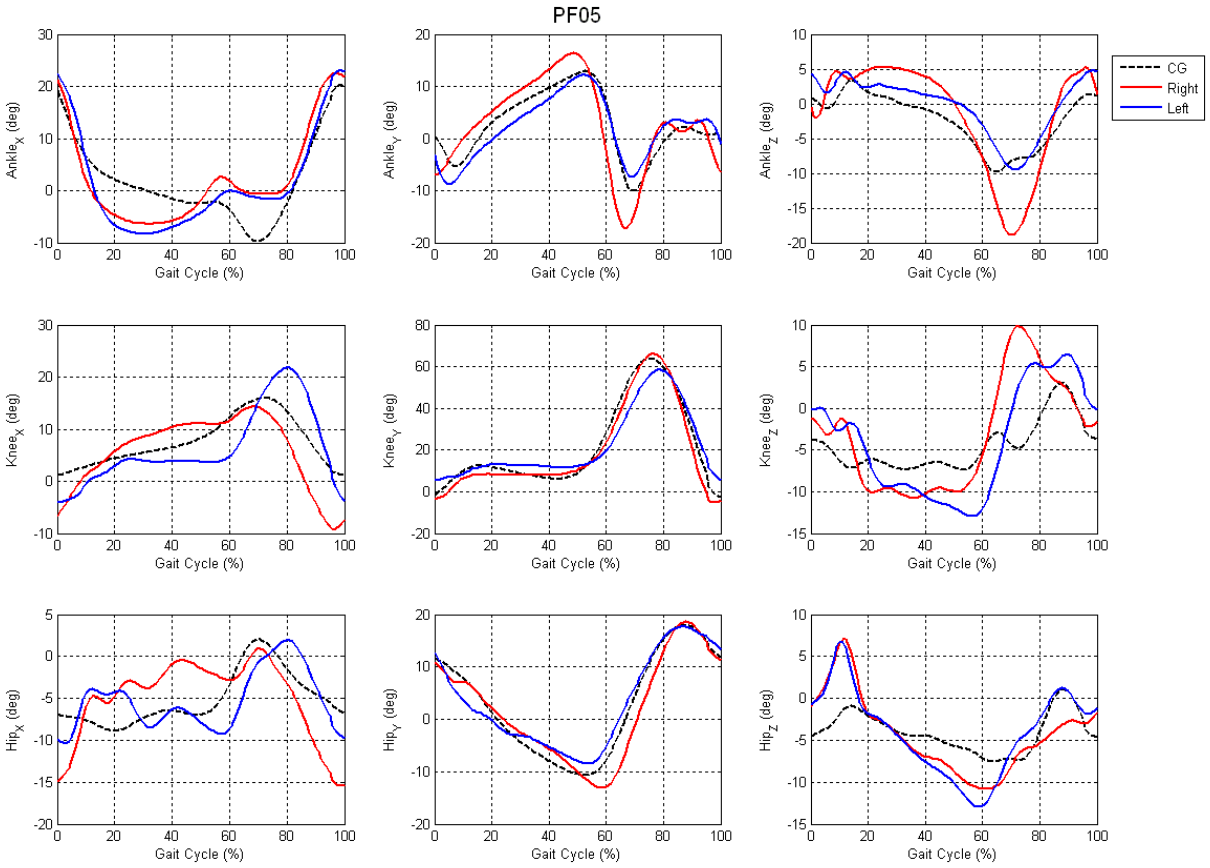

Figure 6.43: Kinetics for PF05. The right lower limb is represented in red, and left lower limb is represented in blue. The control group is represented in black for comparison

Fuzzy similarity is presented on figures 6.44, 6.45 and 6.46. The lack of similarity is evident on sagittal plane for ankle, knee and hip is displayed.

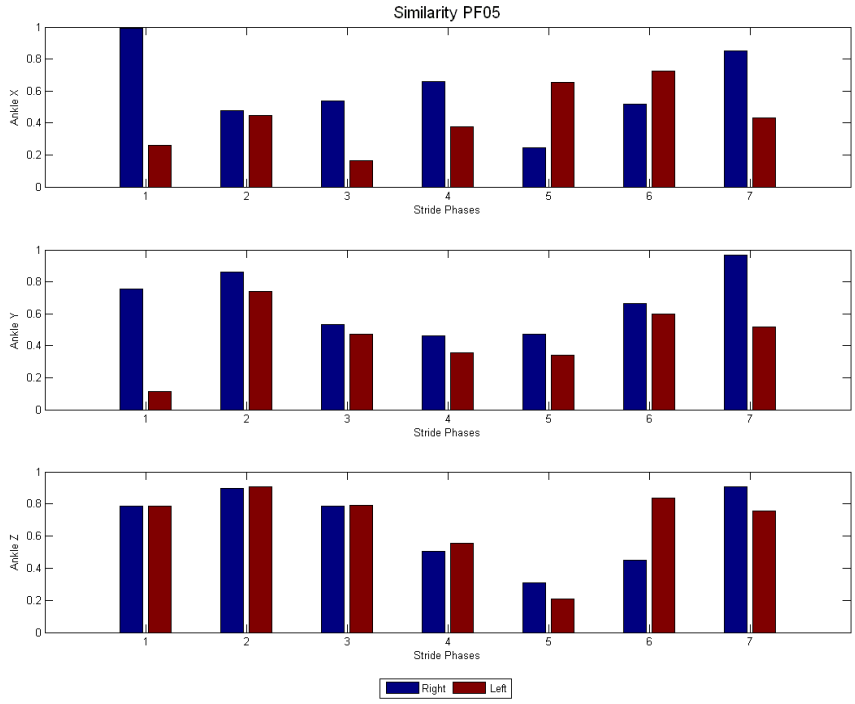

Figure 6.44: Fuzzy Similarity Results from Subtalar Joint of PF05 on X, Y, and Z axes

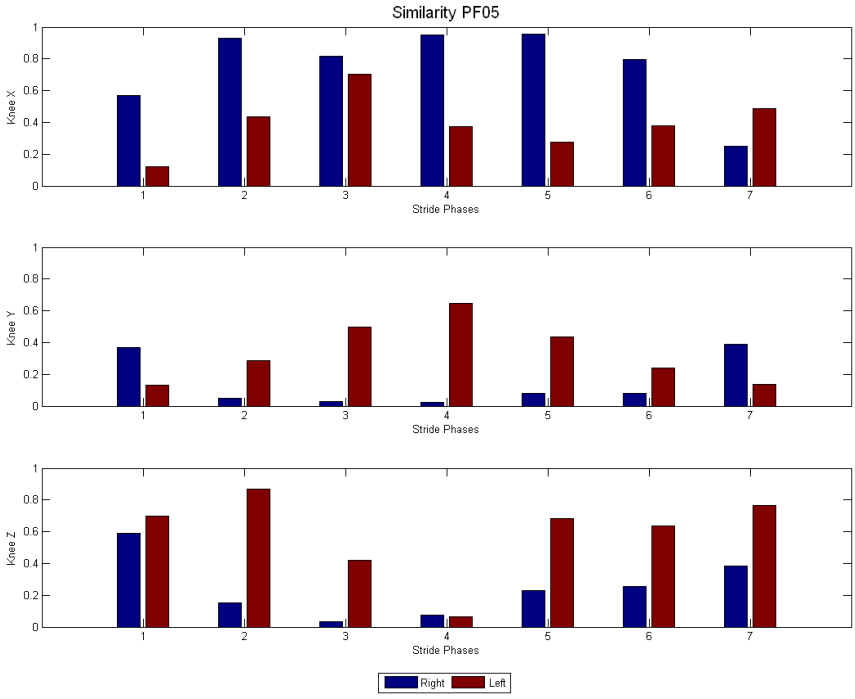

Figure 6.45: Fuzzy Similarity Results from Knee of PF05 on X, Y, and Z axes

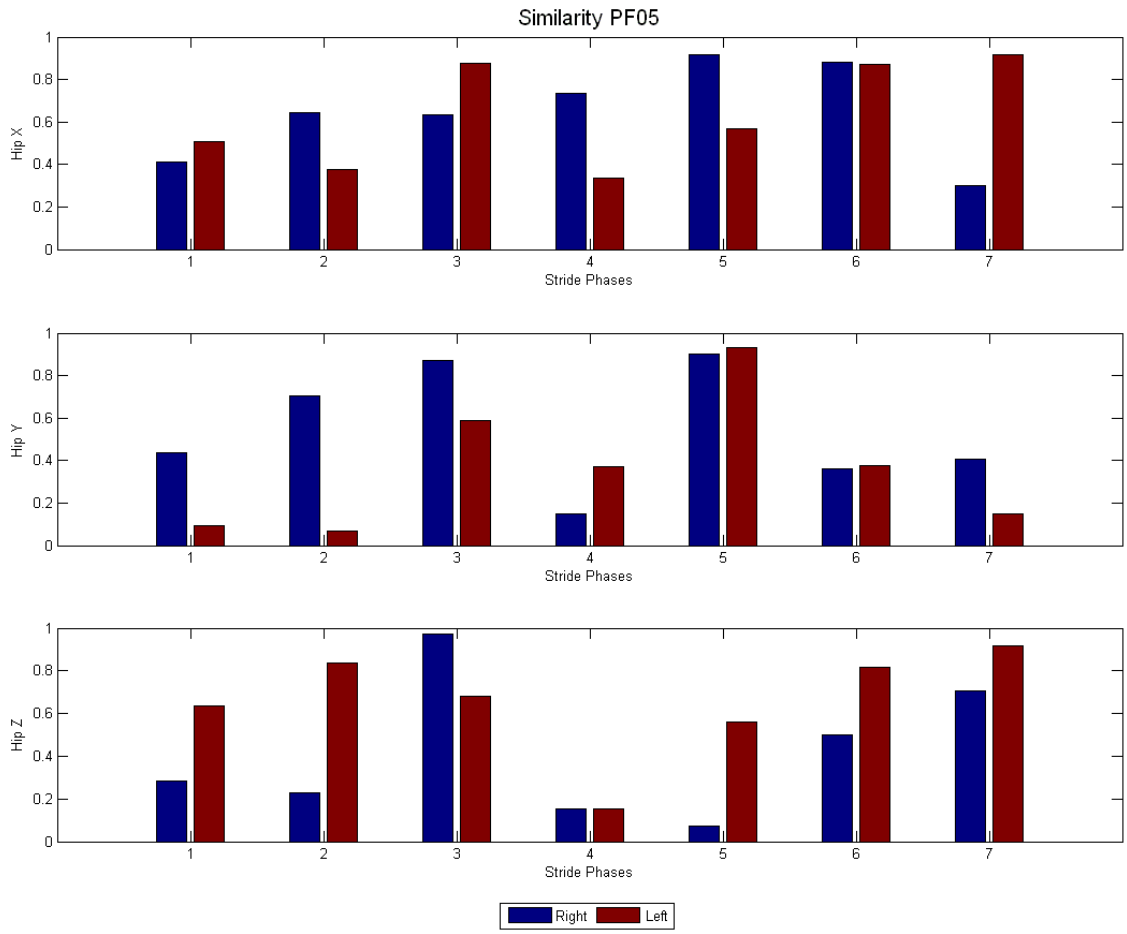

Figure 6.46: Fuzzy Similarity Results from Hip of PF05 on X, Y, and Z axes

The F-scan results show that diabetic neuropathy does not develop at the same time on both feet. We can observe that there is higher pressure on the right foot. Higher pressure on right foot is presented on the four studied areas, for the treadmill trial, and the over ground trial. Figures 6.47 and 6.48 display from left to right the following results; The pressures from the heel that are averaged from the treadmill (AVG TD) trial of the control group, and the pressure of the heel of the over ground (AVG OG) trial of the control group. After these results, we can also observe pressures of the female patient 05 on the treadmill (PF05 TD), and last we can see the information for female patient 05 of the over ground trial (PF05 OG). This format will continue the same for the first metatarsal, third metatarsal, and big toe.

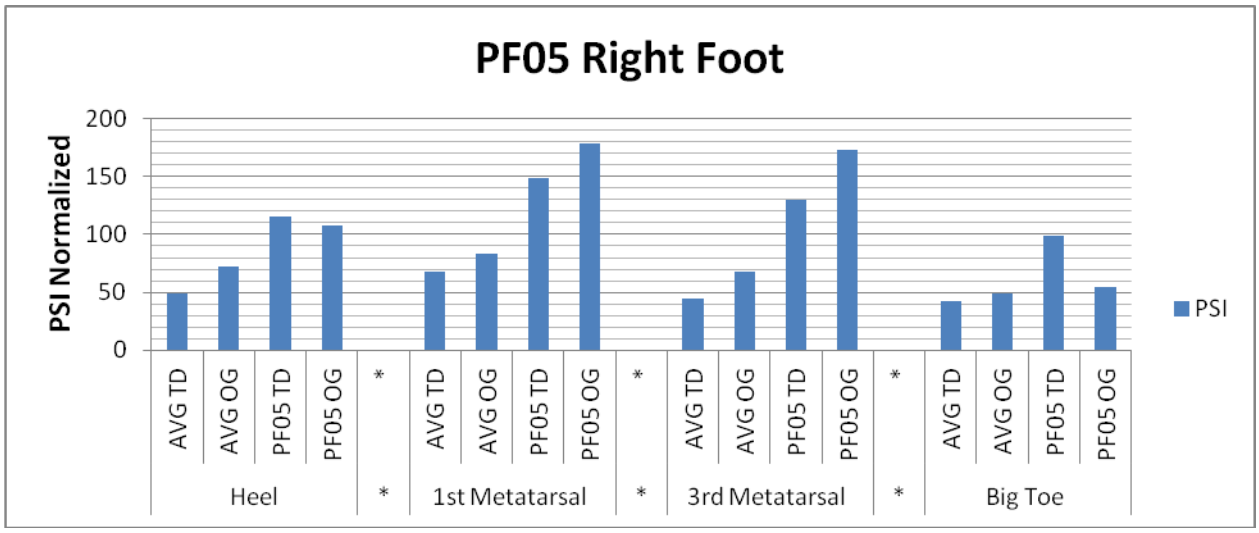

Figure 6.47: F-scan Results from PF05 Right Foot on Four Pressure Points Compared with Control Group

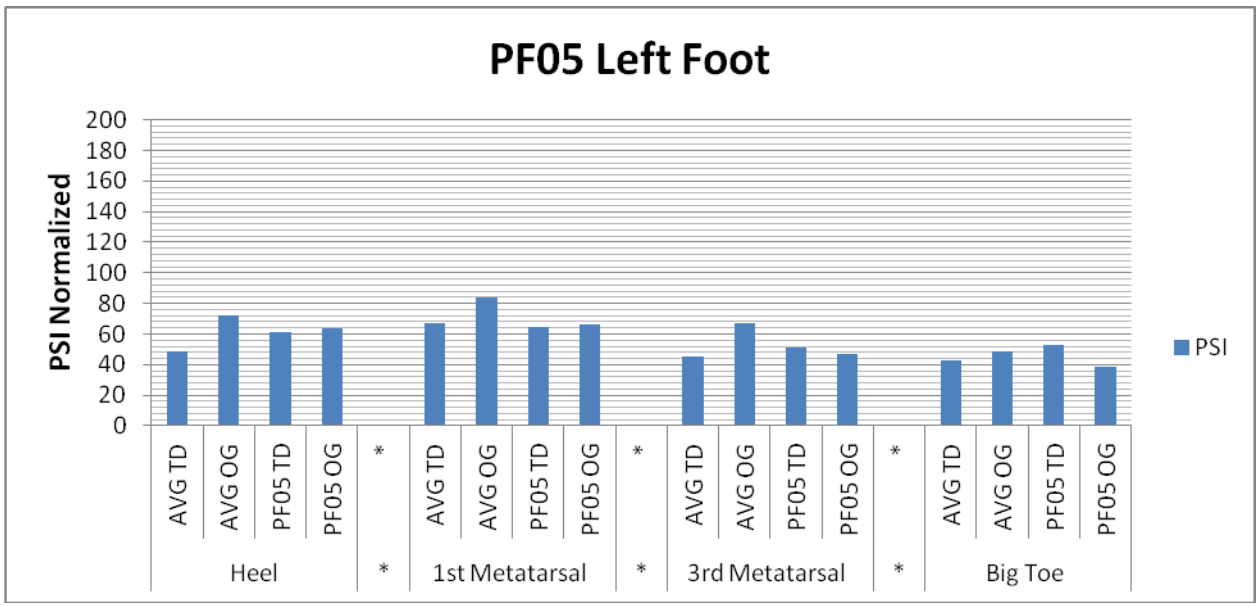

Figure 6.48: F-scan Results from PF05 Left Foot on Four Pressure Points Compared with Control Group

The 10 gram monofilament test was assessed during this experiment and showed that PF05 did not fail on any area. As seen on table 6.5, the results from the 10 gram monofilament test are presented.

Table 6.5: Results from Monofilament test of Female Patient 05. P=Pass, or Fail

Fail 10gr Monofilament Test on more > 2 areas

	Heel		1st Metatarsal		3rd Metatarsal		5th Metatarsal		Big Toe	
	R	L	R	L	R	L	R	L	R	L
PM01	P	P	P	P	P	P	P	P	P	P

6.6 Case Study 6

6.6.1 General Information (PM01)

Male patient 01, identified as PM01, is 44 years-old with a height of 179 centimeters and a body weight of 97.4 kilograms. This patient has been diagnosed with diabetes mellitus for 8 years. By a physical inspection, no callus was found on sole area. A speed was performed on instrumented treadmill trial is not similar to the average speed of the control group (self-selected speed for this patient was 0.57 m/s). The vertical ground reaction force "M" shape tends to become a "N" shape, along with a small delay on stance phase that can be noticed on the X, Y, and Z axes ground reaction forces on both the right and left foot. The Figure 6.49 displays the results of the ground reaction forces of the left foot (blue) and right foot (red).

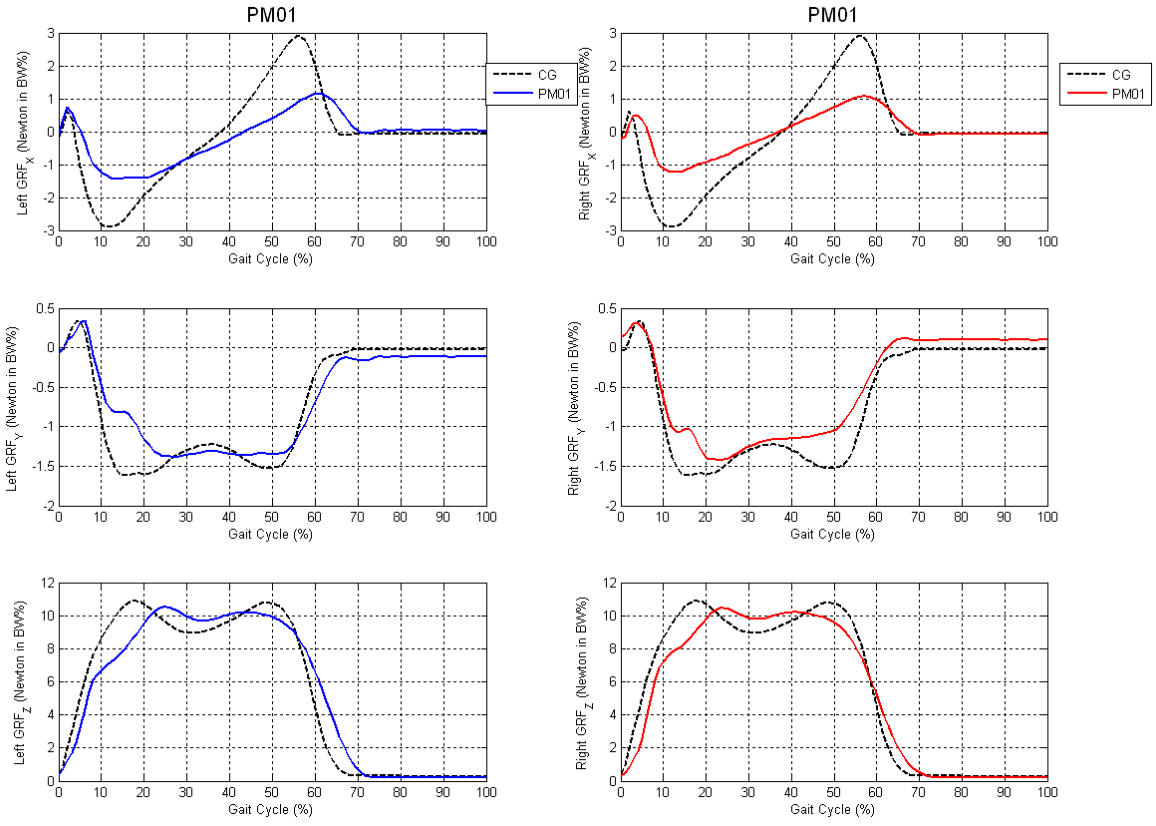

Figure 6.49: Result for Ground Reaction Forces on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

Quantitative results from the ground reaction forces can be shown in figure 6.50 by using the fuzzy similarity between the control group and male patient 01. The ground reaction force results of PM01 that are closest to magnitude 1 conclude that the grade of similarity to the control group is bigger. Fuzzy similarity results can be viewed in figure 6.50.

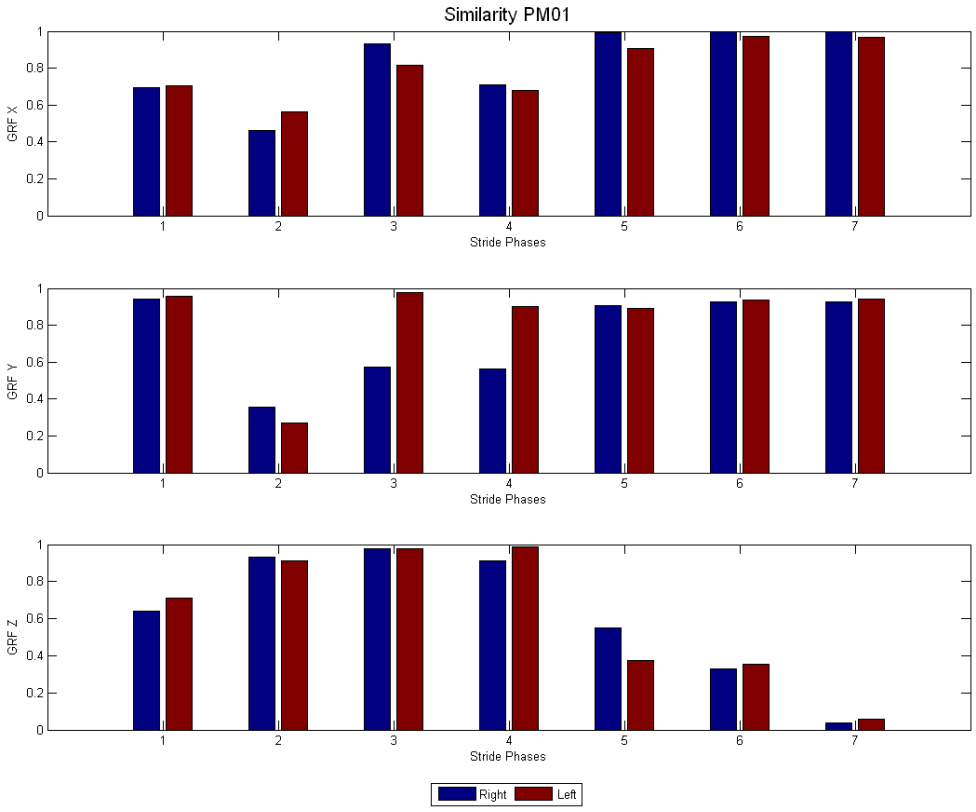

Figure 6.50: Result for Fuzzy Similarity for Ground Reaction Forces of Control Group against PM01, where the left foot is represented in red and right foot is represented in blue

By analyzing the EMG information, we have noticed that muscle weakness is present on lateral grastocnemious for right and left foot. PM01 has also presented an early activation for lateral gastrocnemious on right and left foot. On Figure 6.51 results for the EMG on left foot (Blue) and right foot (Red) compared with control group (Black).

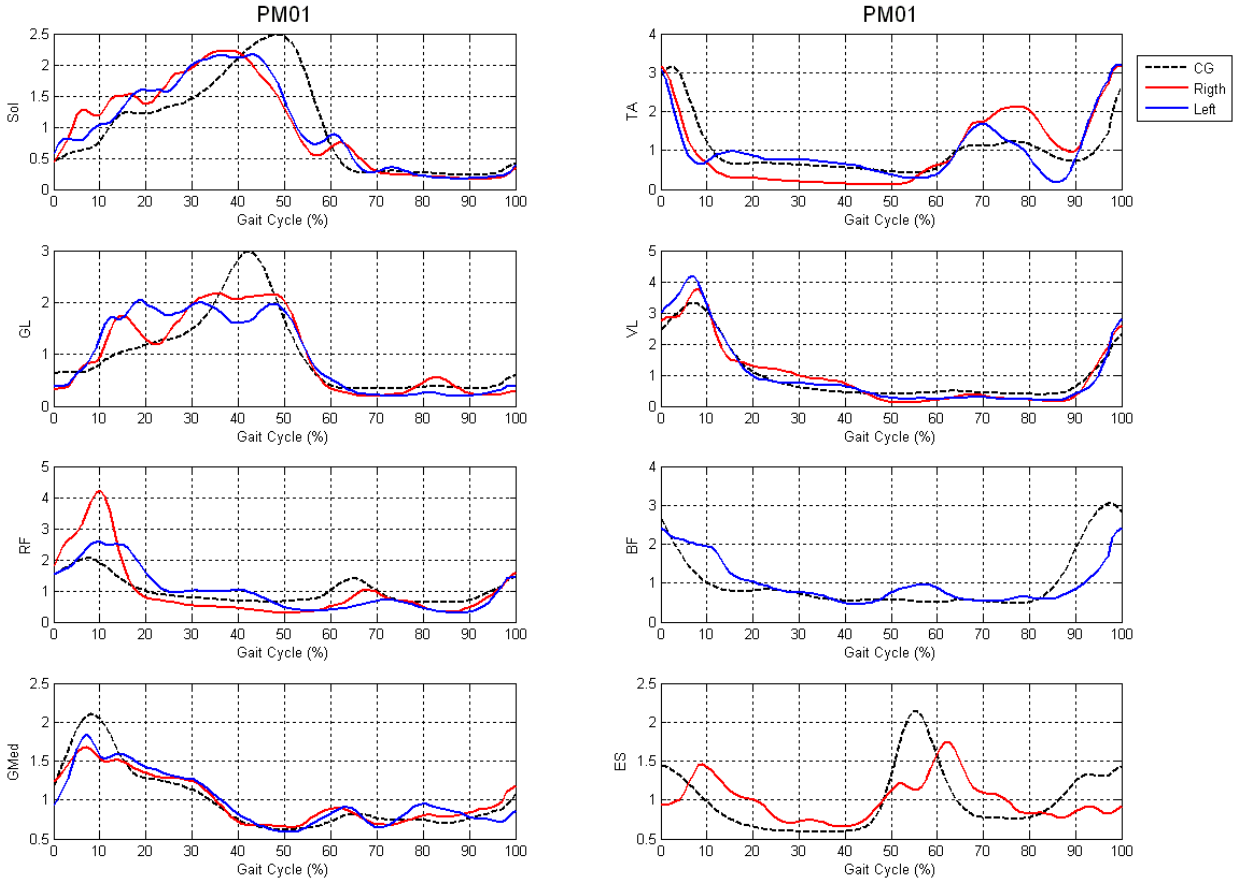

Figure 6.51: Result for EMG on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

This information has been processed with fuzzy similarity to obtain quantitative results. Quantitative results are presented on figure 6.52.

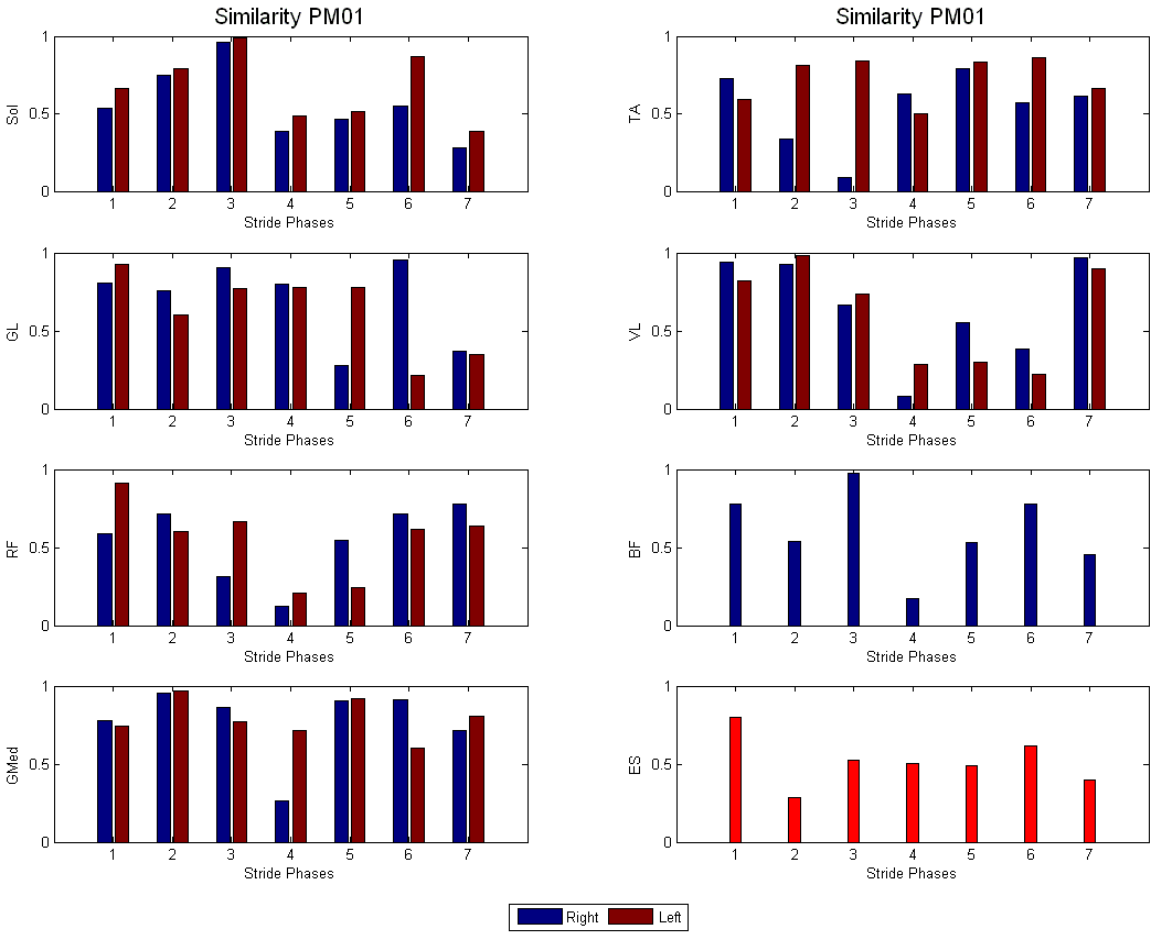

Figure 6.52: Result for Fuzzy Similarity for EMG of Control Group against PM01, where the left foot is represented in red and right foot is represented in blue

Joint kinematics for PM01 has shown that there is a decreased angle in range of motion for subtalar joint on right foot, which is the same lower limb which presented the most muscle weakness on tibialis atnerior and lateral gastrocnemious. Figure 6.53 displays the range of motion of the ankle, knee, and hip on the X, Y, and Z axes. The red color represents the right lower limb while the blue color represents the left lower limb. The black color represents the control group.

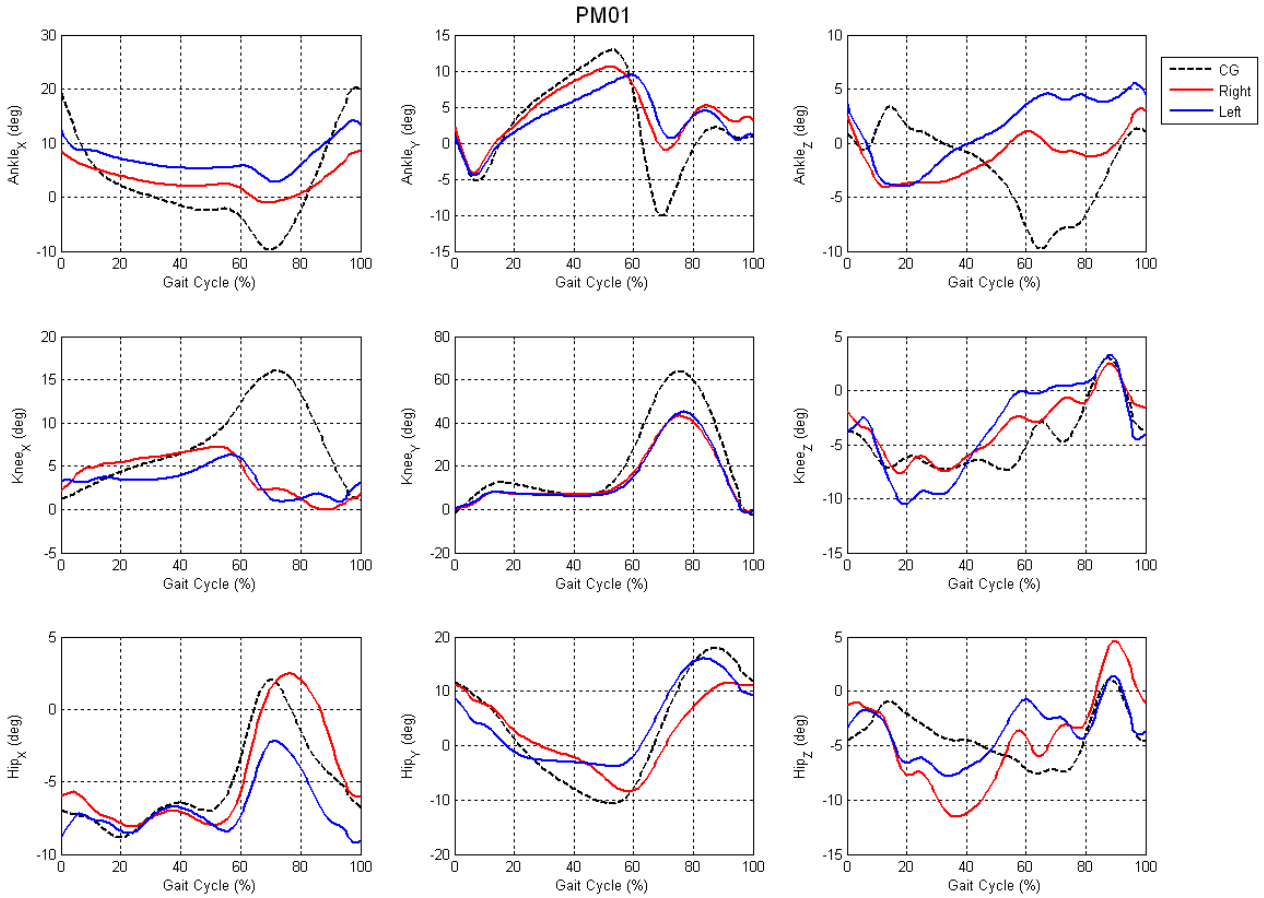

Figure 6.53: Kinetics for PM01. The right lower limb is represented in red, and left lower limb is represented in blue. The control group is represented in black for comparison

Fuzzy similarity is presented on figures 6.54, 6.55 and 6.56. The lack of similarity is evident on sagittal plane for ankle, knee and hip is displayed.

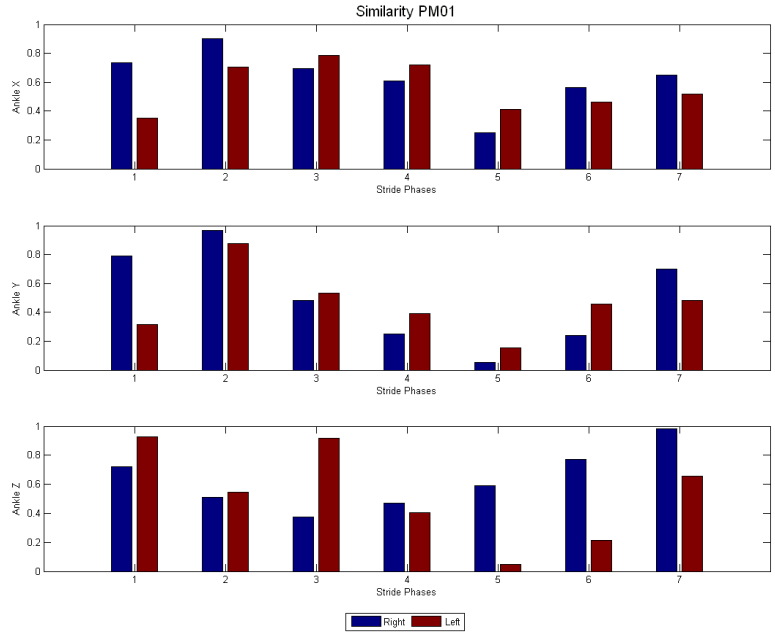

Figure 6.54: Fuzzy Similarity Results from Subtalar Joint of PM01 on X, Y, and Z axes

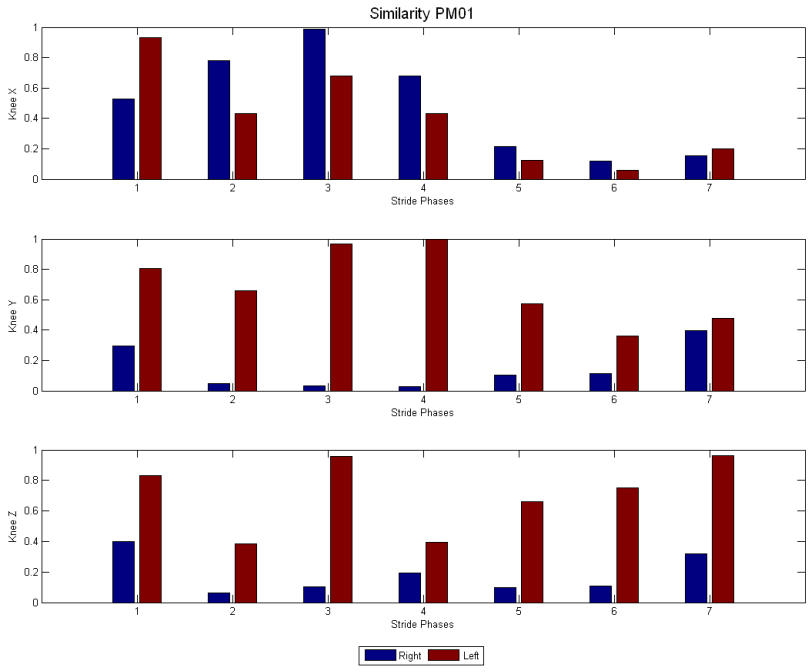

Figure 6.55: Fuzzy Similarity Results from Knee of PM01 on X, Y, and Z axes

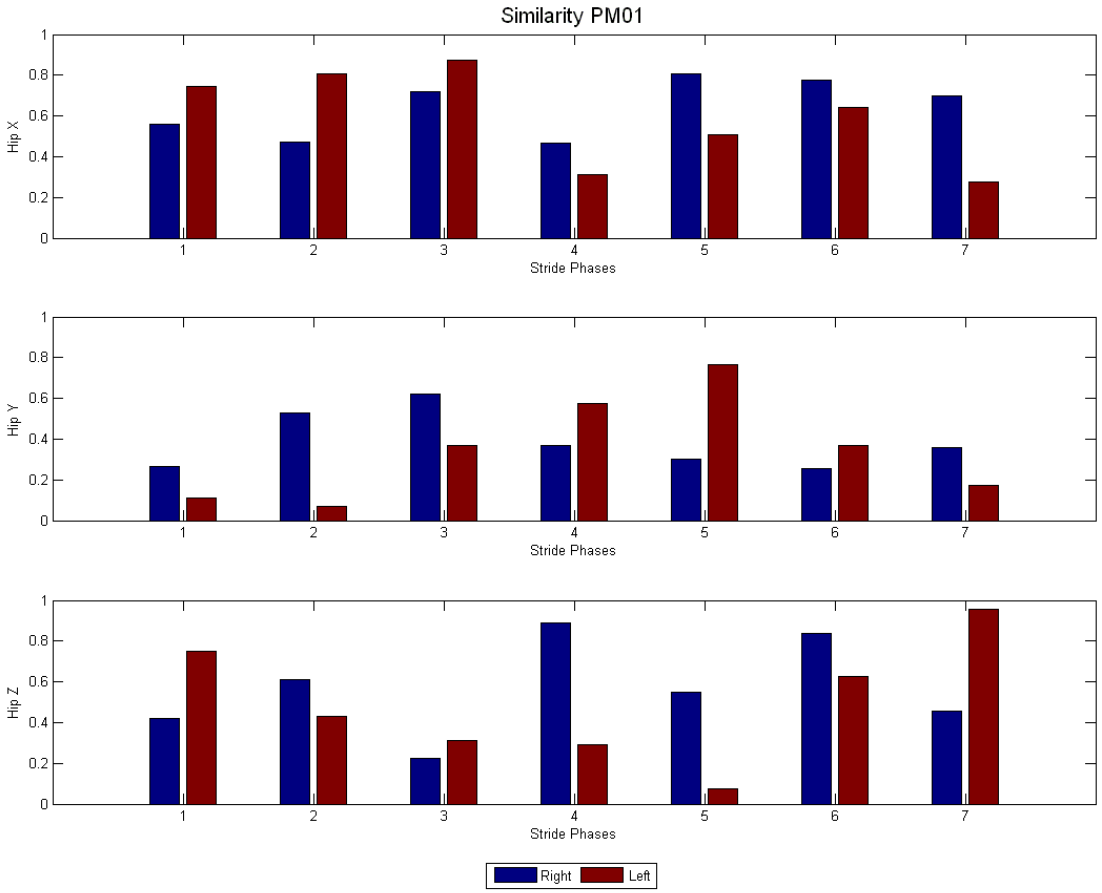

Figure 6.56: Fuzzy Similarity Results from Hip of PM01 on X, Y, and Z axes

The F-scan results show that diabetic neuropathy does not develop at the same time on both feet. We can observe that there is higher pressure shown on the right foot. Higher pressure on right foot is presented on the four studied areas for the treadmill, and the over ground trial. Figures 6.57 and 6.58 display from left to right the following results; The pressures from the heel that are averaged from the treadmill (AVG TD) trial of the control group, and the pressure of the heel of the over ground (AVG OG) trial of the control group. After these results, we can also observe pressures of the male patient 01 on the treadmill (PM01 TD), and last we can see the information for male patient 01 of the over ground trial (PM01 OG). This format will continue the same for the first metatarsal, third metatarsal, and big toe.

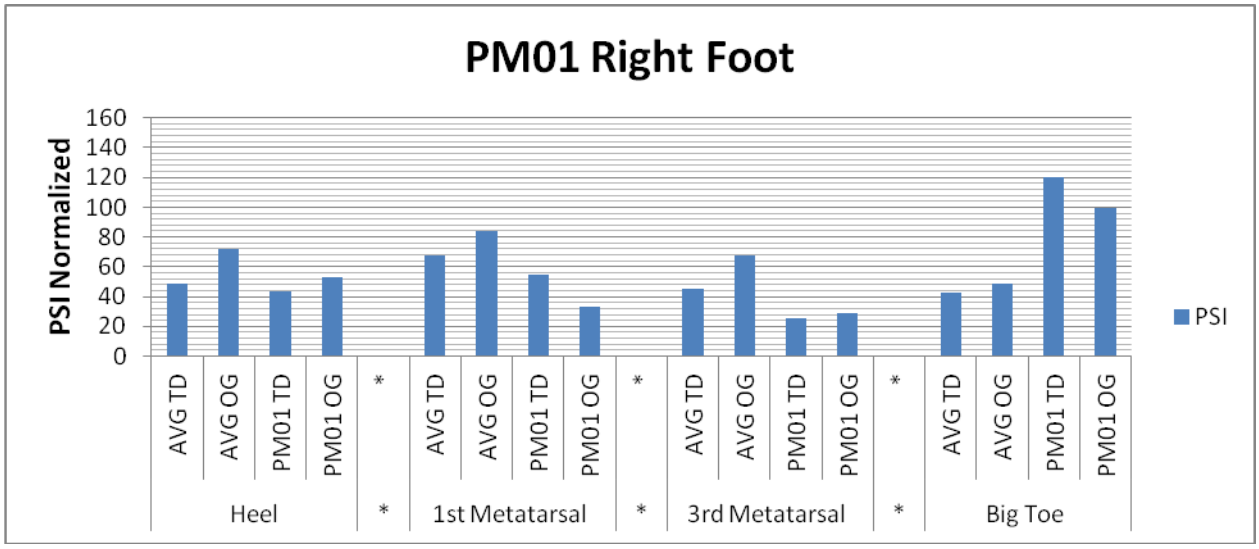

Figure 6.57: F-scan Results from PM01 Right Foot on Four Pressure Points Compared with Control Group

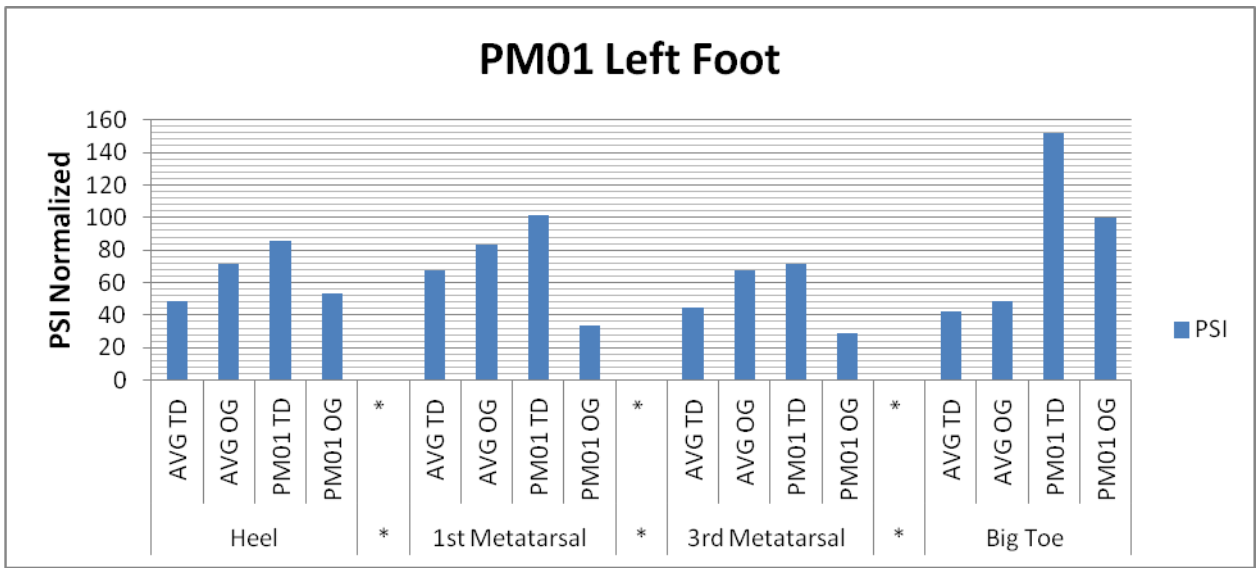

Figure 6.58: F-scan Results from PM01 Left Foot on Four Pressure Points Compared with Control Group

The 10 gram monofilament test was assessed during this experiment and showed that PM01 did not fail on any area. As seen on table 6.6, the results from the 10 gram monofilament test are presented.

Table 6.6: Results from Monofilament test of Male Patient 01. P=Pass, or Fail

Fail 10gr Monofilament Test on more > 2 areas

	Heel		1st Metatarsal		3rd Metatarsal		5th Metatarsal		Big Toe	
	R	L	R	L	R	L	R	L	R	L
PM01	P	P	P	P	P	P	P	P	P	P

6.7 Case Study 7

6.7.1 General Information (PM02)

Male patient 02, identified as PM02, is 52 years-old with a height of 164 centimeters and a body weight of 91.1 kilograms. This patient has been diagnosed with diabetes mellitus for 6 years. By a physical inspection, callus was found on sole area for left and right foot. A speed was performed on instrumented treadmill trial is not similar to the average speed of the control group (self-selected speed for this patient was 0.60 m/s) and an easy lost of balance was observed during treadmill and over ground trial. The vertical ground reaction force "M" shape tends to become a "N" shape, along with a small delay on stance phase that can be noticed on the X, Y, and Z axes ground reaction forces on both the right and left foot. The Figure 6.59 displays the results of the ground reaction forces of the left foot (blue) and right foot (red).

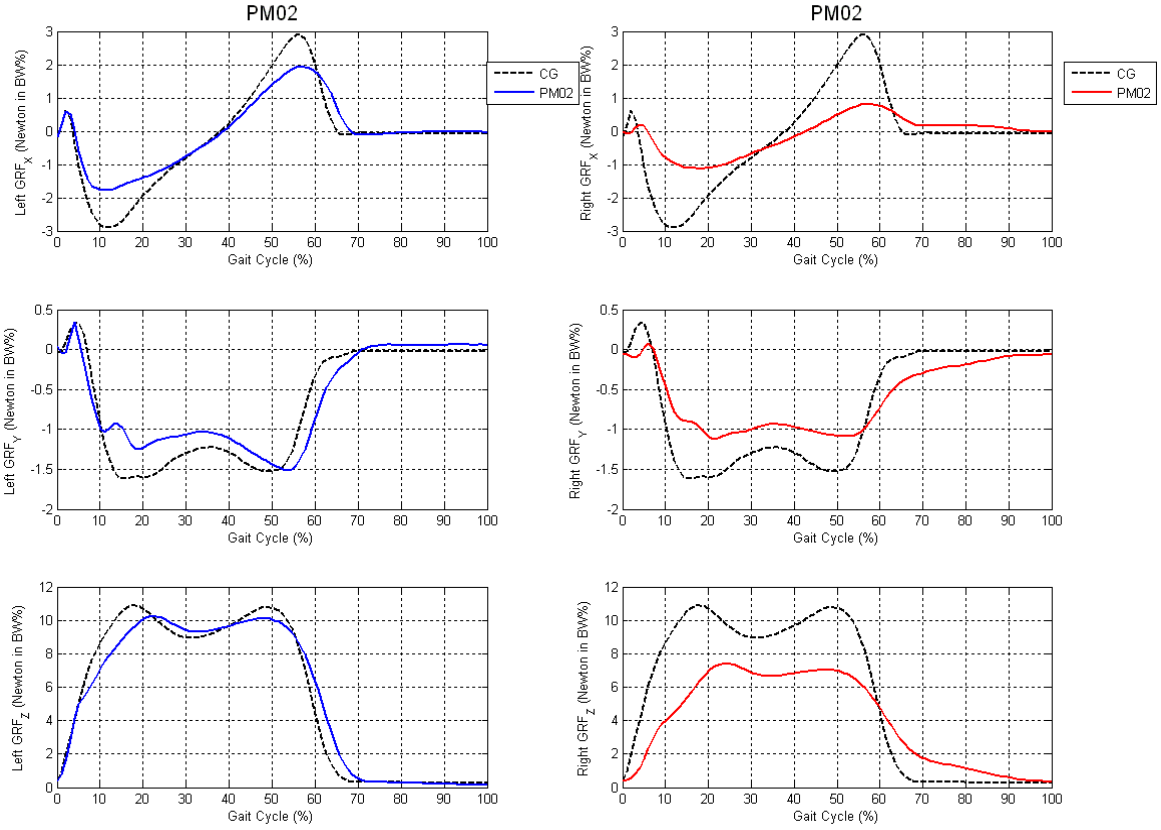

Figure 6.59: Result for Ground Reaction Forces on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

Quantitative results from the ground reaction forces can be shown in figure 6.60 by using the fuzzy similarity between the control group and male patient 2. The ground reaction force results of PM02 that are closest to magnitude 1 conclude that the grade of similarity to the control group is bigger. Fuzzy similarity results can be viewed in figure 6.60.

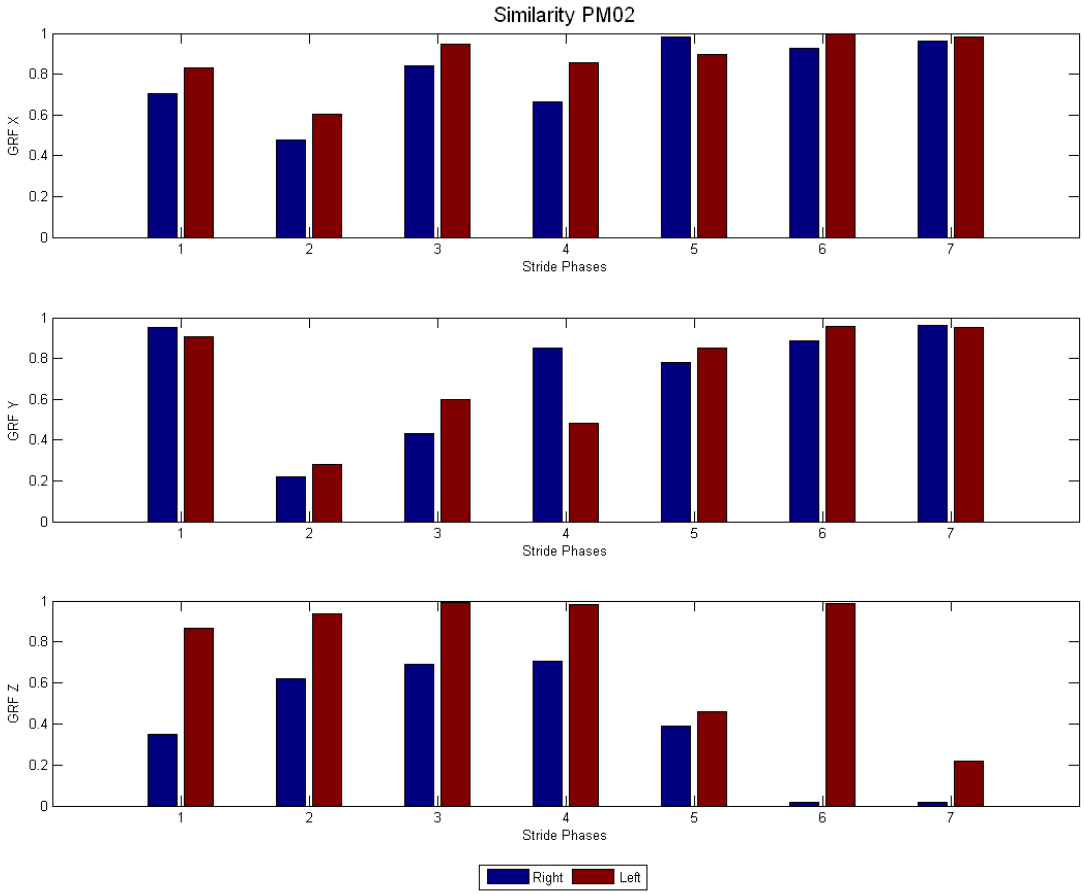

Figure 6.60: Result for Fuzzy Similarity for Ground Reaction Forces of Control Group against PM02, where the left foot is represented in red and right foot is represented in blue

By analyzing the EMG information, we have noticed that muscle weakness is present on soleus, lateral grastocnemious, and tibialis anterior for right and left foot. At the same time, vastus lateralis and rectus femoris for right foot presents muscle weakness. PM02 has presented an early activation for soleous and lateral gastrocnemious on right and left foot. On Figure 6.61 results for the EMG on left foot (Blue) and right foot (Red) compared with control group (Black).

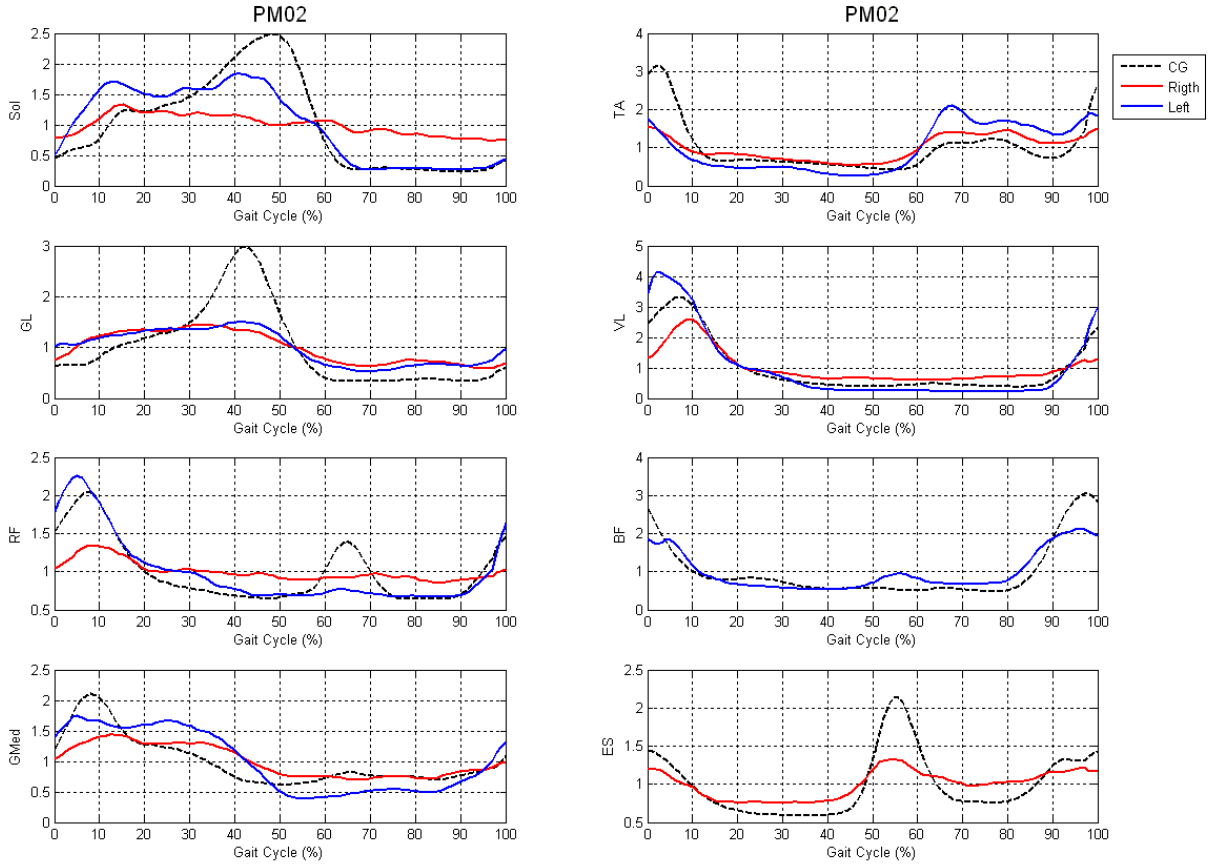

Figure 6.61: Result for EMG on Left Foot (Blue) and Right Foot(Red) compared with Control Group(Black)

This information has been processed with fuzzy similarity to obtain quantitative results. Quantitative results are presented on figure 6.62.

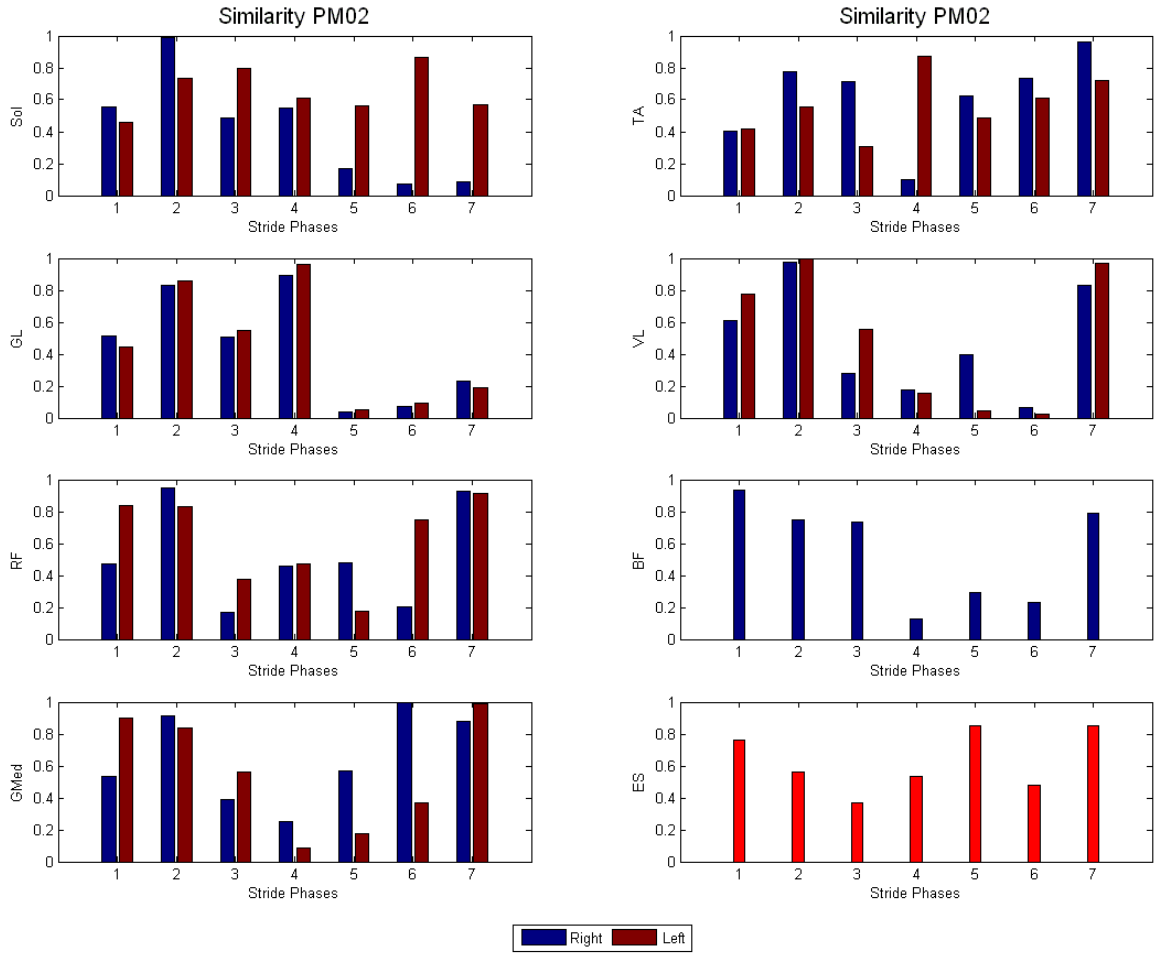

Figure 6.62: Result for Fuzzy Similarity for EMG of Control Group against PM02, where the left foot is represented in red and right foot is represented in blue

Joint kinematics for PM02 has shown that there is a notable decreased angle in range of motion for subtalar joint on right and left foot. Decreased range of motion is also present for the knee on right and left lower limb. Because of the nature of the development of the neuropathy bigger differences regarding range of motion are noticeable between right and left foot. Figure 6.63 displays the range of motion of the ankle, knee, and hip on the X, Y, and Z axes. The red color will represent the right lower limb while the blue color represents the left lower limb. The black color represents the control group.

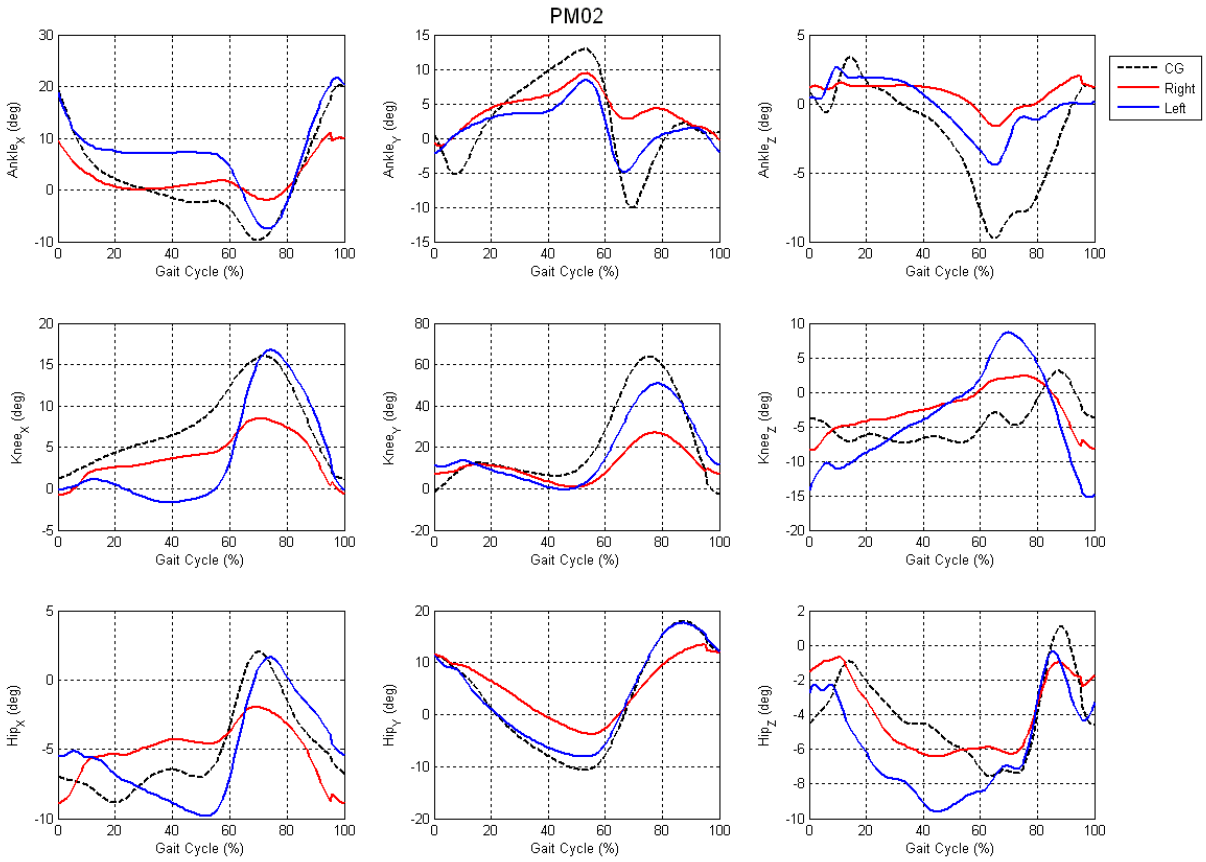

Figure 6.63: Kinetics for PM02. The right lower limb is represented in red, and left lower limb is represented in blue. The control group is represented in black for comparison

Fuzzy similarity is presented on figures 6.64, 6.65 and 6.66. The lack of similarity is evident on sagittal plane for ankle, knee and hip is displayed.

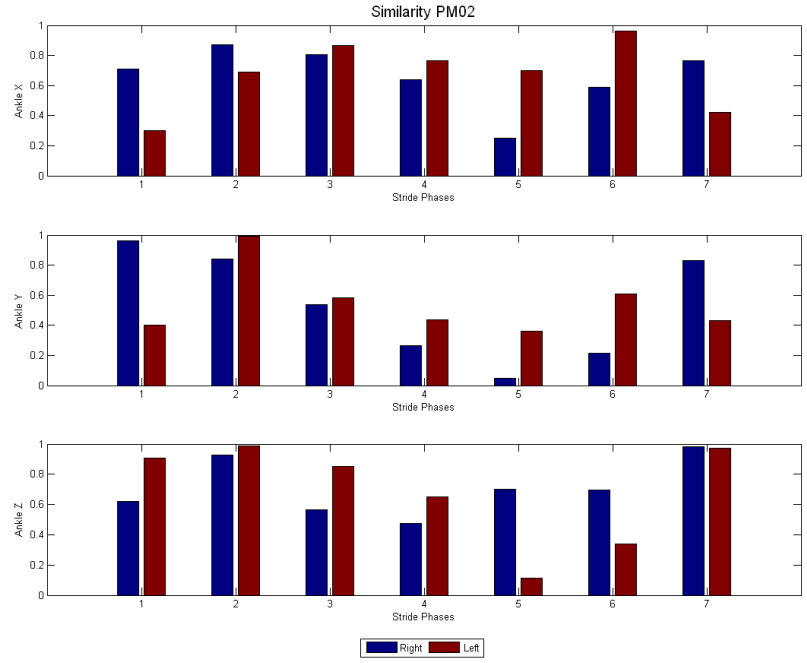

Figure 6.64: Fuzzy Similarity Results from Subtalar Joint of PM02 on X, Y, and Z axes

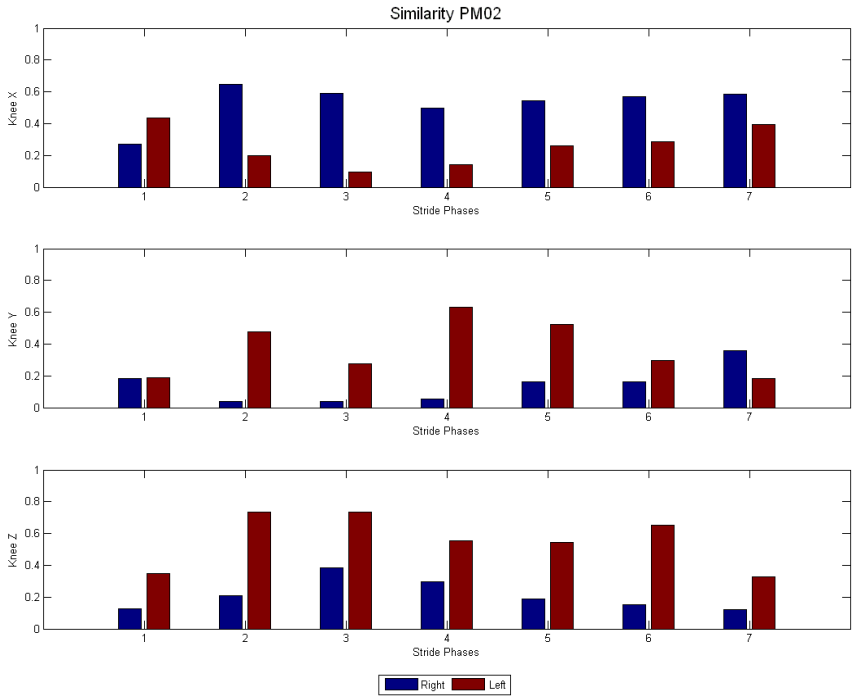

Figure 6.65: Fuzzy Similarity Results from Knee of PM02 on X, Y, and Z axes

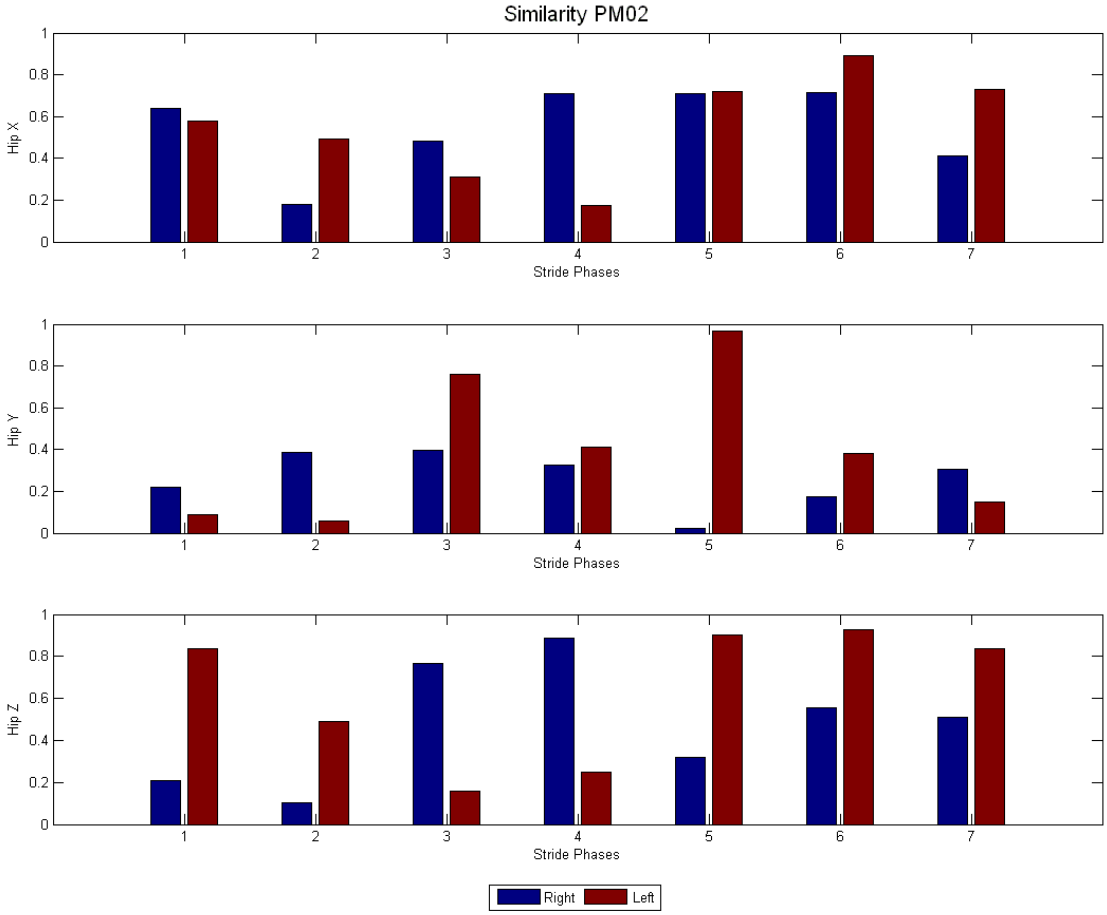

Figure 6.66: Fuzzy Similarity Results from Hip of PM02 on X, Y, and Z axes

The F-scan results show that diabetic neuropathy does not develop at the same time on both feet. We can observe that there is higher pressure shown on the left foot. Higher pressure on left foot is presented on first metatarsal and third metatarsal areas for the over ground trial. Although, when lower speed on treadmill is present, compared with control group, higher pressure is present for heel and big toe for left foot, same as big toe for right foot. Figures 6.67 and 6.68 display from left to right the following results; The pressures from the heel that are averaged from the treadmill (AVG TD) trial of the control group, and the pressure of the heel of the over ground (AVG OG) trial of the control group. After these results, we can also observe pressures of the male patient 02 on the treadmill (PM02 TD), and last we can see the information for male patient 02 of the over ground trial (PM02 OG). This format will continue the same for the first metatarsal, third metatarsal, and big toe.

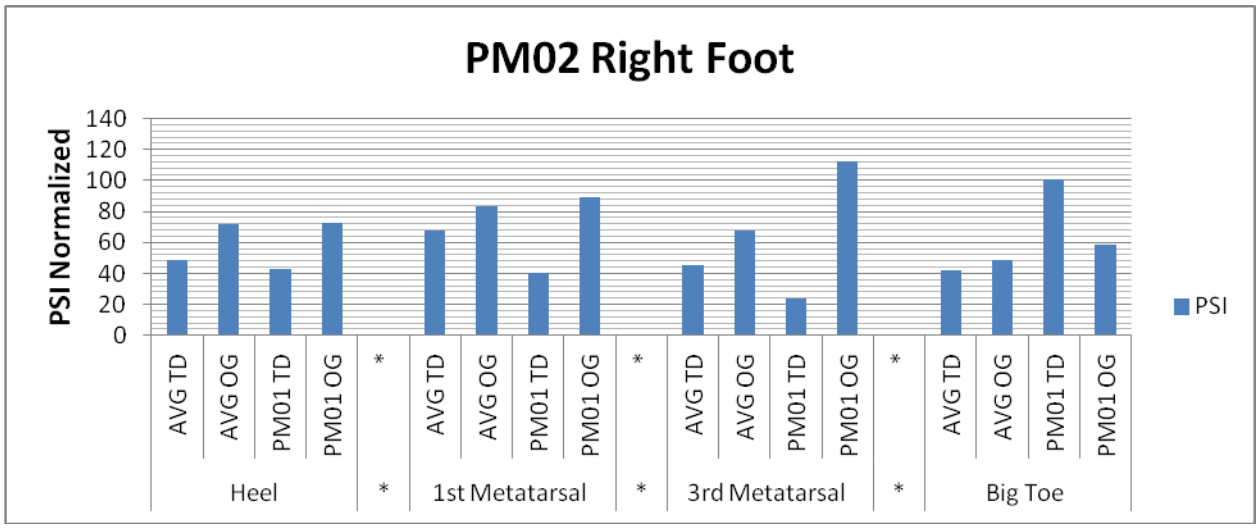

Figure 6.67: F-scan Results from PM02 Right Foot on Four Pressure Points Compared with Control Group

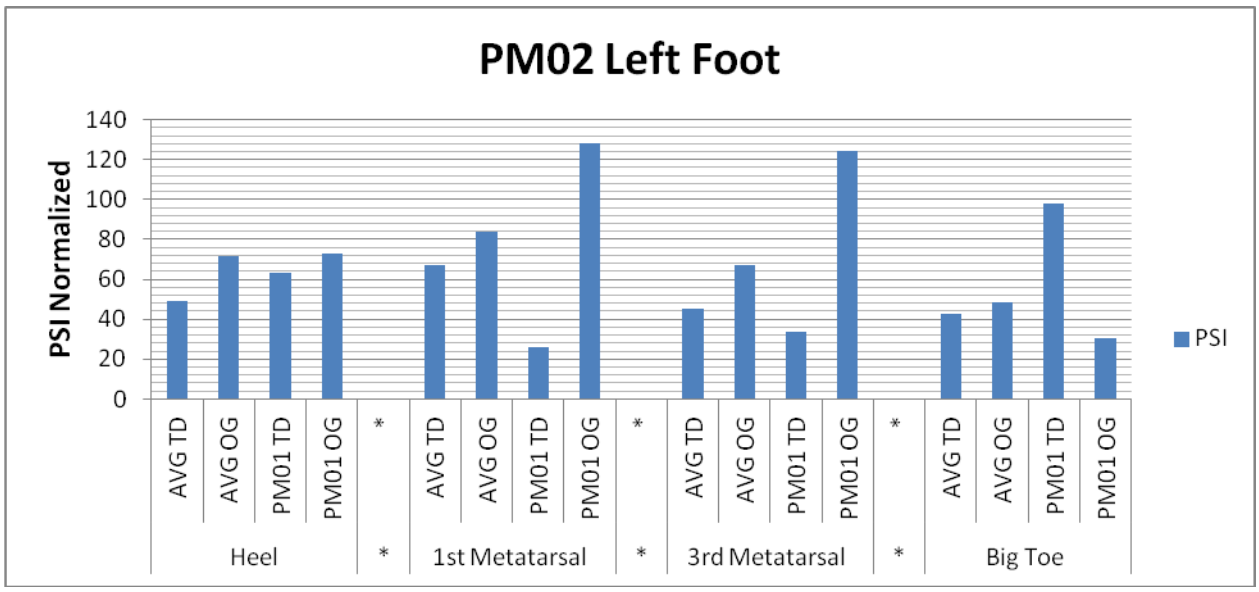

Figure 6.68: F-scan Results from PM02 Left Foot on Four Pressure Points Compared with Control Group

The 10 gram monofilament test was assessed during this experiment and showed that PM02 failed on four areas for left foot. The right foot of PM02 failed only on the fifth metatarsal pressure area. As seen on table 6.7, the results from the 10 gram monofilament test are presented. Because PM02 fail the 10 gram monofilament test, PM02 was a candidate to be tested with a higher pressure monofilament.

Table 6.7: Results from Monofilament test of Male Patient 02. P=Pass, or Fail

Fail 10gr Monofilament Test on more > 2 areas

	Heel		1st Metatarsal		3rd Metatarsal		5th Metatarsal		Big Toe	
	R	L	R	L	R	L	R	L	R	L
PM02	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

Chapter 8: Discussion

This research has demonstrated that there is an evidence of diabetic neuropathy found on some patients inside the diabetic group who were tested. Higher pressure is present during over ground trial compared to the treadmill trial. This is because the instrumented treadmill will reduce the friction while walking. As a result, lower pressure is acquired from the treadmill trial. It is also confirmed that some of the patients show less pressure during treadmill trail, because of the low speed that they have selected, assuming that their low speed selection could be the result of the fear of falling on the treadmill or maybe because they have never used a treadmill before. Patients who have never used a treadmill before have selected a lower speed compared to the average speed from control group.

The EMG information recorded during the experiment has confirmed that the patients with diabetes mellitus present muscle weakness, which is strongly related to the development of neuropathy [4]. The joint kinematics has also verified that the patients with diabetes mellitus have reduced range of motion on the subtalar joint (ankle joint) and knee joint [1][5]. The F-scan information for the control group demonstrates that there are differences between the over ground trial and the treadmill trial. The diabetic patients' F-scan information showed that development of neuropathy differs from one foot to the other. This information also showed that most of the patients suffer from high pressure on specific areas and the 10 gram monofilament test has confirmed some of the high pressure areas. The results were verified for some of the diabetic patients with the 10 gram monofilament because this test is a subjective test which depends on the patient and on the practitioner who perform the test.

I must add that patients PF01, PF02, PF05, PM01, and PM02 shared big discrepancies on their ground reaction forces. Also the patients PF02, PF05, PM01, and PM02 showed muscle weakness, mainly on the lateral gastrocnemious, which also included an early activation too. Lower range of motion of subtalar joint was present on different magnitudes for patients PF01, PF02, PF05, PM01, and PM02. Patients PF01, PF02, PF04, PF05, PM01, and PM02 showed considerable high pressure on all the areas tested. PF03 showed only a slight high pressure on the first and third metatarsal of the left foot.

Chapter 9: Conclusion

The experiment was performed on twenty healthy subjects and seven diabetes mellitus patients. The control group was created using the twenty healthy subjects for the comparison of dynamic behavior of the patients. During the experiment, differences on GRFs, EMG, and joint range of motion patterns were detected. The patients were identified with muscle weakness which resulted in delay or early muscle activity and reduced range of motion on hip, knee and subtalar joint, particularly on subtalar joint was remarkable. The GRFs showed noticeable differences in the pattern (Figure 6.1, 6.9, 6.19, 6.29, 6.39, 6.49, and 6.59).

Diabetes mellitus patients: PF01, PF02, PF04, PF05, PM01, and PM02, showed considerable high pressure on all the areas tested. PF03 showed only a slight high pressure on the first and third metatarsal of the left foot.

The determination of dynamic behavior was provided with a quantitative assessment by using the fuzzy similarity. The results obtained would be helpful to the medical doctors by providing the quantitative comparison between healthy and diabetic subjects.

Chapter 10: Future Work

Suggestion for future work will be to increase the size of the control group to create a more accurate comparison that includes more healthy subjects. The experiment can be enhanced by comparing the control group with the diabetic mellitus patients with previous history of ulceration.

Due to the nature of F-scan system and its sensors, a walkway pressure mapping system from TEKSCAN is suggested for the future work.

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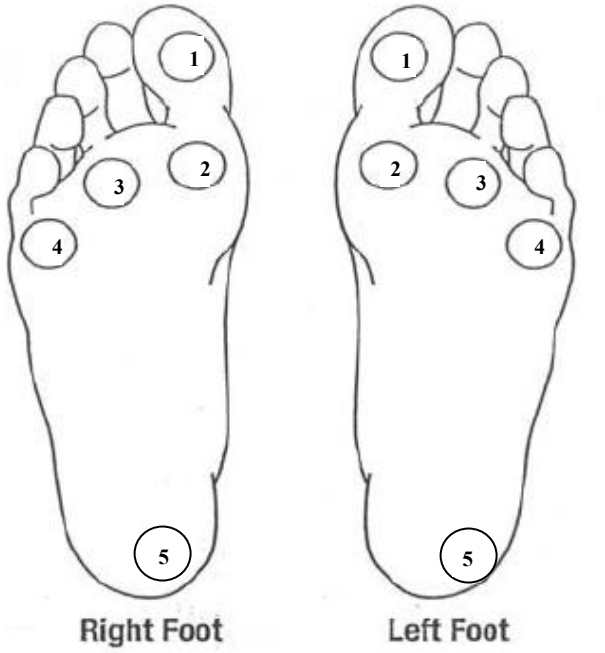
Appendix

Semmes – Weinstein Monofilament Testing Results Sheet

Name: Gender: Age:



- Bow the 10-g MF at a designated site, and ask the patient, “Do you feel it touch you – yes or no?”
- Repeat testing twice at each site and randomly include a “sham” application in which the 10-g MF is not applied. There will be a total of three applications at each site, one of which does not touch the skin.
- Protective sensation is considered to be present if the patient correctly answers two or more of the three applications, one of which was a sham.
- If the patient correctly answers only one or none of the three applications, return and retest that site.
- The patient is considered to have insensate feet if they fail on retesting at just one or more sites on either foot.

10-g/5.07 SW Monofilament Test Results							
		Right			Left		
		1st	2nd	Sham	1st	2nd	sham
1	Great Toe						
2	1st metatarsal						
3	3rd metatarsal						
4	5th metatarsal						
5	Heel						
2.83 SW Monofilament Test Results							
		Right			Left		
		1st	2nd	Sham	1st	2nd	sham
1	Great Toe						
2	1st metatarsal						
3	3rd metatarsal						
4	5th metatarsal						
5	Heel						
3.61 SW Monofilament Test Results							

		Right			Left		
		1st	2nd	Sham	1st	2nd	sham
1	Great Toe						
2	1st metatarsal						
3	3rd metatarsal						
4	5th metatarsal						
5	Heel						
4.31 SW Monofilament Test Results							
		Right			Left		
		1st	2nd	Sham	1st	2nd	sham
1	Great Toe						
2	1st metatarsal						
3	3rd metatarsal						
4	5th metatarsal						
5	Heel						
4.56 SW Monofilament Test Results							
		Right			Left		
		1st	2nd	Sham	1st	2nd	sham
1	Great Toe						
2	1st metatarsal						
3	3rd metatarsal						
4	5th metatarsal						
5	Heel						
6.65 SW Monofilament Test Results							
		Right			Left		
		1st	2nd	Sham	1st	2nd	sham
1	Great Toe						
2	1st metatarsal						
3	3rd metatarsal						
4	5th metatarsal						
5	Heel						

Note:

- Normal: 2.83, 3.61, 4.31
- Protective: 4.56, 5.07
- Severe insensitive: 6.65

Subject Anthropometric Measurement					
Name:			**ID:**		
Sex: **F / M**			**D.O.B:**		
Weight (Kg):			**Height (cm):**		
Upper Body	**Right**	**Left**	**Lower Body**	**Right**	**Left**
Shoulder Height			Knee Circum.		
Armpit Height			Thigh Circum.		
Waist Height			Mid Thigh Circum.		
			Upper Leg Circum.		
Shoulder to Elbow			Calf Circum.		
Forearm to Hand			Ankle Circum.		
Biceps Circum.			Ankle Height Outside		
Elbow Circum.					
Forearm Circum.			Knee Width		
Wrist Circum.			Ankle Width		
			Foot Breadth		
Neck Circum.			Foot Length		
Shoulder Breadth					
Chest Depth			Thigh Length		
Chest Breadth			Calf Length		
Chest Circum.			Knee Height Seated		
Waist Depth			Seated Height		
Waist Breadth			Head Length (Circum.)		
Buttock Depth			Head to Chin Height		
Hip Breadth Standing			Head Breadth		
History information regarding lower limb injury or disorder:					

Vita

Luis G. Sagarnaga Lopez graduated with Bachelor of Science degree in Electrical Engineering from the Instituto Tecnologico De Chihuahua in 2008. He started his Master of Science degree in Electrical Engineering at the University of Texas at El Paso in fall 2009. His thesis "Determination of Dynamic behavior of subjects with Diabetic Neuropathy" addresses the need for quantitative assessment of the diabetic foot. This is an interdisciplinary research that integrates biomedical engineering, human motion analysis, sensor fusion, and fuzzy logic. Luis G. Sagarnaga Lopez successfully completed and defended his Master of Science degree research work under the guidance of Dr. Thompson Sarkodie-Gyan in the Electrical and Computer Engineering Department at UTEP.