2013-01-01

Assessment And Evaluation Of The Dynamic Behavior Of Muscles With Special Reference To Subjects With Diabetes Mellitus

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by

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DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

Department of Electrical and Computer Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2013

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Chapter 1: Introduction

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1.1 Definition and categorization on Diabetes Mellitus (DM):

According to the American Diabetes Association [1], Diabetes mellitus (simply diabetes) is a group of metabolic diseases in which a person has high blood sugar, either because the body does not produce enough insulin, or because cells do not respond to the insulin that is produced. There are three major forms of diabetes that can be categorized as:

- Type 1 diabetes accounts for 5–10% of cases; the cause is an absolute deficiency of insulin secretion resulting from autoimmune destruction of the insulin producing cells in the pancreas [1].
- Type 2 diabetes (90–95% of cases) results from a combination of the inability of muscle cells to respond to insulin properly (insulin resistance) and inadequate compensatory insulin secretion [1].
- Less common forms include gestational diabetes mellitus (GDM), which is associated with a 40–60% chance of developing type 2 diabetes in the next 5–10 years [2]. Diabetes can also result from genetic defects in insulin action, pancreatic disease, surgery, infections, and drugs or chemicals [1, 2].

Pre-diabetes indicates a condition that occurs when a person's blood glucose levels are higher than normal but not high enough for a diagnosis of type 2 DM. Many people destined to develop type 2 DM spend many years in a state of pre-diabetes.

The main focus of this research is Type 2 diabetes subjects categorized as a lifelong (chronic) disease in which there are high levels of sugar (glucose) in the blood.

1.2 Type 2 diabetes treatments

The goal of treatment in type 2 diabetes is to achieve and maintain optimal blood glucose (BG), lipid, and blood pressure (BP) levels to prevent or delay chronic complications of diabetes [13].

Many people with type 2 diabetes can achieve BG control by following a nutritious meal plan and exercise program, losing excess weight, implementing necessary self-care behaviors, and taking oral medications, although others may need supplemental insulin [2] .

1.2.1 Diet and Exercise

Diet and regular exercise (defined as bodily movement produced by the contraction of skeletal muscle that substantially increases energy expenditure) improves blood glucose control and can prevent or delay type 2 diabetes along with positively affecting lipids, blood pressure (BP), cardiovascular events, mortality, and quality of life [4-11], but unfortunately most people with type 2 diabetes are not active enough [12].

It is well documented that contracting muscles increase uptake of BG [14, 15], and the maintenance of normal BG at rest and during exercise depends largely on the coordination and integration of the sympathetic nervous system (one of the two main parts of the autonomic nervous system that aids in the control of most of the body's internal organs), and endocrine system (system of glands, each of which secretes different types of hormones directly into the bloodstream to regulate the body) [14].

Several factors influence exercise fuel use, but the most important are the intensity and duration of exercise [16, 17, 18, and 19]. With increasing exercise intensity, there is a greater

reliance on carbohydrate as long as sufficient amounts are available in muscle or blood [20, 21]. Early in exercise, glycogen (macromolecules as the principal storage form of glucose inside muscle cell) provides the bulk of the fuel for working muscles. As glycogen stores become depleted, muscles increase their uptake and use of circulating BG, along with free fatty acids (FFA) [22, 23].

During moderate-intensity exercise in non-diabetic subjects, the rise in peripheral glucose uptake is matched by an equal rise in hepatic glucose production, the result being that BG does not change except during prolonged, glycogen-depleting exercise. In individuals with type 2 diabetes performing moderate exercise, BG utilization by muscles usually raises more than hepatic glucose production, and BG levels tend to decline [42].While hyperglycemia (the body's inability to properly handle large amounts of sugar) can be worsened by exercise in type 1 diabetic individuals who are insulin deficient (due to missed or insufficient insulin), very few persons with type 2 diabetes develop such a profound degree of insulin deficiency. Therefore, individuals with type 2 diabetes generally do not need to postpone exercise because of high BG, provided that they are feeling well, and they are adequately hydrated [56, 57]. Any kind of exercise specifying duration and intensity must be prescribed by a doctor to avoid any further complication.

1.2.2 Brisk Walking as moderate exercise reduce risk type 2 diabetes

The Centers for Disease Control and Prevention classifies brisk walking as a moderate-intensity activity [49]. On a scale relative to your personal capacity, it is a 5 or 6 on a scale of 0 to 10. The talk test is a simple method that allows you to establish your brisk walking pace. The aim is to be able to walk at a speed that allows you to hold a conversation without losing your

breath. Difficulty breathing while talking indicates the subject must slow down, whereas the ability to sing indicates the subject should increase his/her pace.

Data shows that moderate exercise such as brisk walking reduces risk of type 2 diabetes [24,25, 27-29], and all studies support the current recommendation of 2.5 h/week of a moderate exercise activity or typically 30 min/day for 5 days/week for prevention. A combination of moderate exercise and resistance training may be more effective for BG management than either type of exercise alone [38, 39]. Any increase in muscle mass that may result from resistance training could contribute to BG uptake without altering the muscle's intrinsic capacity to respond to insulin, whereas moderate exercise enhances its uptake via a greater insulin action, independent of changes in muscle mass [38]. Reports indicate that combining brisk walking with resistance training led to a greater total duration of exercise and caloric use than when training was undertaken alone [38, 40, 41].

It is now well established that participation in regular physical activities improves blood glucose control and can prevent or delay type 2 diabetes, in addition positively affecting: lipids, blood pressure, cardiovascular events, mortality, and quality of life [43].

1.2.3 Key research studies on brisk walking and control type 2 diabetes

The participation in regular exercise improves BG control and can prevent or delay onset of type 2 diabetes [30-35]. Other observational studies have reported that greater fitness is associated with a reduced risk of developing type 2 diabetes even if only moderate-intensity exercise is undertaken [36,37] .

Some examples of key research studies and reports that support the impact of walking on the prevention and control type 2 diabetes [44] are:

- Walking can lower blood glucose levels after the walk (demonstrated reduction 2.2 millimoles per liter (mmol/l)). No effect after a period of rest [45].
- Moderate physical activity, such as walking, can reduce risk of developing type 2 diabetes [46].
- Group brisk walking was equally effective as individualized fitness programmers for blood-sugar control and reduction of cardiovascular risk profile [47].
- Adults with diabetes who walk at least one mile per day are less than half as likely as sedentary adults with diabetes to die from all causes combined [48].

These findings suggest the importance of studying muscle energy management on DM patients during normal walking to understand how muscle are gaining strength to help regulate BG consumption.

1.2.4 Studies show importance in muscle energy management on DM

Individuals with type 2 diabetes mellitus, shows BG utilization by muscles usually raises more than hepatic glucose production, and BG levels tend to decline [43]. Some studies has been made to determine the progression of muscle weakness in long-term diabetes and its relation to the neuropathic condition, concluding the decline of muscle strength at some muscles was significant when compared with matched control subjects [63]. Participation in regular physical activities improves blood their glucose control and can prevent or delay this illness [30-35]. Both moderate walking and vigorous activity have been associated with a decreased risk, and greater volumes of physical activities may provide the most prevention [25]. These findings support the importance of focus in muscle energy management on type 2 DM patients during normal walking.

1.2.5 Research Contributions

Three specific aims to science are explained in this dissertation:

a. **Dynamic muscle energy expenditure analysis** (Section 4.2.6).
b. **Natural fuzzy logic method for differential analysis in muscle/joint activation pattern** (Section 4.3)
c. **Infer T equation muscles/joint in DM patients** (Section 4.3)**.**

Actually the most common method to help in the monitor of the DM is the BG, but foods that contain carbohydrates affect blood glucose levels the most. How quickly and how much blood glucose levels rise depends on: food composition, portion size, and timing [1]. Meanwhile, the first proposed help to monitor DM using non-invasive technology, showing how muscle can absorb the energy available in the BG. The second method reinforces the results of the previous method detecting physical changes based in a special equation that infer muscle activity and joints range of motion.

Chapter 2: Requirement to assess all muscles in a normal walking behavior

In an everyday environment, the state of health or age of a person is recognizable by how they walk, observing their gait cycle. For example, people generally walk more slowly as they get older and may start to shuffle (short, uncertain steps) [70]. Those that have suffered a stroke may drag one of their legs [71] and people with an injured knee or hip joint will walk with a definite asymmetry [72]. Clinical research has identified clear links between human gait characteristics and different medical conditions, such as: Osteoarthritis [69], fall detection on elderly [70], hydrocephalus [73], Parkinson's disease [74], and many more like Diabetes [75]. Historically, as many as 50% of people with type 2 diabetes are said to develop significant peripheral neuropathies [76] including injury to both the somatic (voluntary) and autonomic nervous systems (involuntary). In addition, these neuropathies also affect a variety of bodily systems, including the vestibular system (auditory) [77, 78] and vision [79]. Poor balance, neuropathies and muscle weakness, either together or individually, can lead to gait abnormalities including improper pressure distribution on the foot, a longer stance phase and shorter steps than observed in people without diabetes [80, 81]. These gait and balance impairments in diabetes shows that they are 15 times more likely to report experiencing a fall-related injury during standing and walking when compared to people without diabetes [82, 83]. These studies show why human gait analysis may be a significant factor in the assessment/treatment of diabetes.

2.1 Human Gait Cycle

The human gait cycle begins when one foot contacts the ground and ends when that foot contacts the ground again. A normal healthy subject has a stance phase approximately of the first 60% of the gait cycle, and the swing phase of the remaining 40% (Fig. 1). Each of these major phases is then subdivided on functional phases of gait:

Stance: Initial contact, Loading Response, Mid Stance, Terminal Stance, and Pre Swing.

Swing: Initial Swing, Mid Swing, and Terminal Swing.

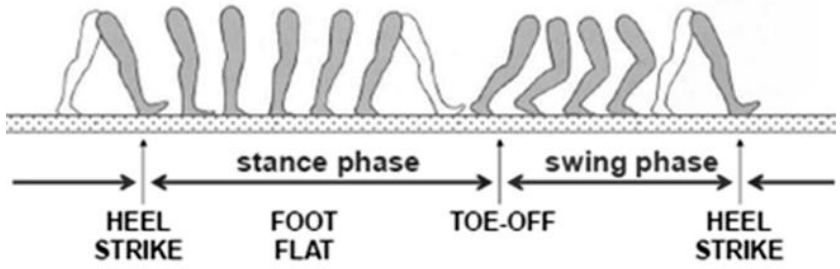


Figure 1 Human Gait Cycle

Each gait cycle percentage and functional phase description are indicated in Table 1 [22].

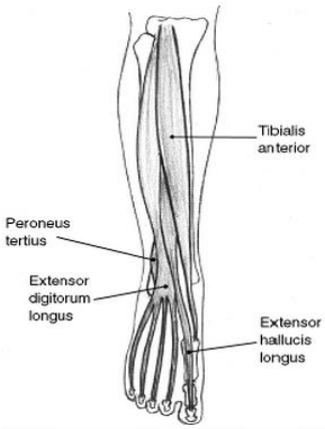
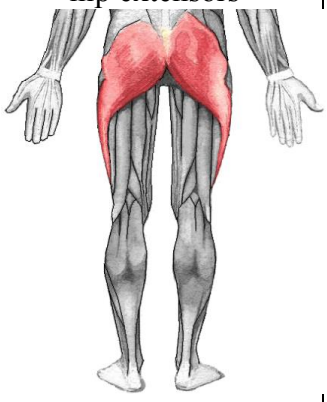
Table 1 Functional phases of gait cycle

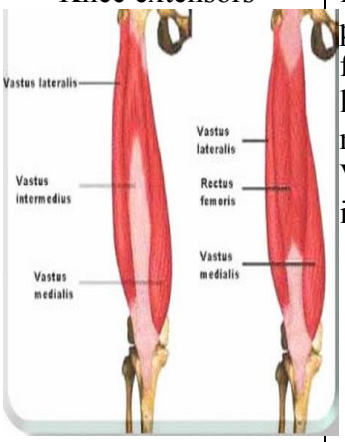
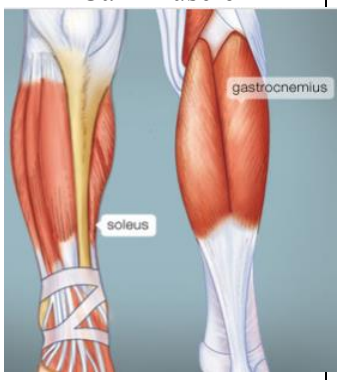
Major phase	Functional Phase	Gait Cycle Percentage	Description
Stance	Initial Contact	(0~2%)	the moment when the heel strikes the floor
	Loading Response	(0~10%)	from the initial contact until the other foot toes off
	Mid Stance	(10~30%)	from the other foot toes off until body weight is aligned over the forefoot
	Terminal Stance	(30~50%)	from the end of the mid-stance until the opposite foot contact
	Pre Swing	(50~60%)	begins with the initial contact of the opposite foot and ends with ipsilateral (on the same side) toe-off
Swing	Initial Swing	(60~70%)	from the toe-off even until the maximum knee flexion occurs
	Mid Swing	(70~85%)	from the maximum knee flexion until the tibia is in a vertical position
	Terminal Swing	(85~100%)	from the vertical tibia to the ipsilateral foot contact

2.2 Muscle Influence on human gait cycle.

The influence of some limb muscles (Tibialis Anterior (TA), Gluteus Maximus (GMx), Gluteus Medius & Minimus and Quadriceps) are well known to be active during the gait cycle and haves been studied when the subject's muscle strength is insufficient to meet the demands of walking, which can be caused by disuse resulting in muscular atrophy or neurological impairment [50-54]. Some results of these studies, including muscle weakness and long term effects are summarized in table 2 [50-55].

Table 2 The influence of some limb muscles during walking [summarized from 50-55]

Muscle on Gait Cycle	Group	Normal Gait	Muscles Weakness	Long term effects
Tibialis Anterior (TA) 	Anterior group muscle member with the peroneus tertius, extensor digitorium longus and the extensor hallucis longus	Is concentric during initial contact, then the action changes to eccentric during loading response (to prevent foot slap).	Inability to counteract the plantar flexion moment, excessive plantar flexion, entire foot and toes would strike the floor at initial contact (lack of normal heel strike), toe drag during swing phase.	Fatigue due to increased energy expenditure as a result of the compensation
Gluteus Maximus (GMx) hip extensors 	Gluteal muscles is a group of four muscles: gluteus maximus, gluteus medius, gluteus minimus. The fourth and smallest of the muscles is the tensor fasciae latae, which is located anterior and lateral to the rest.	During initial contact and loading response, the vGRF lies anterior to the hip joint creating flexion moment which is compensated by the action of the gluteus maximus of the supporting leg.	Inability to counteract the flexion moment, tendency for excessive hip flexion and anterior pelvic tilt.	Excessive lumbar lordosis
Gluteus medius/minimus hip abductors	Gluteal muscles group	Pelvis and trunk to drop laterally to the opposite side (toward the swing limb) by the effect of adduction moment.	Inability to counteract the adduction moment, so the pelvis will drop towards the swing side	Lateral spinal curve (functional scoliosis)

Quadriceps Knee extensors 	subdivided into four separate portions: Rectus femoris, Vastus lateralis, Vastus medialis and Vastus intermedius	During loading responses, the GRFV lies posterior to the knee joint creating flexion moment which is compensated by the eccentric action of the quadriceps muscle.	Tendency for excessive knee flexion during loading response and instability at heel strike	Degeneration of the ligaments supporting the hyper-extended knee
Calf Muscle 	It is a two group muscles: Gastrocnemius and soleus	During mid-stance, terminal stance and pre-swing, the vGRF lies anterior to the ankle joint creating dorsiflexion moment the calf muscles contract eccentrically1st to oppose the dorsiflexion moment and control tibial advance, then contract concentrically to plantar flex the ankle in the later part stance phase	Inability to counteract the flexion moment, Tendency for excessive knee flexion during loading response and instability at heel strike	Increased demand on quadriceps to counteract tibial instability Terminal stance knee extension is lost and replaced with flexion

Ground Reaction Forces are the forces exerted to be analyzed on three planes during walking: Mediolateral plane (X), Anterior Posterior plane (Y), and Vertical plane (Z). Since muscles dominate the vertical ground-reaction forces, analyzing muscle contributions to the vertical ground-reaction force (vGRF) affords further insight into how support is generated in

walking [55]. To facilitate analysis some kinematics gait markers on the vGRF can be defined, as indicated on figure 2 as:

HS = heel-strike,

FF = foot-flat;

CTO = contralateral toe-off,

HO= heel-off,

CHS = contralateral heel-strike;

MO = metatarsal-off;

and TO =toe-off.

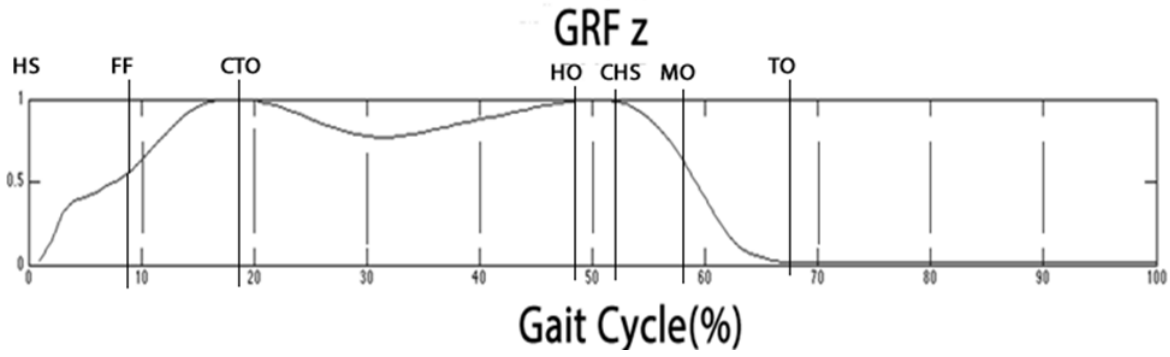


Figure 2 vGRF and markers [55]

Inertial, centrifugal gravitational and muscle forces supply the total vGRF applied to the leg. Muscles made the largest contribution to support, accounting for 50 to 95% of the vertical ground-reaction force generated in stance. To simplify the study, a muscle's potential for generating support can be defined as its contribution to the vertical ground reaction per unit of muscle force (calculated by dividing each muscle's contribution to the vGRF by time history of force developed by the muscle). The summary results of which muscles contribute to support while walking are shown on table 3 [55].

Table 3 Muscles contributed to support while walking [summarized from 55]

Gait	Muscle potential for support	Description
Early stance	Ankle dorsiflexors , Gluteus Maximus, Vasti Lateralis and Gluteous Medius/Minimus (9-15%)	Just after heel-strike (HS), but before foot-flat (FF), support was provided mainly by the ankle dorsiflexors. From FF to just after contralateral toe-off (CTO), gluteus maximus, vasti, and posterior posterior gluteus medius/minimus on the first maximum seen in the vertical ground-reaction reaction.
Midstance	Gluteus maximus, vasti (three knee extensor muscles: vastus intermedius, vastus lateralis and Vastus medialis) , soleus and gluteous medius/minimus	With a significant assist from the passive resistance of the joints and bones to gravity, anterior and posterior gluteus medius/minimus generated nearly all support evident in midstance. Posterior gluteus medius/ minimus provided support throughout midstance, while anterior gluteus medius/minimus contributed significantly only toward the end of midstance.
Late Stance	Soleus and Gastrocnemius	Soleus and gastrocnemius generated nearly all support in late stance. Thus, the ankle plantarflexors were mainly responsible for the second maximum seen in the vGRF. Soleus generated roughly twice as much support as gastrocnemius.
Note:	Other muscles in the model also contributed very little to support, despite developing large forces. These muscles include: hamstrings and rectus femoris, erector spinae, the internal and external obliques, adductor magnus, and iliopsoas (developed a substantial amount of force during late stance but did not make either positive or negative contributions to support at this time). In humans, it is likely that muscles whose tendons cross the metatarsal joint, rather than ligaments, are actually responsible for the contributions made to the vertical ground-reaction force after metatarsal-off.	

The influence of some limb muscles during normal walking on healthy subjects has been studied in numerous research [50-55], and the importance of the study of muscles and joint range of motions on diabetic mellitus (DM) subjects has been reported that Diabetic patients were generally less flexible than non-diabetic subjects [3,64-66]. The need to assess muscle and joint on healthy patients and DM subjects is a priority for this research.

Chapter 3 Variance identification through muscle activation pattern

The number of people with type 2 diabetes mellitus is rising rapidly around the world, making it imperative to develop and introduce new methods of preventing and monitoring the condition. A series of clinical trials over the last decade has shown conclusively that lifestyle interventions focusing on physical activity, diet, and weight loss can reduce the risk of developing type 2 diabetes mellitus by approximately 60% [58]. Exercise, dietary changes and medications are frequently used in the management of type 2 diabetes. However, it is difficult to determine the independent effect of exercise from some trials because exercise has been combined with dietary modifications or medications, or compared with a control which includes another form of intervention [59].

3.1 Right Exercise for DM Subjects

Many people with diabetes have special needs that should be addressed for the right exercise and this must be approved by their doctor. Some of the most common problems are:

- Hypoglycemia (Low Blood Sugar); exercise can cause your blood glucose levels to drop too much, especially if the DM subject takes insulin or some other glucose-lowering medications.
- Hyperglycemia (Poor Blood Sugar Control); exercise can also cause blood sugar levels to rise.
- Diabetic Retinopathy (damaged blood vessels in the retina of the eye): exercise could damage eyesight.

- Reduced Sensation or Pain in Extremities (nerve damage and blood circulation interference); many people with diabetes can lose all or part of the sensation in their feet.

For these reasons, moderate exercise such as brisk walking, is highly recommended by doctors as an important and effective method that can be used to help manage diabetes and weight. This moderate exercise for DM subjects improves blood sugar control and this effect is evident even without weight loss. Furthermore, exercise decreases body fat content, thus the failure to lose weight with exercise programs is probably explained by the conversion of fat to muscle [59].

3.1 Exercise feedback for DM Subjects

Due to the importance of exercise in DM subjects some solutions have been developed to avoid latency in DM subjects such as Accelerometers [61] and Pedometers [60]. Data collected based on recording daily activity using triaxial accelerometers, created a computerized graph of their physical activity for the period between counseling sessions, and had counseling based on this objective data. Pedometers were useful tools for observing levels of exercise, setting personal goals for walking, and helping evaluate whether daily goals were met. Negative experiences were associated with functional failures, pedometers' unsuitability for exercise other than walking.

The most common method used as feedback for DM subjects is to track the blood sugar before, during (if it is more than 30 min) and after exercise, records will reveal how the subjects body responded to exercise as shown on table 4 [62].

Table 4 Diabetes zones based on blood glucose tracking [62]

Blood sugar level milligrams per deciliter (mg/dL) or millimoles per liter (mmol/L)	**Diabetes Zones**	**Recommendation**
Lower than 100 mg/dL (5.6 mmol/L).	Blood sugar may be too low to exercise safely.	Eat a small carbohydrate-containing snack, such as fruit or crackers, before the DM subject begin exercise.
100 to 250 mg/dL (5.6 to 13.9 mmol/L)	For most people, this is a safe pre-exercise blood sugar range.	Do exercise
250 mg/dL (13.9 mmol/L) or higher	This is a caution zone	Before exercising, test DM subject urine for ketones — substances made when your body breaks down fat for energy. Excess ketones indicate that your body doesn't have enough insulin to control your blood sugar.
300 mg/dL (16.7 mmol/L) or higher	Your blood sugar may be too high to exercise safely	Postpone DM subject workout until blood sugar drops to a safe pre-exercise range

Blood glucose tracking has been a preferred method used as a feedback in how food, physical activity, and medicine affect the blood sugar levels on type 2 DM subjects in general.

This research involves methods based on collected data values from: muscles and joint range on motion during brisk walking. The huge amounts of information collected on every subject must be analyzed, and then reported as the indications of muscles and their energy consumption. To obtain these results a common technique is to use differential analysis to establish variances in the muscle activation pattern.

The main four approaches to analyzing these kinds of data are [67]:

- Classic method: Assume a Euclidean framework (classic geometry) and smooth the data shape.
- Classic differential analysis: Assume low level representation is important only in the way that it "interacts" with certain functions. This interaction defines an operator which is differentiable; to be used in generalized derivatives that can be used in place of the representation.
- Fuzzy convert to classic differential analysis: Assume that the data shape is Fuzzy (approximate rather than fixed and exact) but constrained in such a way that can be embedded in a normed space, which allows classical differential methods to be applied.
- Natural Fuzzy method: Assume that the data shape is Fuzzy and introduce a natural vector space structure, so that the notion of fuzzy differentiation follows naturally without the imposition of a norm.

The natural Fuzzy method is based on Fuzzy logic, which has potential as a tool capable of emulating human reasoning. An assessment was designed for the evaluation of muscle activation patterns within the gait phases and its relation with joint angles. A relational matrix is define to express a fuzzy relation, based on fuzzy-rules that models the coordination of Joint angles, Dynamic Muscle Activity (sEMG) and vGRF, for detecting variance on muscle activation pattern.

3.2 The significance of this research

Based on the importance of moderate exercise of the limb muscles involved during the gait cycle on the prevention or delay of type 2 DM illness, this research focuses on sensor monitor signals from limb muscles using surface Electromyography (sEMG) and joint angles (Goniometers), during the human gait cycle, analyzing vertical Ground Reaction Forces vGRF on an instrumented treadmill. The study develop algorithms using differential analysis for establish variances in the muscle/joint activation pattern and energy consumption on some limb muscles during brisk walking. The results can be used as an additional exercise feedback besides the traditional blood sugar tracking, adding suggestions over which muscles/joint of each limb need more attention to improve exercise and help in BG control for DM type 2 subjects.

The results of type 2 diabetes subjects are compared with a healthy subjects control group, during brisk walking [30-35]. This kind of walking, as a moderate activity, suggests further study muscle, regarding energy management on type 2 DM patients to understand how muscles are gaining strength to help regulate their BG consumption [45-48], or losing strength when compared with matched control subjects [63].

The patterns of dynamic muscle activation and their coordination with joints angles during gait cycle are analyzed to help variance detection due to poor balance, neuropathies and muscle weakness; these can lead to gait abnormalities including improper pressure distribution on the foot, longer stance phase, shorter steps, delays on muscle activation, and reduction of range of motions in joints. An assessment using a natural Fuzzy method (fuzzy logic) emulating human reasoning was designed, where the results can be used as mentioned previously. This assessment can help BG control for DM type 2 subjects. To achieve these goals an appropriate experimental design was created, where a set of equipment/devices are used to measure the signals acquired from electronic sensors on subjects selected under a special criteria.

Chapter 4 Methodology – Design of experiments

The experimental design (Fig. 13) is organized into four steps: data acquisition, muscle energy expenditure analysis, natural fuzzy differential analysis for muscle/joint activation, and results consolidation.

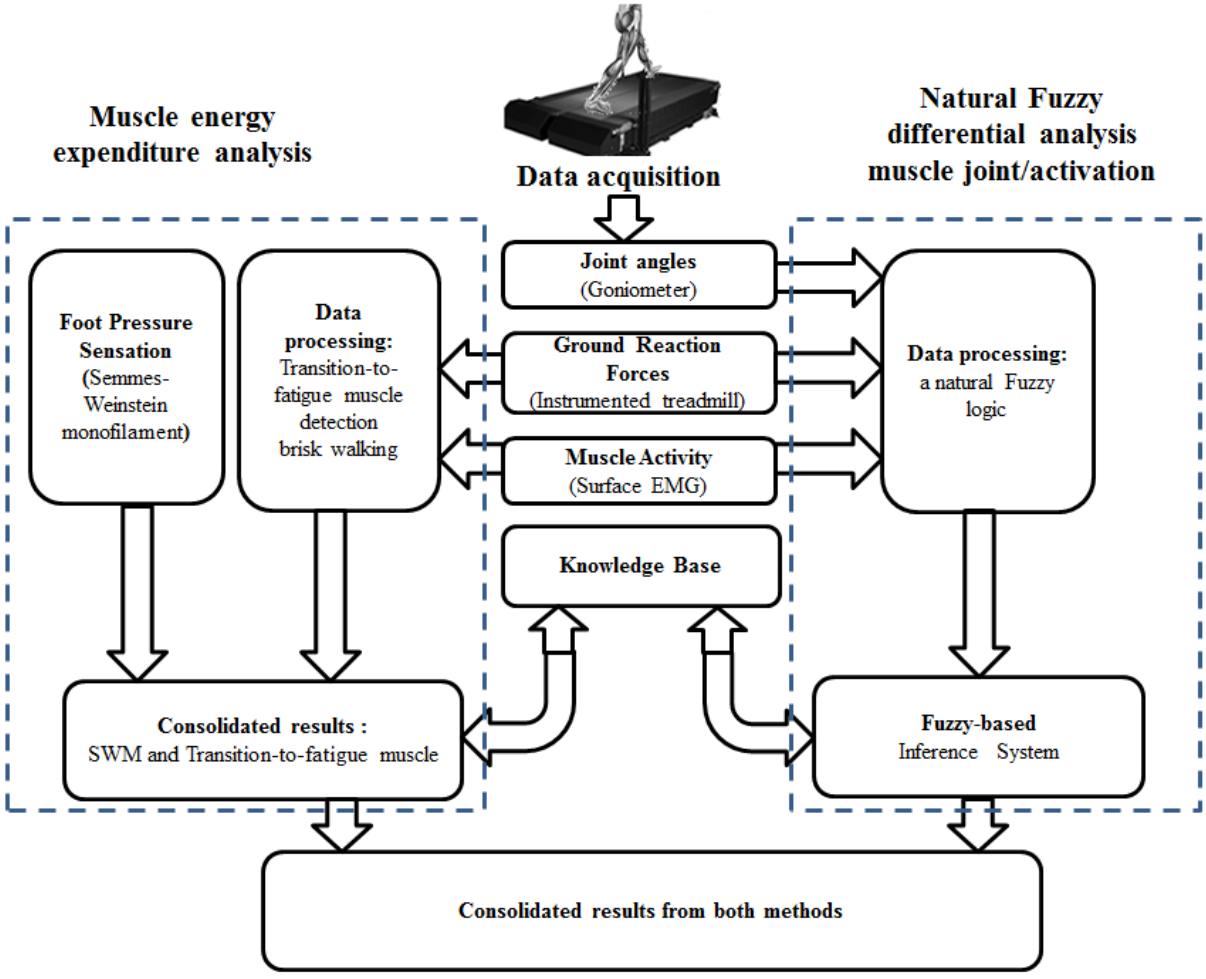


Figure 13 Experimental designs: Muscle energy analysis expenditure and natural fuzzy differential analysis on muscle/joint activation pattern

4.1 Data acquisition

Data acquisition is obtained from three different kinds of instruments/ equipment (Fig. 3):

- Instrumented Treadmill: Dynamic kinetics measurement, using force sensor platforms obtained the ground reaction forces (GRF) data signal.
- Surface Electromyography (sEMG): Muscles function through the inquiry of their electrical signals.
- Goniometers: Range of motion (ROM) of joints.

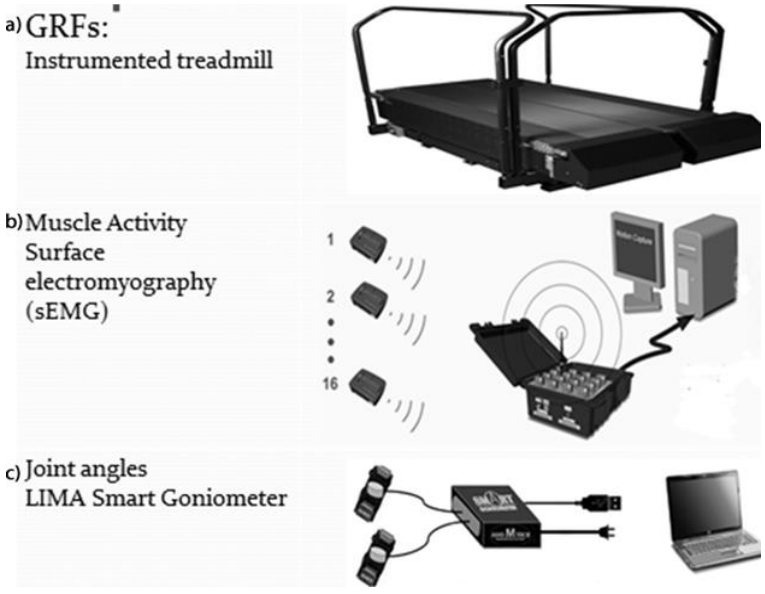


Figure 3 Experimental design: Instruments/devices

4.1.1 Instrumented treadmill

A dual belt instrumental treadmill from Bertec® contains two independent force plates that measure the ground reaction forces (Fig 3a). These force plates measure the forces and the joint moment (rotational potential of forces acting on joint) applied by the foot to the ground.

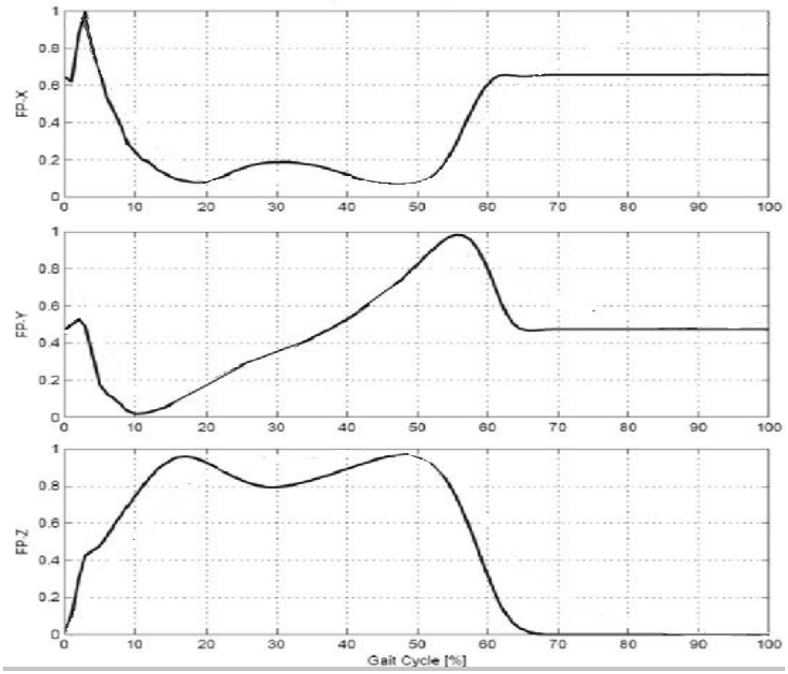


Figure 4 Typical healthy subject GRF signals normalized to max value. [125]

As mentioned before The GRF signals have three-dimensional components: X axis (medio-lateral), Y axis (anterior posterior), and Z axis (vertical planes). The z-axis signal is known as the vertical ground reaction force (vGRF). The three axis ideal signals ground reaction forces are shown on Fig. 4 [125]; from these signals the following spatial-temporal variables allow the analysis of the human gait cycle (Fig. 5):

- **Gait stride** or **gait cycle is** normally from the initial contact heel strike of one foot to the following contact heel strike of the same foot.
- **Step length** as the linear distance between corresponding successive points of heel contact of the opposite feet.
- **Stride length** is the linear distance between the initial heel contacts of the same foot. In normal gait double the step length.

- **Stride/step width** is the side to side linear distance between lines of the two feet.
- **Stride/step time** is the stride measured time.
- **Double-supported phases** are the two periods on stance phase supported by both legs, at these times the body's center of gravity is at its lowest, and is at normal gait approx. 10% each.
- **Cadence** as the number of steps per minute (normal 100-115 step/min)
- **Velocity** is the product of cadence and step length, expressed in meters per second.

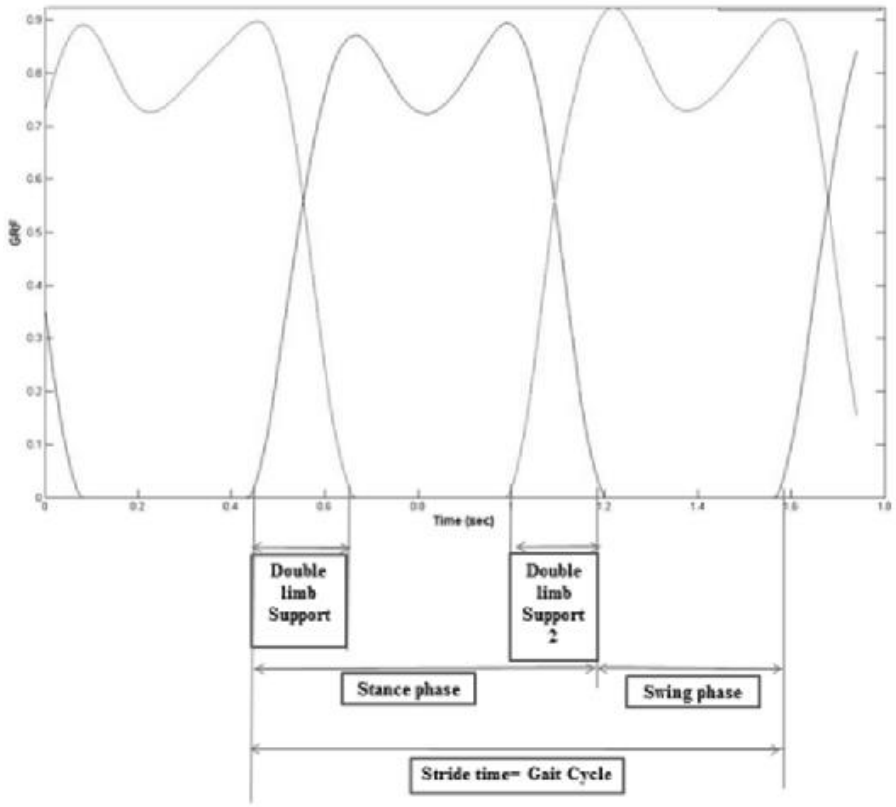


Figure 5 Spatial-temporal variables processed from vGRF

Patients with diabetes frequently exhibit a conservative gait strategy as: slower walking speed, wider base of gait, and prolonged double support time [84]. The GRF data will show variations in gait compensatory strategy to overcome musculoskeletal deficits [86]. vGRF

usually increases in magnitude and frequency when the velocity is increased and decrease in lower velocity. Subjects with diabetes and peripheral neuropathy have a high incidence of injuries while walking; some changes are observed in medio-lateral GRF (x-axis) ,which are indications for bad balance control [85].

4.1.2 Surface Electromyography (sEMG) instrument

Surface electromyography (sEMG) instruments record electrical activities from muscles as a non-invasive technology. A Trigno Delsys Wireless sEMG (Fig. 3b) with 64 channels (16 EMG /48 accelerometers) was used to monitor eight muscles for each limb: Erector Spinae (ES), Gluteus Medius (GM), Biceps Femoris (BF), Gastrocnemius Lateralis (GL), Rectus Femoris (RF), Vastus Lateralis (VL), Tibialis Anterior (TA), and Soleus (SL). These sEMG sensors are indicated on limb muscles in figure 6 and their position are described on table 5.

Table 5 Muscles with sensor position description

Muscle	**Acronym**	**Sensor position description**
Erector Spinae	ES	Lumbar region of the spine, at two finger width lateral from medial L1
Gluteus Medius	GM	Three centimeters towards the spin, going from the hip bone
Biceps Femoris	BF	Half way between the ischial tuberosity (lowest of the three major bones that make up each half of the pelvis.) and the lateral epicondyle (rounded articular area) of the tibia.
Gastrocnemius Lateralis	GL	Upper half of the posterior aspect of the calf
Rectus Femoris	RF	Medial anterior surface of the thigh, approximately half the distance between the hip and the knee.
Vastus Lateralis	VL	Lateral surface of the lower third of the thigh, approximately 6cm above the kneecap.
Tibialis Anterior	TA	A third of the distance from the knee to the ankle, at lateral to the tibia bone and anterior surface of the lower leg
Soleus	SL	Lateral, posterior side of lower leg.

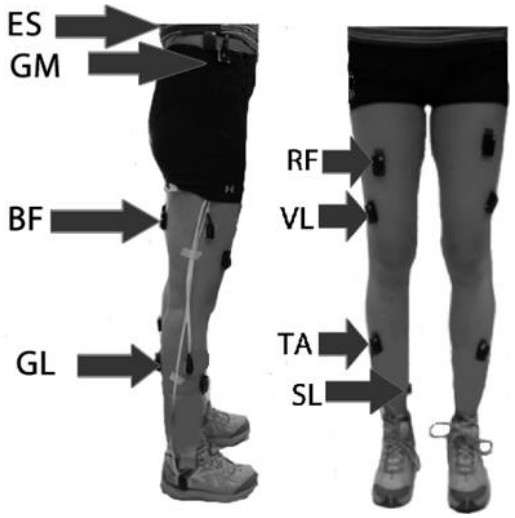


Figure 6 sEMG sensors indicated positions on limb muscles

During dynamic movements, such as walking, the comparison of amplitude measurement alone (i.e. peak RMS) across muscle groups can be very misleading without first normalizing the sEMG data. For this research, the most common method for sEMG normalization in dynamic movement cycle is used, based on the maximum sEMG values (mean of EMG signal) from the walking cycle, discarding the first and second repetitions [87], so that the EMG amplitude ranged between 0 and 1. Figure 7 shows eight typical normalized sEMG signals from eight muscles in one gait cycle.

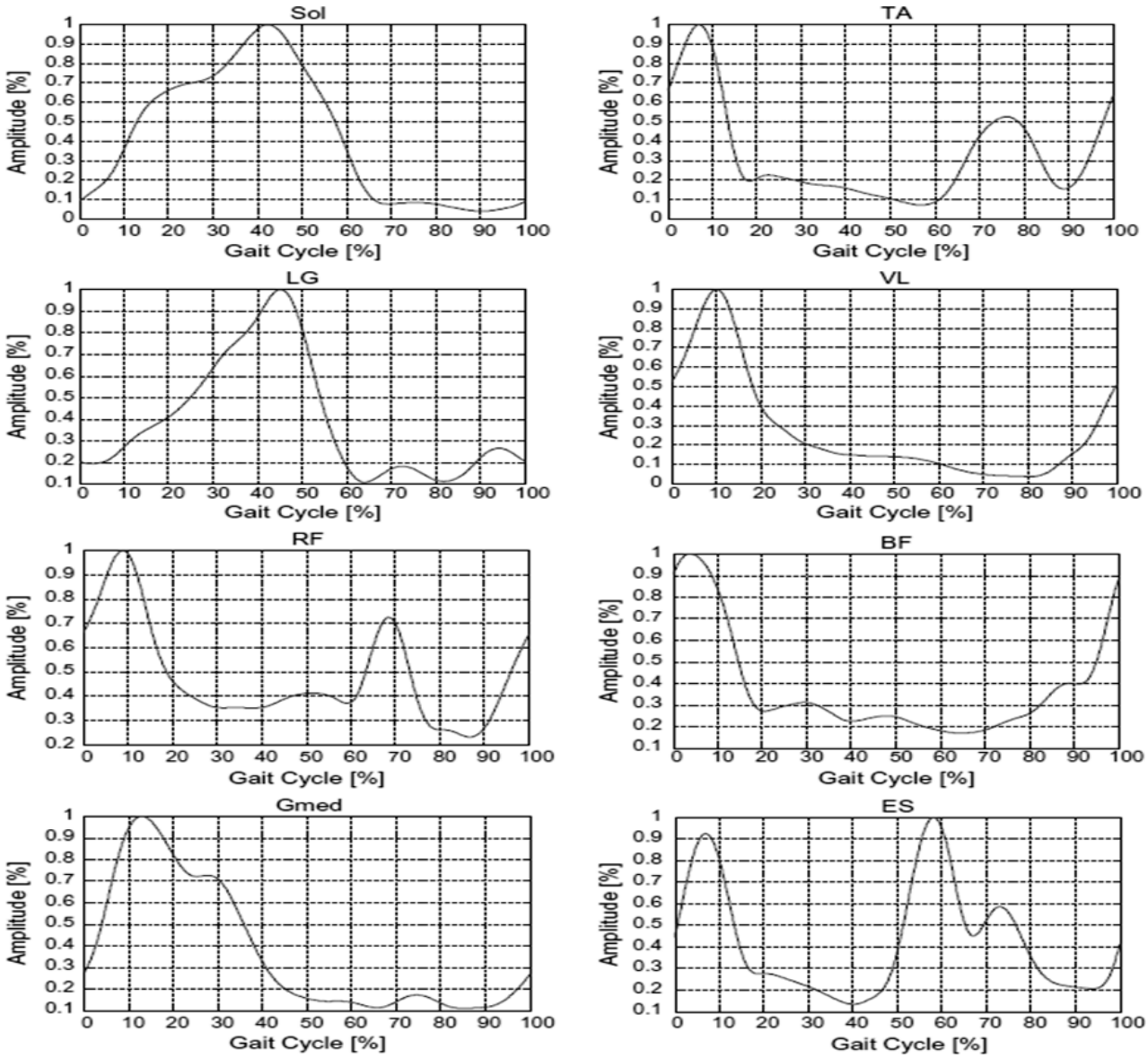


Figure 7 Normalizing averaged sEMG signal during full gait cycle [124]

Some researchers have reported important issues related to sEMG on Diabetic subjects: during walking, diabetic subjects' preliminary results show that sEMG can be considered as an efficient tool in highlighting the presence of muscle fatigue [89]. sEMG responses of the thigh and leg muscles in the diabetic neuropathic group were delayed if compared to the normal recruitment pattern, especially in the Tibialis Anterior and Vastus Lateralis [88]. Diabetic individuals had a delay in the lateral gastrocnemius EMG activity [90].

4.1.3 Goniometers instrument

Goniometers are instruments used to measure joints range of motion. The LIMA Smart Goniometer (Fig. 3c) developed in UTEP LIMA LAB [91] is based on electronic wearable sensors, known as Gyroscopes that measure the range of motion in degrees in three axes, to obtain joint kinematics of the ankle ($\emptyset_{ANKLE}$), knee ($\emptyset_{KNEE}$) , and hip ($\emptyset_{HIP}$) in real time (Fig 8b) . Each electronic sensor is based on triaxial Gyroscope device for measuring orientation based on the principles of angular momentum. Each range of motion in degrees is calculated by the LIMA Smart Goniometer from the combination of two gyroscopes aligned as indicated on Figure 8b. The Gyroscope sensors limb positions are show on Figure 8a and each position is described in table 6.

Table 6 LIMA Goniometer description for sensors position

Gyroscope	**Position**
Foot (GF)	Outside of foot which is 1.5 centimeters approximately from the ankle
Shank (GS)	located between knee and ankle
Thigh (GT)	between knee and hip
Hip (GH)	hip itself

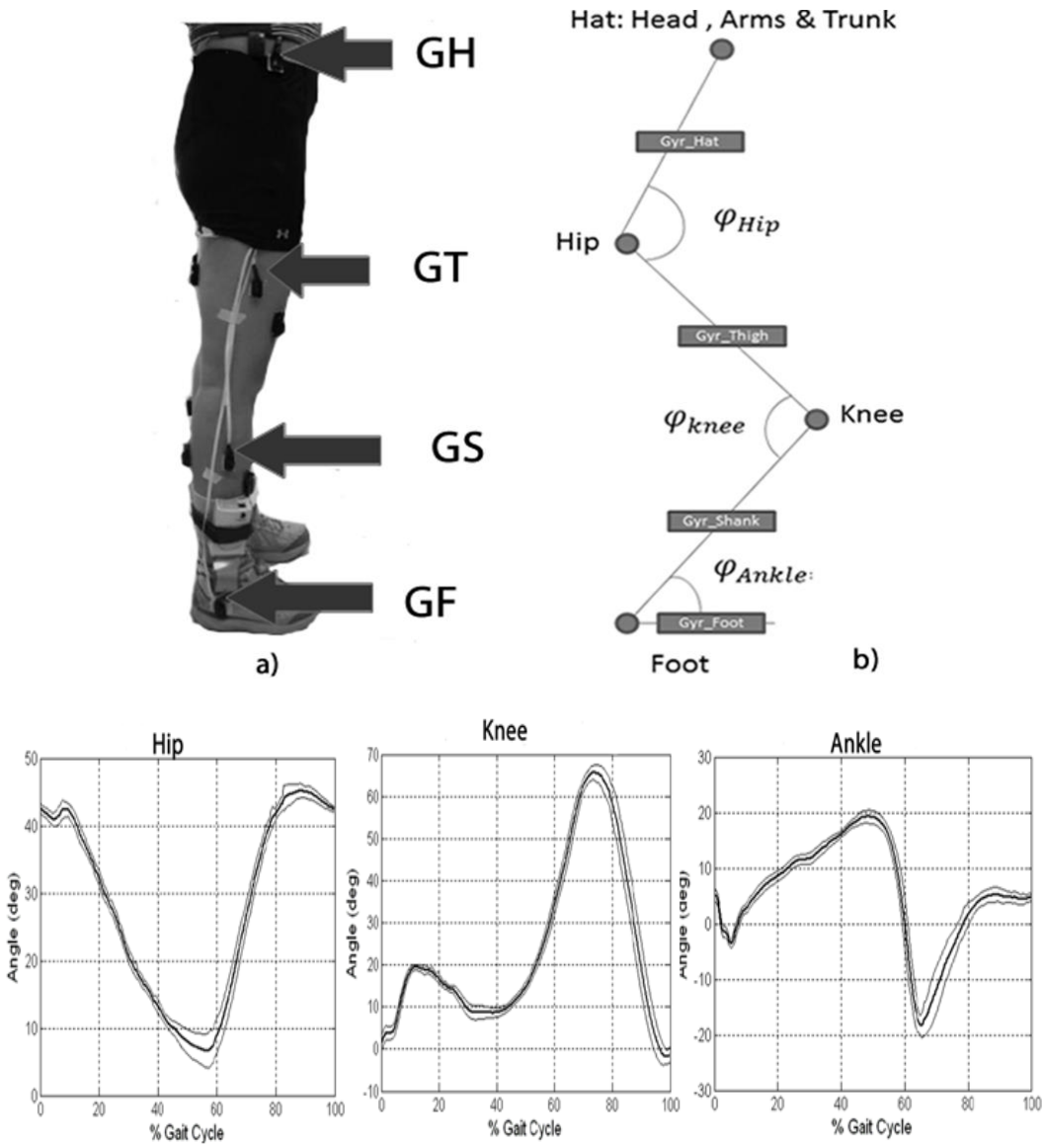


Figure 8 Gyroscopes from LIMA Smart Goniometer a) sensor placement, b) Joint Angles, and c) Angles Averages healthy subject: Hip, Knee and Ankle [91, 92]

A normal healthy subject's signals from ankle angle in a sagittal plane (vertical plane which passes from ventral (front) to dorsal (rear) dividing the body into right and left halves) are shown on Figure 9 where the Black line denotes the means from number of strides, and the grey lines denote the upper and lower limit of the standard deviation [91, 92].

Some previous studies have reported that diabetic mellitus (DM) subjects show less: ankle mobility, ankle movement, ankle power, velocity, and stride length during walking compared to healthy subjects. Low Joint Mobility (LJM) in patients with DM had significantly less total ankle (17.9° vs. 31 or 28.4°) [93]. DM subjects with an at-risk foot have reduced joint mobility and elevated pressure-time integrals PTIs on the plantar, placing them at risk for subsequent ulceration [94]. DM subjects appeared to use hip strategy (pulling their legs forward using hip flexor muscles) rather than ankle strategy (pushing the legs forward using plantar-flexor muscles) [95].

4.2 Participants

For this study two groups of volunteers were integrated: a healthy control group, and a type 2 DM group. From the healthy control group, average dynamic parameters during gait cycle are being compared to the diabetes mellitus group. The data collection used here has been used on anterior different research for different purposes and results [91].

4.2.1 Healthy control group

A healthy control group was recruited from the campus of the University of Texas at El Paso (UTEP), with ages ranging from 19-38 years old, without any motor impairment, and no medications being used at the time of data collection.

A total of twelve males and eight females (age: 28.5 $\pm$ 9.5 years; weight: 65.4 $\pm$ 24.6 kg; height: 173.5 $\pm$ 18.5 cm; BMI%: 22.31 $\pm$ 6.76) volunteered to participate in this study.

4.2.2 DM group

A type 2 diabetic mellitus group was recruited from students' relatives from the campus (UTEP), with age ranging from 26-60 years old, with two or more years with the illness and no previous foot ulceration history.

A total of two males and five females, (age: 43 ± 17 years; weight: 101.8 ± 39.5 kg; height: 162.5 ± 16.5 cm; BMI%: 39.64 ± 10.42, year diagnosed: 12 ± 10) with type 2 diabetic mellitus, volunteered to participate in this research.

There are many instruments used for detecting early neuropathy based on foot sensory testing possible areas of ulceration. One area for testing is based on the vibration threshold of the Biothesiometer [119] or pressure as the Semmes-Weinstein monofilament (SWM) [96]. The SWM is a commonly used as a reliable instrument used for podiatrists, family physicians, or endocrinologists to evaluate foot sensory perception. This is instrument used on all subjects for this research.

4.2.3 Semmes-Weinstein monofilament test

During the Semmes-Weinstein monofilament (SWM) test, the physician touches the subject's foot with a little plastic string, and asks if they can feel it when their eyes are closed. This nylon 'string' is specifically calibrated in stiffness (difficult to bend) to represent a baseline level of sensation that can be considered 'the line' between having possible neuropathy and having normal sensation. When it is placed against the foot and slightly bent, due to the pressure of pushing it onto the foot, a person with normal sensation should feel it, though extra precautions need to be practiced to protect the foot from poor sensation. If its pressure is not felt in at least four out of ten predefined areas, then it is a reasonable suggestion [97, 98] that diabetic neuropathy is present. Nevertheless, the monofilament test should never be used alone to determine, if neuropathy is present in a diabetic who has never had neuropathy before.

For the type 2 diabetic mellitus group the Semmes-Weinstein monofilament (SWM) device from BASELINE® (Fig. 8a) was applied using two different nylon monofilaments: one of 10 grams and if the test fails, one of 300 grams, were used to assess foot pressure during a subjective test [99, 100]. The subject with their eyes closed is asked if he/she can feel the pinch, and the place. This test was performed with a random order on five sites of each foot: big toe, first metatarsal, third metatarsal, fifth metatarsal, and heel (Fig. 8b).

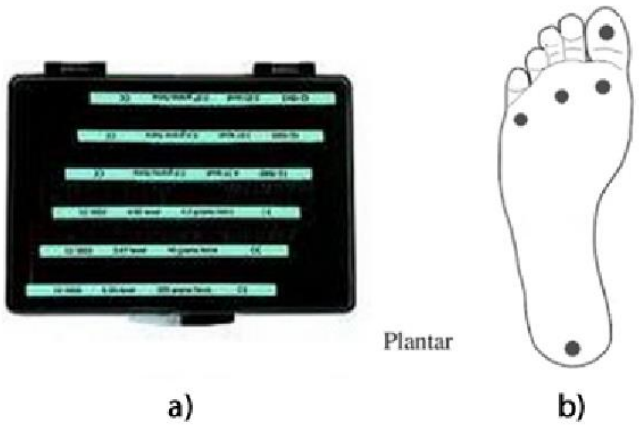


Figure 8 a) On Semmes-Weinstein monofilament from BASELINE® b) 5 Test sites

The assessment was performed by the following procedures: Once the subject has his eyes closed, the test was performed using a 10 gram monofilament 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 bent. Once the test was performed, pressure from the monofilament was removed and the subject was asked if he/she felt something and in which area. If subjects failed more than two areas, the procedure was performed again with another monofilament of 300 gram.

All healthy subjects that were tested with a monofilament passed the test with the 10 gram monofilament. These monofilament test results were used as an acceptable reference. The summarized results of using the monofilament test for our type 2 diabetic mellitus group is indicated in table 7. Where: H=Heel, 1M=1 metatarsal, 3M=3 Metatarsal, 5M=5 Metatarsal, BT=Big Toe, X means a failed monofilament test of 10 gr, and an empty cell means a successful monofilament test of 10gr.

Table 7 SWM test results on type 2 diabetic mellitus group

Type 2 DM Subject	Age	Years Diagnosed	Monofilament >2 areas failed (10gr)	Right Foot Monofilament test 10 gr					Left Foot Monofilament test 10 gr				
				H	1M	3M	5M	BT	H	1M	3M	5M	BT
M1-DM	44	8	No										
M2-DM	52	6	Yes	X	X	X	X	X	X	X	X	X	X
F1-DM	60	22	Yes	X	X	X	X	X	X	X	X	X	X
F2-DM	56	2	Yes				X		X	X	X	X	
F3-DM	47	3	Yes		X					X	X		
F4-DM	26	4	No										
F5-DM	34	4	No										
Where: : H=Heel, 1M=1 metatarsal, 3M=3 Metatarsal, 5M=5 Metatarsal, BT=Big Toe **X** = Fail Test, **Empty cell** = Pass test													

The results indicate that four of the seven type 2 DM subjects failed more than two areas during the 10 gram monofilament test. These four subjects could develop diabetic neuropathy, and precautions need to be practiced to protect their foot from future sensory impairment, especially subjects M2-DM and F1-DM, who failed all the monofilament tests in both feet.

The SWM testing protocol is a reliable instrument for identifying the loss of protective sensation on DM subjects; it is a subjective test because it is dependent on a subject's personal perspective. Clinicians always consider a combination of examination items to confirm their results as the Biothesiometer test. For this research two additional novelty methods are proposed: muscle energy expenditure detection as a transition-to-fatigue limb muscles, and a natural fuzzy differential analysis for muscle/joint activation pattern.

4.2.4 Transition-to-Fatigue limb muscle detection

Some studies have shown the progression of muscle weakness in long-term diabetes and its relationship to the neuropathic condition [63, 102]. Others have concluded that type 2 DM may have muscle weakness related to the presence and severity of peripheral neuropathy (peripheral nerves are not working properly to carry information to and from the brain) [101]. Muscle weakness in DB is a progressive condition usually detected as neuropathy when a group of nerves is damaged. As nerves become more damaged, they can no longer stimulate muscle fibers, leading to the permanent shortening of a muscle (contracture)[120]. Actual BG control is used as a monitor for the prevention of further nerve damage, and physical therapy is recommended to help improve muscle strength. The new proposed method to detect muscle weakness as a Transition-to-Fatigue limb muscle may be used for improving prevention, as an exercise feedback besides the traditional blood sugar tracking, and the SWM tests. The proposed method also indicates which limb muscles need more attention to improve muscle strength for DM type 2 subjects.

Localized muscle fatigue occurs after a prolonged, relatively strong muscle activity. This is referred to as the process of a decline in force during a sustained muscle activity; the inability to exert any more force or power defined as physiological fatigue [104-106]. Muscles that are fatigued absorb less energy before they are stretched to such a degree that it causes injuries. Three parts of localized muscle fatigue are described on the electromyography signal: Non-Fatigue, Transition-to-Fatigue, and Fatigue [107,108]. Non-Fatigue is when the fresh muscle is able to exert its maximum force. Fatigue relates to the onset of fatigue during a muscle contraction. Transition-To-Fatigue is the step between the two. Once the onset of Transition-to-Fatigue is detected, what follows is a progressive process until fatigue onset is achieved. By identifying this transitional fatigue stage, it is possible to predict when fatigue will occur [109].

Due to the variability of inter-personal muscle characteristics, there is no simple function or method for muscle load and timing that defines a precise muscle fatigue threshold [105, 110]. A surface electromyography (sEMG) technique records electrical activities of the muscle as a non-invasive technology where signals can be analyzed to detect muscles on Transition-to-Fatigue, by examining the changes in measurements, as a highlight to predict the onset of the fatigue class. It was recently found that the changes due to fatigue in the sEMG signal are detected as increases in amplitude and decreases in frequency [111].The electrical impulse is carried down the motor neuron to the muscle. Muscle fatigue causes Motor Unit (MU) recruitment and the MU firing rate increases as a function of the elapsed time suggesting, that the recruitment of MU firing rates correlates with sEMG amplitude of the motor unit action potential (MUAP) detected [111, 112]. It is common to study the sEMG in both the time and frequency domains. The Fourier Transform allows representation as a function of frequency rather than time, revealing its individual frequency components. Two of the most common frequency-dependent features in sEMG analysis are the mean frequency (MNF) and median frequency (MDF) [111, 113-117]. These two features are mostly applicable in sustained contraction: the mean frequency (MNF) is the average frequency of the power spectrum and is defined as its first-order moment; and the median frequency (MDF) is the frequency at which the spectrum is divided into two parts of equal power as indicated [118]. Based on the mean power spectrum and Median Frequency (MDF) of each of the sEMG signals segmented in samples of 2.5sec, a methodology was developed and published [103]. Using this technique allows researchers to detect the sEMG signal into a meaningful sequence of Non-Fatigue to Transition-to-Fatigue for limb muscles.

The Transition-to-Fatigue limb muscle detection can be tested under static condition (isometric exercise) and dynamic condition (brisk walking).

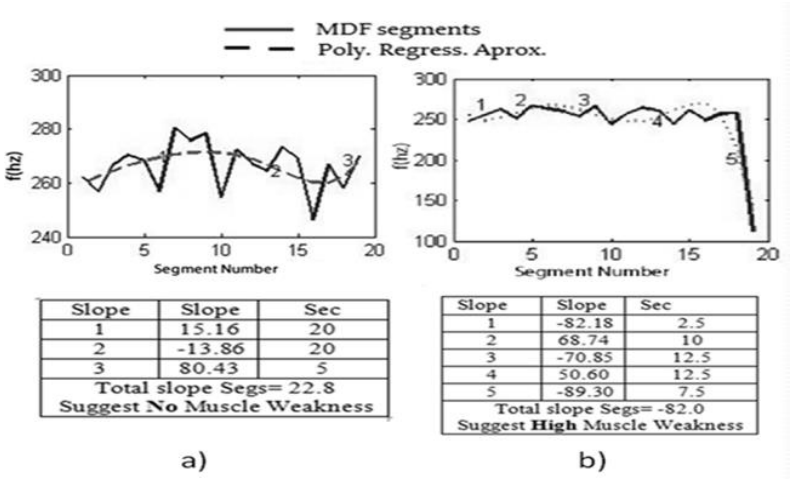
4.2.5 Transition-to-Fatigue limb muscle detection during Static position

Isometric exercise (static position) is a type of strength test in which the joint angle and muscle length do not change during contraction. Isometrics are done in static positions, rather than being dynamic through a range of motion. The joint and muscle are either worked against an immovable force (overcoming isometric) or are held in a static position while opposed by resistance (yielding isometric). This allows for the transition-to fatigue muscle detection in a very short time. For this research, these tests were applied only to a selected healthy group, where twelve healthy subjects volunteered to participate in this study without any motor impairment, and no medications being take at the time of data collection with: (age: 26.7 ± 6.67 years; height: 172.4 ± 8.46 cm; mass: 86.0 ±17.29 kg; BMI: 28.8 ± 3.60). This research was approved by UTEP's Institutional Review Board (IRB) for human subjects studies.

The experimental procedure was explained to the subjects and all participants were asked to sign a written informed consent before testing. sEMG signals were recorded from four muscles: Soleus (Sol), Tibialis Anterior, (TA), Gastrocnemius Lateralis (GL), and Vastus Lateralis(VL). Each subject was asked to repeat the isometric exercise (see Fig. 9) in the following sequence of four tests: one minute followed by a one minute break, another one minute followed by a one minute break, two minutes followed by a two minute break, and finally three minutes. Subjects can stop anytime based upon their capabilities. From the 12 healthy subjects, only five could complete all four tests and seven had to stop after the third test. The first two tests were warming-up tasks, and the third and/or fourth tests were analyzed to predict the Transition-to-Fatigue (fatigue task).

Figure 9 Isometric exercise tests [103]

The sEMG signals were stored on a computer with a sampling frequency of 2000 Hz. All data was segmented in windows of 2.5 sec. [103]. Each segment was converted to frequency domain using Fast Fourier transform and the mean power spectrum was calculated in order to obtain the Median Frequency (MDF)[103]. Then, a Polynomial Regression Analysis Model was applied for each window or segment, and values of linear slope were obtained for consecutive segments with the same sign. Finally, the results are charted [103]. Some typical muscle behaviors under this isometric test are shown in Figure 10, where a normal muscle maintains its MDF in range from 250 to 280 Hz. Its frequency is maintained almost stable (Fig. 10 a). The muscle on Fig. 10 b) shows sharp decay on MDF values with a range from 250 to 110 Hz. This is an detection of muscle weakness during transition-to-fatigue.



Slope	Slope	Sec
1	15.16	20
2	-13.86	20
3	80.43	5
Total slope Segs= 22.8		
Suggest **No** Muscle Weakness		

Slope	Slope	Sec
1	-82.18	2.5
2	68.74	10
3	-70.85	12.5
4	50.60	12.5
5	-89.30	7.5
Total slope Segs= -82.0		
Suggest **High** Muscle Weakness		

Figure 10 Isometric Test muscle behavior: a) Typical Normal, and b) Typical Transition-to-Fatigue (Weakened)

From these isometric exercise tests [103] the conclusions are as follows:

- Detection of the Transition-to-Fatigue stage on muscles during isometric exercise is important because it will soon progress to the fatigue onset. By identifying this transitional fatigue stage, it is possible to predict when fatigue will occur; by consequence a muscle weakness is detected.
- The segmented data based on MDF assessment was a useful methodology for the detection of Transition-to-Fatigue.
- Muscle activities can vary across subjects due to anthropometric differences, but also vary from different muscles in a subject's left and right side of their legs.
- There were seven subjects which showed Transition-to-Fatigue on VL, followed by Tibialis Anterior with six subjects and the Soleus with five subjects. Gastrocnemius Lateralis was the least affected muscle in this isometric exercise.

This methodology also provides insight into the contributions that functional differences between muscles have on lower extremity disorders as well as serving as an index of underlying change in neuromuscular function before injury and in conjunction with injury treatment and rehabilitation.

As previously mentioned: brisk walking has been recommend as a moderate exercise, because it reduces risk of type 2 diabetes [24, 25, 27-29, 30-35, 46-48]. The results suggest the importance of studying muscle energy management on DM subjects during normal walking using a dynamic transition-to-fatigue limb muscle detection, to understand how muscle are gaining strength to help regulate BG consumption.

4.2.6 Dynamic Transition-to-Fatigue limb muscle detection

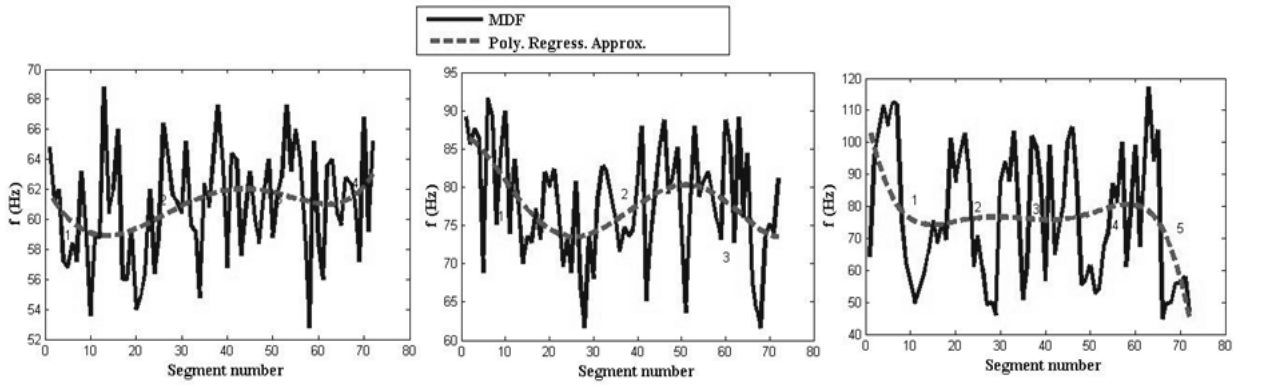
To study the behavior of muscle energy expenditure during dynamic exercise, the Transition-to-Fatigue limb muscle detection methodology using segmented (windows) data based on MDF as explained on the Isometric Exercise based, is now applied on brisk walking for the type 2 DM group; two males and five females, (age: 43 ± 17 years; weight: 101.8 ± 39.5 kg; height: 162.5 ± 16.5 cm; BMI%: 39.64 ± 10.42, year diagnosed: 12 ± 10) with type 2 diabetic mellitus, who volunteered to participate in this research.

The test is explained to the subjects and all participants are asked to sign a written informed consent form (IRB). Then, the sixteen sEMG sensors from the Trigno Delsys® Wireless (Fig. 3b) are placed with a proper skin preparation: cleaned and shaved area if necessary and always in the middle of the muscle and aligned to its orientation. The muscles under test are: Erector Spinae (ES), Gluteus Medius (GM), Biceps Femoris (BF), Gastrocnemius Lateralis (GL), Rectus Femoris (RF), Vastus Lateralis (VL), Tibialis Anterior (TA), and Soleus (SL). The 16 sEMG sensor positions are described on table 5 and their limb positions are shown on Fig. 6. Each subject used comfortable shoes, and performed over the instrumented treadmill two trials of 3 min each at a self-selected speed, based on the criteria for brisk walking described in section 1.2.2. The first is a warming-up task, where data is discarded. And the second tests are saved to analyze data from the surface electromyography (SEMG) electrodes, which measures the dynamic activities to detect the Transition-to-Fatigue during the gait cycle.

The same algorithm described on the static isometric test is used on this dynamic test. The sEMG signals are stored on a computer with a sampling frequency of 2000 Hz, data segmented in windows of 2.5 sec. Each segment is converted to frequency domain using Fast Fourier transform and the mean power spectrum is calculated in order to obtain the Median Frequency (MDF). Then, a

Polynomial Regression Analysis Model is applied for each window (segment), and values of linear slope are obtained for consecutive segments with the same sign. Finally, the results are charted.

Some typical muscle behaviors under this dynamic test are shown in Figure 11: a) Shows that a normal muscle maintains its MDF in reasonable range, in this case from 52.8 to 62.8 Hz (almost stable) with a total slope in all segments of 9.4 degrees. The muscle on Fig. 11 b) shows that a slow decay on MDF values, due to slow brisk walking selected for this subject, a range from 91.6 to 61.6 Hz (slow transition-to-fatigue) is detected and a total negative slope in all segments of -16.2 deg. This is an indication that muscle fatigue has been initiated, and Figure 11c) shows that a sharp decay chart on MDF behavior with range frequency from 108 to 46 Hz (fast transition-to-fatigue). This is a typical detection of muscle weakness during the transition-to-fatigue stage.



Slope Num.	Slope Degrees	Segs
1	-17.5	12
2	+12.1	31
3	-7.5	18
4	+24.7	10
Total slope segs = + 9.4 (degrees) Median=60.8, Max=68.8, Min=52.8 (Hz)		
Suggest NO muscle weakness		

a) No transition-to-fatigue

Slope Num.	Slope Degrees	Segs
1	-18.5	25
2	16.7	25
3	-18.0	21
Total slope segs = -16.2 (degrees) Median=77.7, Max=91.6, Min=61.6 (Hz)		
Suggest muscle weakness		

b) Slow transition-to-fatigue

Slope Num.	Slope Degrees	Segs
1	-81.1	14
2	+5.2	14
3	-5.2	12
4	+10.5	18
5	-81.7	13
Total slope segs = - 43.2 (degrees) Median=76.5, Max=108, Min=46 (Hz)		
Suggest muscle weakness		

c) Fast transition-to-fatigue

Figure 11 Dynamic Transition-to-Fatigue limb typical muscle detection

The result for all subjects with type 2 DM are summarizing on table 8. Showing results from the dynamic transition-to-fatigue during brisk walking in the 8 muscles of both limbs.

Table 8 Transition-to-fatigue muscle test results for type 2 diabetic mellitus group

Type 2 DM Subject	speed	Right Limb								Left Limb							
Muscle	(m/s)	SL	TA	GL	VL	RF	BF	GM	ES	SL	TA	GL	VL	RF	BF	GM	ES
M1-DM	0.57						S				S						
M2-DM	0.60				S					S			S				
F1-DM	0.40	S	S	F			S			F	F	S		F			F
F2-DM	0.50										S		S		S		
F3-DM	0.85			S					S						S		
F4-DM	0.85				S				S						F		
F5-DM	0.70					S							S	S	S	S	
Where: SL= Soleus, TA=Tibialis Anterior, GL= Gastrocnemius Lateralis, VL=Vastus Lateralis RF=Rectus Femoris, BF=Biceps Femoris, GM=Gluteus Medius, ES= Erector Spinae S= Slow transition-to-fatigue, F= Fast transition-to-fatigue, Empty cell= no transition-to-fatigue																	

The general results obtained from table eight suggest:

- BF, VL and TA are the muscles with more transition-to-fatigue detected in this DM group.
- GM is the muscle with less transition-to-fatigue detected for this DM group.
- Subject F1-DM has more amounts of muscle weakness, five **F** (Fast transition-to-fatigue) and four **S** (Slow transition-to-fatigue). For this subject, the left limb is more affected (tree **S** and one **F**), than the right one (one **S** and four **F**). This female, is 60 years old, 22 years DM diagnosed illness, and her brisk walking speed is the slowest of the group at 0.4 m/sec.
- Subject M1-DM has only two S, the smallest amount of muscle transition-to-fatigue in this group. Male, age 44 and eight year DM diagnosed illness, and his brisk walking speed is 0.57 m/sec

4.2.7 Differences SWM test and Muscle energy expenditure analysis

Up to this point the experimental design (Fig. 13), has two results for the evaluation of type 2 DM subjects: the Semmes-Weinstein monofilament (section 4.2.3) test and the dynamic transition-to-fatigue limb muscle detection during brisk walking (section 4.2.6). In the SWM the foot pressures sensations are detected and summarized on table 7. The dynamic transition-to-fatigue limb muscle detection during brisk walking results is summarized on table 8. To establish differences between the two tests both tables are consolidated on table 9, and final results are stored on the knowledge base (Fig. 13). A case study for each subject is described to simplify the results.

Table 9 Consolidated results type 2 DM group using: SWM and Transition-to-fatigue test

Type 2 DM	Monofilament areas failed (10gr)		Dynamic transition-to-fatigue muscle detection		Speed m/s
	Right limb	Left Limb	Right limb	Left Limb	
M1-DM			1	1	0.57
M2-DM	5	5	1	2	0.60
F1-DM	5	5	4	5	0.40
F2-DM	1	4		3	0.50
F3-DM	1	2	2	1	0.85
F4-DM			2	1	0.85
F5-DM			1	4	0.70

Case study 1 for Muscle energy expenditure analysis: Subject M1-DM

- Male 44 years old, height 179 cm, weight 97.4 kg, body mass index 30.39 Kg/m^2, and 8 years of being diagnosed with type 2 DM.
- No detection of any poor pressure sensation during the SWM test.
- Two soft transition-to-fatigues are detected during the brisk walking test (0.57 m/s.): one in right limb BF and another left limb TA.

The SWM didn't report any poor pressure sensation, and none Fast transition-to-fatigue detected in any muscle. Both methods seem to complement each other on the results.

Case study 2 for Muscle energy expenditure analysis: Subject M2-DM

- Male 52 years old, height 164 cm, weight 91.1 kg, body mass index 33.87 Kg/m^2, and 6 years of being diagnosed with type 2 DM.
- He failed all SWM tests, and callus was found on sole area for left and right foot.
- Three soft transition-to-fatigues are detected during the brisk walking test (0.6 m/s.): one in right limb VL and two on the left limb in SL and VL. He showed easy loss of balance during treadmill.

The SWM method report a callus with all test failed. The dynamic transition-to-fatigue muscle weakness detection suggests more attention to some limb muscle to delay the DM illness. The suggested group muscle affected during brisk walking are: quadriceps knee extensors muscle (VL both legs), and calf muscle (SL left limb). Both methods seems to complement each other, adding additional information

Case study 3 for Muscle energy expenditure analysis: Subject F1-DM

- Female 60 years old, height 155 cm, weight 95.5 kg, body mass index 39.75 Kg/m^2, and 22 years of being diagnosed with type 2 DM.
- She answered unsecured during the SWM tests, and for this reason failed all of them. No physical calluses were found on the sole areas.
- Four soft and five fast transition-to-fatigues are detected during the slow brisk walking speed of 0.40 m/s, the slowest from this DM group. The high muscles fatigue suggested

during brisk walking, on right limb is the GL muscle, and for the left limb are: SL, TA, RF and ES. Slow muscles fatigue is detected on the right limb: SL, TA, and BF. And in left limb the GL muscle

The SWM method reports all tests failed. The left muscle limb results indicate is that this muscle is more affected. The suggested group of muscle affected during brisk walking in the left leg are: TA, ES, quadriceps knee extensors muscle (RF), and calf muscle (SL). Both methods agree on the results, suggesting urgent attention to delay the DM illness.

Case study 4 for Muscle energy expenditure analysis: Subject F2-DM

- Female 56 years old, height 154 cm, weight 69.9 kg, body mass index 29.47 Kg/m^2, and 2 years of being diagnosed with type 2 DM.
- No physical calluses were found on sole areas. On the monofilament test she failed: one on the right foot (5M) and four on the left foot (H, 1M, 3M, 5M).
- During the dynamic transition-to-fatigue brisk walking of .50 m/s only the left limb muscles present slow fatigue: TA, VL and BF.

The WSM method report five failed tests and the suggested group muscles affected during brisk walking in the left leg are: TA, hamstrings (BF), and quadriceps knee extensors muscle (VL). Both methods seem to complement each other again on the results obtained.

Case study 5 for Muscle energy expenditure analysis: Subject F3-DM

- Female 47 years old, height 146 cm, weight 62.3 kg, body mass index 29.22 Kg/m^2, and 3 years of being diagnosed with type 2 DM.

- No physical calluses were found on sole areas. On the monofilament test she failed: one right foot (1M), and three on left foot (1M, 3M).
- During the dynamic transition-to-fatigue brisk walking of 0.85 m/s only three muscles presented slow weaknesses: two in left limb (GL and ES) , and one in the right limb BF.

SWM method reports 4 test failed. The suggested group of muscles affected during brisk walking are: left Calf (GL), left erector spinae (ES), and the hamstring (BF). Both methods seem to complement each other on the results obtained.

Case Study 6 for Muscle energy expenditure analysis: Subject F4-DM

- Female 26 years old, height 161 cm, weight 100.7 kg, body mass index 38.84 Kg/m^2, and 4 years of being diagnosed with type 2 DM.
- No physical calluses were found on sole areas. She passed all monofilament tests of 10 gr.
- During the dynamic transition-to-fatigue brisk walking test with 0.85 m/s, one muscle present fast weakness in the left limb BF. And two slow transition-to-fatigues in the right limb: VL and ES.

For some reason the monofilament test doesn't report any loss of foot sensation and the dynamic transition-to-fatigue report an urgent attention suggestion on the hamstring (BF). Possible the dynamic transition-to-fatigue methods detect weakness muscle before some physical foot loss sensation is present, or some subjective results are wrong on the monofilament

test. Another possibly explanation for these muscles weakness detection is this subject overweight.

Case Study 7 for Muscle energy expenditure analysis: Subject F5-DM

- Female 34 years old, height 168 cm, weight 141.3 kg, body mass index 50.06 Kg/m^2, and 4 years of being diagnosed with type 2 DM.
- No physical calluses were found on sole areas. She passed all monofilament tests of 10 gr.
- During the dynamic transition-to-fatigue brisk walking test with 0.70 m/s, five slow muscles weakness are reported: one in right limb (RF), and four left limb: VL, RF, BF and GM.

Again the SWM method doesn't report any poor sensation. The suggested group of muscles affected during brisk walking is: left and right quadriceps knee extensors muscle (RF), right hamstring (BF), and right Gluteal muscle (GM). Possible the overweight of this subject affect the muscle weakness.

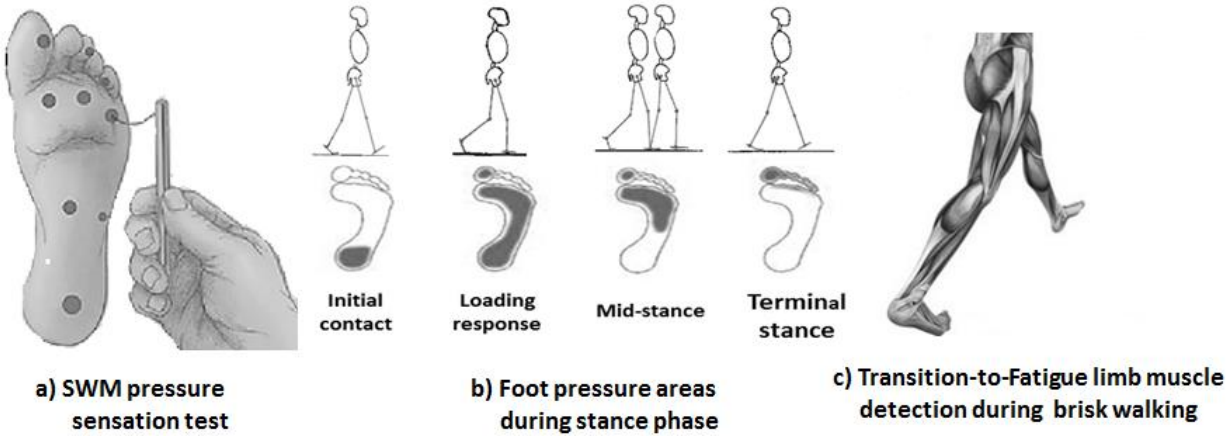


Figure 12 A) SWM test detect foot pressure sensation [97], b) Foot pressures areas during stance [127] Transition-to-fatigue limb muscle activity during brisk walking test. See conclusions of relation between both methods (section 4.2.8)

4.2.8 Muscle energy expenditure analysis and monofilament test

Based on cases studies from one to five (M1, M2, F1-F3-DM), both method results seem to complement each other. The Semmes-Weinstein monofilament test (Fig.12a) indicates the foot pressure sensation from the subject's personal perspective. The second method dynamic transition-to-fatigue muscle detection (Fig. 12c) reports the muscles limbs energy expenditure during brisk walking; applying specific foot pressures areas (Fig.12 b).

The last two study cases (F4 – F5 DM) report muscle fatigues, without apparently any loss of foot pressure sensation, the common parameters in both cases are that the subjects are overweight. The BMI normal ranges are: underweight (BMI <18.5), normal (18.5-25), overweight (25-30), obese (BMI>30) [121]. These support the general knowledge that overweight people get more easily tired [121]. Research as reported that weight gain is associated with substantially increased risk of diabetes among overweight adults, and even

modest weight loss was associated with significantly reduced diabetes risk. Minor weight reductions may have major beneficial effects on subsequent diabetes risk in overweight adults at high risk of developing diabetes [122, 123].

These results are going to be consolidated again with the result of the next method in this research: an assessment using a natural Fuzzy logic model, to establish differences in the muscle/joint activation pattern during brisk walking as indicated in the experimental design (Fig. 13).

4.3 Natural Fuzzy logic method for differential analysis in muscle/joint

The natural Fuzzy differential analysis method is focused on the muscle/joint activation pattern during brisk walking as shown in Fig. 13. During this test, data signal are drawn from three instruments previously described on section 4.1. These are: Ground Reaction Forces (GRF) form instrumented treadmill BERTEC®, surface electromyography (sEMG) muscle activity from instrument Delsys®, and joint angles from the instrument Lima Smart Goniometer. All information is stored, then processed, and analyzed using differential analysis. During the last step fuzzy results are inferred, and stored on the knowledge base. The Fuzzy inferred conclusion is then consolidated with the first method results, to give the final diagnostic and overall conclusions.

This test is explained to the same volunteered subjects, where all participants already signed the IRB. As well as the sixteen sEMG sensors already in place from the last method (Fig. 3b and Fig. 6), the gyroscope sensors from the LIMA Goniometer are place on the limb as described in section 4.1.3, and summarized in table 6. This allows us to obtain the joint angles from: hip, knee, and ankle (fig. 8). Each subject performs through the instrumented treadmill two trials: one of 1 min, and the second of 3 min at self-selected speed, based on the criteria for brisk walking described on section 1.2.2. The first is a warming-up task, where sensors are tested and data is discarded. The second test is saved to analyze data from: Ground reaction forces, surface electromyography (SEMG), and the Gyroscope sensors, with the objective to measures the dynamic activities for muscle/joint during the gait cycle, using the second method of Natural Fuzzy differential analysis.

4.3.1 Data Processing

For this method the raw signals of the three instruments (Fig. 3) are stored and data is pre-process to be used free of noise and instability. The anatomical planes defined in this analysis and processes are: 1) x-axis is the transverse plane; 2) y-axis is the sagittal plane, and 3) z-axis is the coronal plane, respectively.

- Ground reaction forces (GRF) signals collected by the instrumented treadmill, with a sampling frequency of 100 Hz are filtered to eliminate noise due to the vibration of the treadmill. A low pass second order Butterworth filter of 20 Hz is used and then a threshold value is applied to the vertical ground reaction forces (z-axis). Finally all signals are normalized to the maximum value as indicated in fig. 4.

- Surface Electromyography (sEMG) signals collected by the sEMG electrodes, with a sampling frequency of 2000 sample/sec are processed using the following steps: Second order Butterworth band-pass filter from 20 to 200 Hz, a full wave rectification is used to eliminate the negative values, a Linear envelope (moving average) using a second order Butterworth low-pass digital filter with a cutoff frequency of 7 Hz [126], and all sEMG signals filtered are resampled to 100 Hz. Finally signals are normalized with an amplitude range from 0 to 1, where the maximum values of EMG signals (mean EMG signal) are shown in Fig. 7.

- Smart Goniometer signals are collected using the gyroscope sensors, indicated in Fig. 8 to obtain the joint angles, with a sampling of 100 Hz, and a low pass second order Butterworth filter with a cutoff frequency applied. All values of each joint angle type are normalized for the maximum value.

The first three strides are eliminated to avoid instability to reach brisk walking, and then a verification method for synchronized signals is applied. Finally a natural Fuzzy logic (FL) [124] is used for the evaluation of muscle/joint activation patterns within the seven gait phase (table 1).

The relationship between the electrical activities of the muscles with respect to the seven gait phases is established as a relational matrix as indicated on fig. 14a. Where sEMG are: SL = Soleus, TA = Tibialis Anterior, GL = Gastrocnemius Lateralis, VL = Vastus Lateralis, RF = Rectus Femuris, BF = Biceps Femuris, GM = Gluteus Medius, ES = Erector Spinae. And vGRF are divided: Phase 1 = Loading Response (0-10%), Phase 2 = Mid Stance (10-30%), Phase 3 = Terminal Stance (30-50%), Phase 4 = Pre Swing (50-60%), Phase 5 =Initial Swing (60-70%), Phase 6 = Mid Swing (70-85%), and phase 7 - Terminal Swing (85-100%). Using this matrix a fuzzy set is defined for the sEMG signals from a muscle activity collection (type x) with respect to the seven functional gait phases (type y), $\mu(x, y)$ represents the mean of EMG data samples within each gait phase as indicated by the equation in Fig 14 b. The relational fuzzy matrix R(x, y) describes the association, interaction or interconection between elements of muscle activities and the functional gait phases.

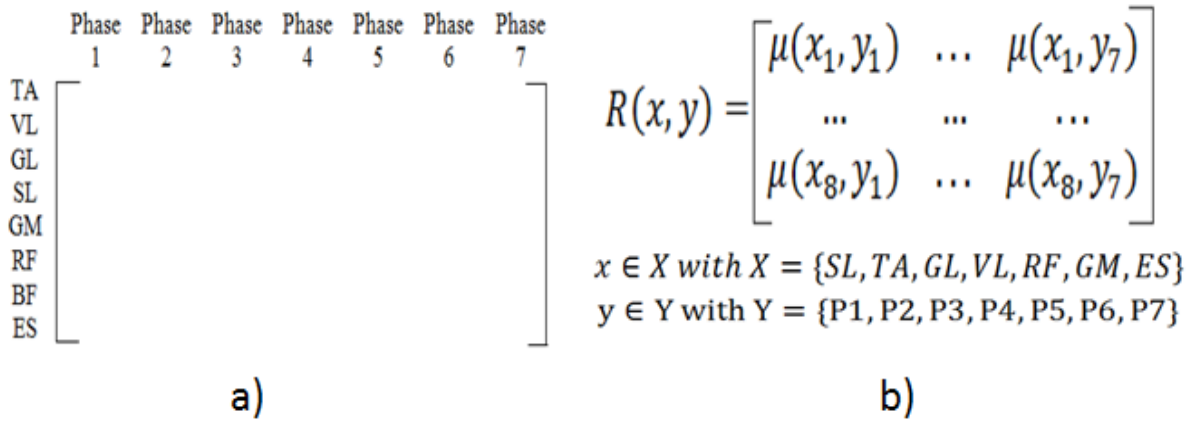


Figure 14 sEMG/vGRF: a) Relational matrix specification, b) R (x, y) Fuzzy Set Equation

Another relational matrix for the fuzzy set, that describes the relation of seven functional gait phases (type y) with respect to the Joint Angles (type z), is shown in Fig. 15a, where the fuzzy relation equation $\mu(y, z)$ represents the mean of the joint angles within each gait phase (as indicated in Fig. 15b). The relational fuzzy matrixS(y, z) describes the association, interaction or interconection between elements of the functional gait phases with the Joint angles indicated as: AJ = Ankle Joint, KJ = Knee Joint, HP = Hip Joint.

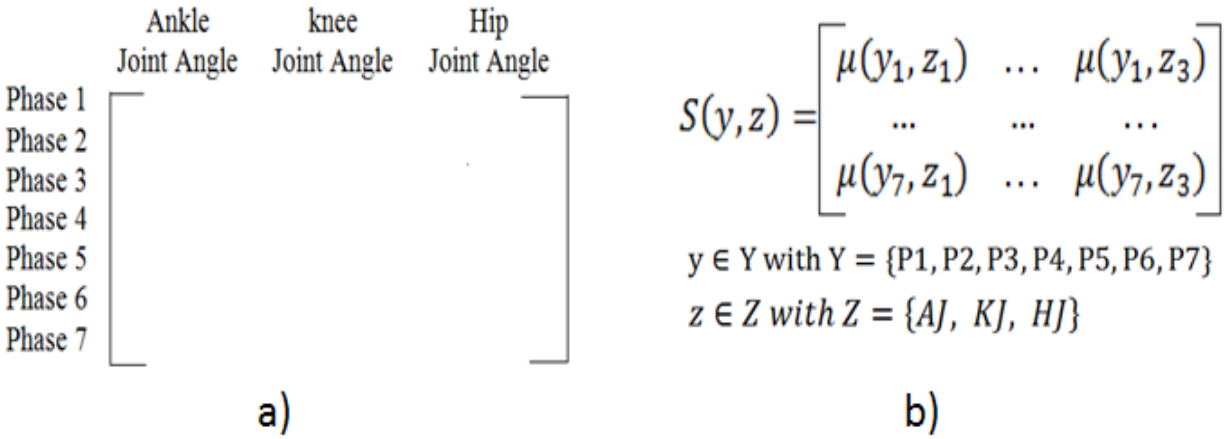


Figure 15 vGRF/Joint Angles: a) Relational matrix specification, b) S (y, z) Fuzzy Set Equation

A result can be inferred from the relation between dynamic muscle activity and Gait phases represented as fuzzy set R(x,y) , with the gait phases and joint angles represented as fuzzy set S(y,z) using the Fuzzy rule-based reasoning max-min to obtain T(x,z) as shown by the equation in Fig 16 (128). The relational results fuzzy matrix T(x,z) describes the association, interaction or interconection between elements of muscle activities with the joint angles.

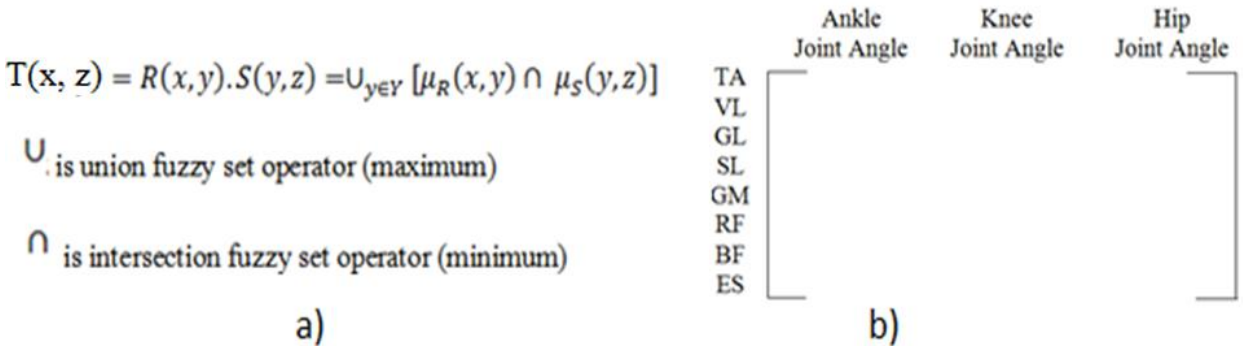


Fig. 16 Muscle/Joint Angles: a) T(x, z) Fuzzy result equation b) Relation matrix specification

A pattern analysis of the mapping of kinematic (motion of objects without consideration of the causes of motion) , kinetics (study of motion and its causes), and the electromyographic data within the seven gait phases can be made for determining the presence/absence of association, and interaction with joint angles during the gait dynamic.

Each DM subject feature pattern is compared with the reference feature obtained from the average healthy control group using the Fuzzy similarity algorithm. This provides an evaluation method to determine the behavior of muscles, joint angles and ground reaction forces within the functional gait phases. The fuzzy similarity measures the comparison between the reference pattern features $\mu_{ref}(x,z)$ from control group (healthy volunteers) , and the measured DM subject $\mu_{DM}(x,z)$ feature patterns using the equation described in Fig. 17 . The resulting

similarity between the reference and test attributes are between 0 (no similarity) and 1 (complete similarity). [125]

$$Fuzzy\ Similarity = \frac{\mu_{ref}(x,z) \cap \mu_{DM}(x,z)}{\mu_{ref}(x,z) \cup \mu_{DM}(x,z)}$$

$\cup$ is union fuzzy set operator (maximum)

$\cap$ is intersection fuzzy set operator (minimum)

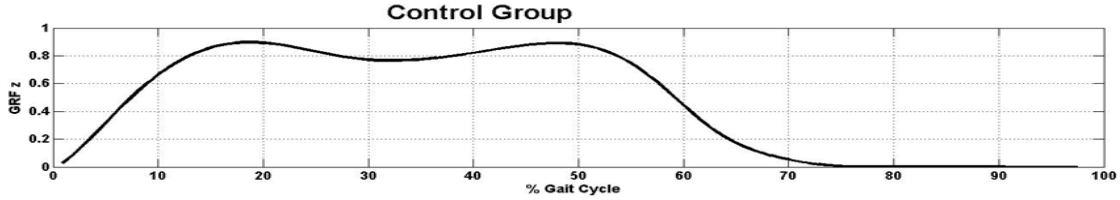
Figure 17 Fuzzy Similarity

A male control group is obtained with the average of twelve healthy males and a pattern analysis, using the fuzzy similarity algorithm, is made for the two DM males from the DM group. Another female control group is obtained with an average of eight healthy females and another pattern analysis using the fuzzy similarity algorithm, is made for the five DM subjects from these group. There were not big difference between the similarity analysis between the average male healthy control group,and the average female healthy control group. Then, all DM subjects are analyzed with the reference with the average healthy control group (HCG).

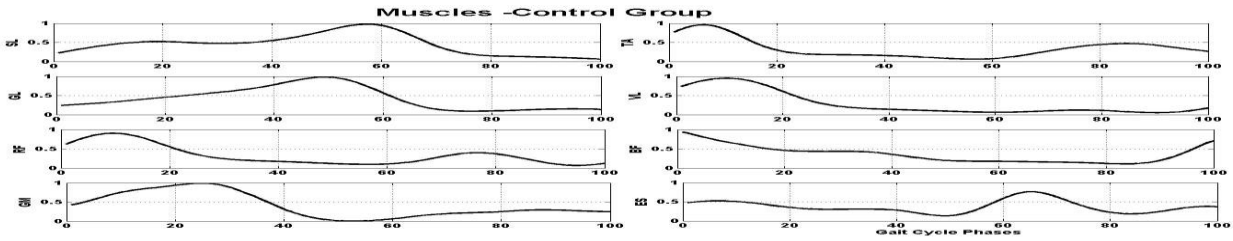
Chapter 5 Computational results and findings

The healthy control group data was based on a total of twelve males and eight females as explained in section 4.2.1. The strides were extracted from the z axis ground reaction forces (vGRF) as a reference, and averaged (Table 10a). There are two methods to analyze the EMG information: present EMG data by normalizing by the maximum value and normalized using the mean value allows focusing in its amplitude. On this research the sEMG was normalized by the maximum value; by consequence values between 0-1 in amplitude are obtained, and allow us to focus on muscle delays related with muscle weakness [52]. Finally the signals are average based on the strides (Table 10b). From these results the fuzzy set equation R (sEMG, Gait phases) is obtained as indicated in Table 10c.

Table 10 Healthy control group a) vGRF) average, b) sEMG signal normalized to his maximum values, and c) fuzzy set equation R (sEMG, Gait phases)



a) (vGRF)



b) sEMG

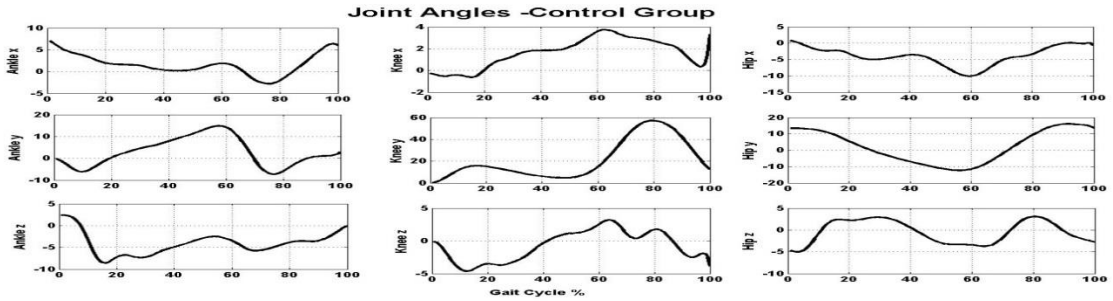
R (sEMG, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.3356	0.4954	0.6338	0.9426	0.4990	0.1432	0.0795
TA	0.8925	0.3591	0.1410	0.0692	0.2232	0.4390	0.3162
GL	0.2811	0.4697	0.8326	0.6523	0.2019	0.1150	0.1190
VL	0.8761	0.5609	0.1343	0.0679	0.0772	0.1004	0.1730
RF	0.8014	0.5245	0.1681	0.1116	0.2540	0.2748	0.1576
BF	0.7972	0.4821	0.3208	0.1783	0.1622	0.1322	0.4817
GM	0.5941	0.5358	0.2098	0.2102	0.4648	0.6875	0.6301
ES	0.5104	0.3638	0.2432	0.4836	0.6358	0.2726	0.3688

c) Fuzzy set equation: R (sEMG, Gait phases)

The joint kinematic average values are calculated based on the strides z-axis GRF, these charts are shown on Table 11a. To obtain the fuzzy set S (Joints, Gait Phases) each joint was normalized to the maximum possible value obtained from all the universal data obtained from all subjects, as indicated on Table 11b. From the normalized result, the fuzzy set S (Joints, Gait Phases) for each axis is obtained (Table c). Finally the relational matrix T (sEMG, Joints) is calculated based on the equation indicated in Fig 16.

Table 11 Healthy control group a) Joint angles averaged, b) Max values to normalize, c) Fuzzy set S (Joints, Gait phases), and d) Fuzzy Result Equation T (sEMG, Joints)



a) Joint angles

Max Value	x	y	z
A	35	30	25
K	45	75	40
H	45	75	40

b) Max values to normalize

S (Joint x, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.2330	0.1476	0.0978	0.1141	0.1014	0.0261	0.1962
K	0.0062	0.0258	0.0799	0.1133	0.1385	0.1138	0.0680
H	0.3811	0.2671	0.2299	0.0567	0.0841	0.2624	0.3959

S (Joint y, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0843	0.1540	0.3377	0.4719	0.3362	0.0492	0.1798
K	0.0731	0.1903	0.0931	0.1140	0.3779	0.7209	0.4399
H	0.6353	0.4473	0.1396	0.0089	0.1205	0.4774	0.6919

S (Joint z, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.2100	0.0308	0.0797	0.1302	0.0801	0.0944	0.1382
K	0.0340	0.0102	0.0527	0.0825	0.0958	0.0760	0.0374
H	0.0283	0.1788	0.1350	0.0434	0.0442	0.1719	0.1003

c) Fuzzy set equation: S (Joints, Gait phases)

T (sEMG, Joint x)

	A	K	H
SL	0.2330	0.1385	0.3356
TA	0.2330	0.1385	0.3811
GL	0.2330	0.1385	0.2811
VL	0.2330	0.1004	0.3811
RF	0.2330	0.1385	0.3811
BF	0.2330	0.1385	0.3959
GM	0.2330	0.1385	0.3959
ES	0.2330	0.1385	0.3811

T (sEMG, Joint y)

	A	K	H
SL	0.4719	0.3779	0.4473
TA	0.2232	0.4390	0.6353
GL	0.4719	0.2019	0.4473
VL	0.1730	0.1903	0.6353
RF	0.2540	0.2748	0.6353
BF	0.3208	0.4399	0.6353
GM	0.3362	0.6875	0.6301
ES	0.4719	0.3779	0.5104

T (sEMG, Joint z)

	A	K	H
SL	0.2100	0.0958	0.1788
TA	0.2100	0.0958	0.1788
GL	0.2100	0.0958	0.1788
VL	0.2100	0.0772	0.1788
RF	0.2100	0.0958	0.1788
BF	0.2100	0.0958	0.1788
GM	0.2100	0.0958	0.1788
ES	0.2100	0.0958	0.1788

d) Fuzzy Result Equation T (sEMG, Joints)

5.1 Cases studies Fuzzy logic method differential analysis muscle/joint

The results for this analysis for the seven diabetes mellitus subject are :

Case study 1 Fuzzy logic method differential analysis: Subject M1-DM

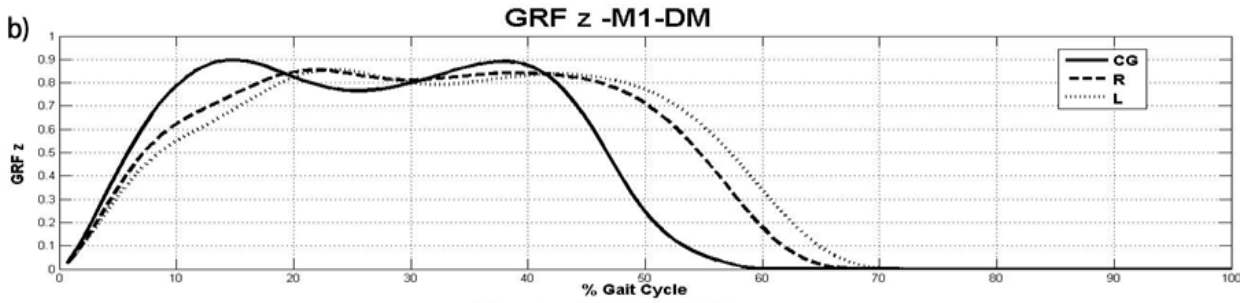
The anthropometric data from this subject is shown in Table 12 a), the average z axis ground reaction forces of all strides (Table 12 b), and the fuzzy similarity with respect to healthy control group (Table 12c) using the equation indicated in Fig 17.

Table 12 Case study for M1-DM a) Anthropometric data, b) vGRF, and c) Fuzzy Similarity

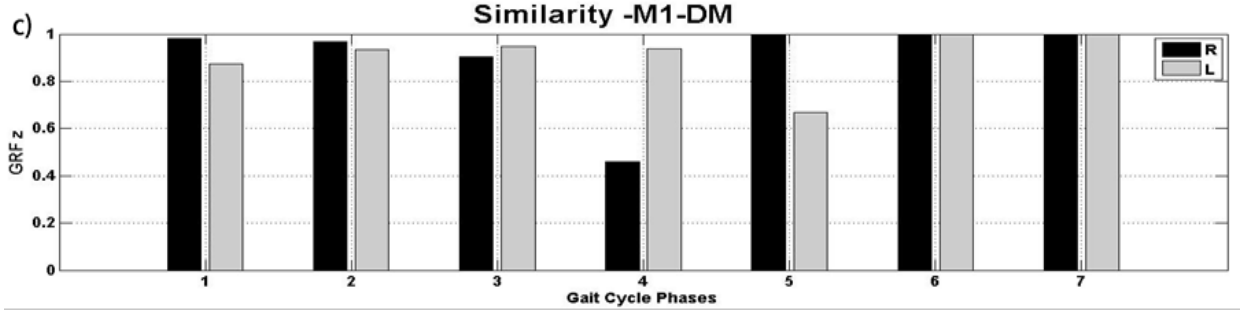
a)

Anthropometric Data						
Age (Years)	Gender	Height (cm)	BMI (Kg/m^2)	DM Years	DM Type	Brisk walking speed (m/s)
44	Male	179	30.39	8	2	0.57

b)

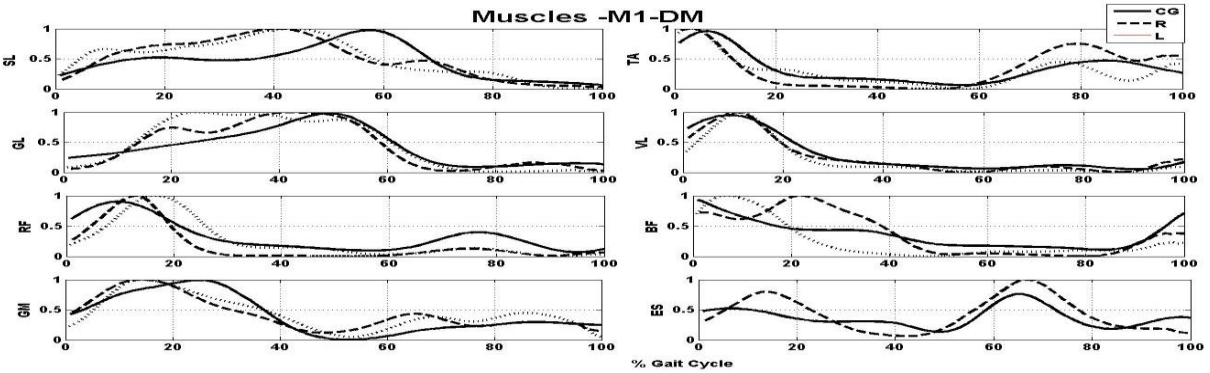


c)



The sEMG average muscles of both sides, and the sEMG muscles healthy control group are charted in Table 13a, the fuzzy set equation R (sEMG, Gait phases) for both limbs are shown in table 13b, and the Fuzzy Similarity in Table 13c.

Table 13 Case study for M1-DM a) sEMG averaged, b) Fuzzy set equations R (sEMG, Gait phases), and Fuzzy similarity between Fuzzy set R with respect to healthy control group



a) sEMG averaged

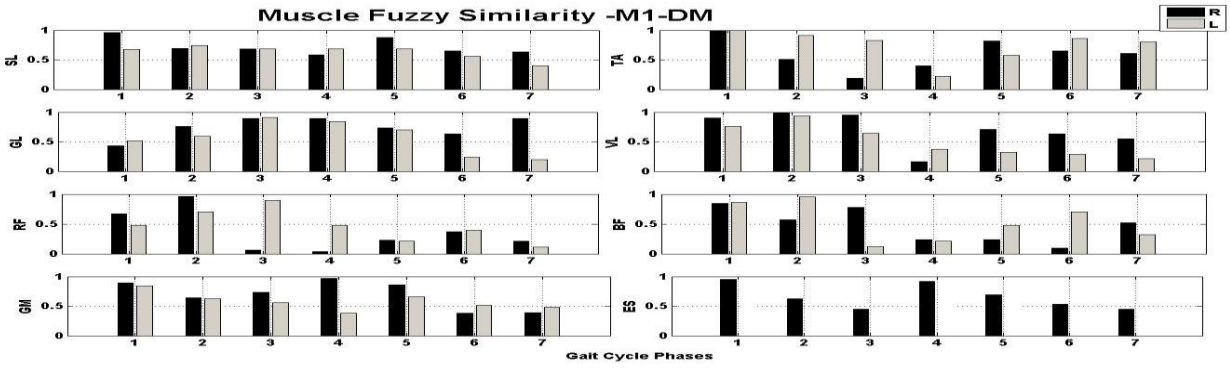
R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.3242	0.7128	0.9242	0.5490	0.4401	0.2200	0.0504
TA	0.9027	0.1814	0.0264	0.0275	0.2711	0.6761	0.5174
GL	0.1224	0.6159	0.9300	0.7291	0.1488	0.0727	0.1061
VL	0.7903	0.5518	0.1408	0.0111	0.0550	0.0636	0.0945
RF	0.5377	0.5054	0.0108	0.0041	0.0591	0.1028	0.0336
BF	0.6748	0.8440	0.4096	0.0420	0.0386	0.0123	0.2503
GM	0.6659	0.8338	0.2861	0.2046	0.4003	0.2650	0.2439
ES	0.4848	0.5820	0.1083	0.4467	0.9172	0.5074	0.1664

R (sEMG left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.4992	0.6647	0.9221	0.6495	0.3409	0.2559	0.0320
TA	0.8916	0.3266	0.1172	0.0155	0.1286	0.3780	0.2531
GL	0.1450	0.7899	0.9115	0.7750	0.2877	0.0275	0.0234
VL	0.6686	0.5233	0.0863	0.0256	0.0250	0.0290	0.0368
RF	0.3856	0.7478	0.1500	0.0535	0.0536	0.1088	0.0171
BF	0.9203	0.5038	0.0377	0.0382	0.0779	0.0926	0.1563
GM	0.4993	0.8616	0.3747	0.0804	0.3083	0.3579	0.3066
ES	0.9782	0.9633	0.9519	0.9564	0.9154	0.9348	0.7869

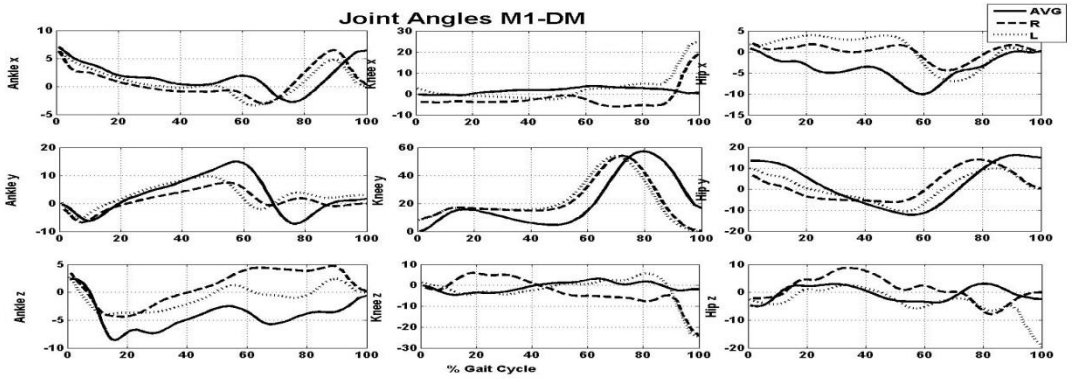
b) Fuzzy set for each limb: R (sEMG, Gait phases)



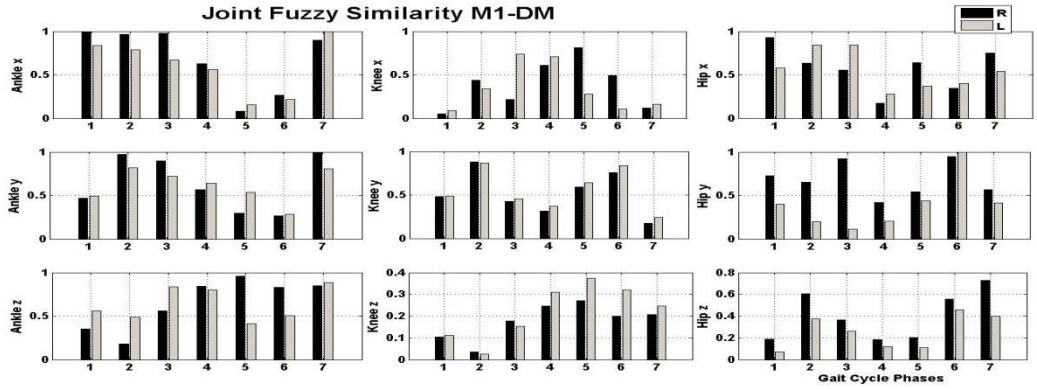
b) Fuzzy similarity

The averaged Joint angles for this subject are charted with the HCG in Table 14a, the fuzzy similarity between them are charted in Table 14b, and the fuzzy set equation S(Joint axis, Gait Phases) for each side and each axis are represented in Table 14c.

Table 14 Case study for M1-DM a) Averaged Joint Angles, b) Fuzzy Similarity Joint angles, and c) Fuzzy set equations for each axis: S (Joints, Gait phases)



a) Joint Angles



b) Fuzzy Similarity Joint angles

S (Joint x right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.2302	0.1425	0.0956	0.0716	0.0086	0.0979	0.1758
K	0.1201	0.0587	0.0173	0.0689	0.1709	0.2293	0.5676
H	0.3547	0.4211	0.4143	0.3228	0.0541	0.0909	0.2968

S (Joint x left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.1950	0.1163	0.0656	0.0642	0.0156	0.1211	0.1951
K	0.0685	0.0755	0.1079	0.1598	0.0386	0.0120	0.4251
H	0.2211	0.2261	0.1945	0.2027	0.0313	0.1056	0.2148

S (Joint y right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0395	0.1585	0.3027	0.2668	0.0997	0.1844	0.1776
K	0.1524	0.2166	0.2183	0.3609	0.6399	0.5454	0.0767
H	0.4613	0.2915	0.1286	0.0211	0.2211	0.4526	0.3913

S (Joint y left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0418	0.1261	0.2434	0.3037	0.1799	0.1717	0.1450
K	0.1501	0.2188	0.2049	0.3089	0.5922	0.6038	0.1068
H	0.2571	0.0901	0.0156	0.0437	0.2752	0.4795	0.2882

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0742	0.0056	0.0447	0.1096	0.0833	0.0783	0.1175
K	0.3261	0.2784	0.2959	0.3351	0.3524	0.3807	0.1802
H	0.1483	0.2951	0.3670	0.2353	0.2189	0.0954	0.1374

S (Joint z left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.1173	0.0150	0.0953	0.1630	0.1937	0.1870	0.1562
K	0.3060	0.3865	0.3432	0.2648	0.2561	0.2380	0.1518
H	0.3920	0.4736	0.5100	0.3615	0.3953	0.3765	0.2511

c) Fuzzy set equations: S (Joints, Gait phases)

The Fuzzy result equation (Fig. 17) is calculated and the results are shown in Table 15a.

Finally the fuzzy similarity with respect to the HCG is obtained and charted on Table 15b-d.

Table 15 Case study for M1-DM: a) Fuzzy Result Equation T (sEMG, Joints), and Fuzzy Similarity T (sEMG, Joints) with respect to the HCG in b) x-axis, c) y-axis, and d) z-axis

T (sEMG right, joint x right)

	A	K	H
SL	0.2302	0.2200	0.4211
TA	0.2302	0.5174	0.3547
GL	0.1425	0.1488	0.4211
VL	0.2302	0.1201	0.4211
RF	0.2302	0.1201	0.4211
BF	0.2302	0.2503	0.4211
GM	0.2302	0.2439	0.4211
ES	0.2302	0.2293	0.4211

T (sEMG right, joint y right)

	A	K	H
SL	0.3027	0.4401	0.3242
TA	0.1844	0.5454	0.4613
GL	0.3027	0.3609	0.2915
VL	0.1585	0.2166	0.4613
RF	0.1585	0.2166	0.4613
BF	0.3027	0.2183	0.4613
GM	0.2861	0.4003	0.4613
ES	0.2668	0.6399	0.4613

T (sEMG right, joint x right)

	A	K	H
SL	0.1096	0.3409	0.3670
TA	0.1175	0.3780	0.2951
GL	0.1096	0.3351	0.3670
VL	0.0742	0.3261	0.2951
RF	0.0783	0.3261	0.2951
BF	0.1175	0.3261	0.2951
GM	0.1175	0.3579	0.3670
ES	0.1175	0.3807	0.3670

T (sEMG left, joint x left)

	A	K	H
SL	0.1950	0.1598	0.2261
TA	0.1951	0.2531	0.2261
GL	0.1450	0.1598	0.2261
VL	0.1950	0.0863	0.2261
RF	0.1950	0.1079	0.2261
BF	0.1950	0.1563	0.2261
GM	0.1951	0.3066	0.2261
ES	0.1951	0.4251	0.2261

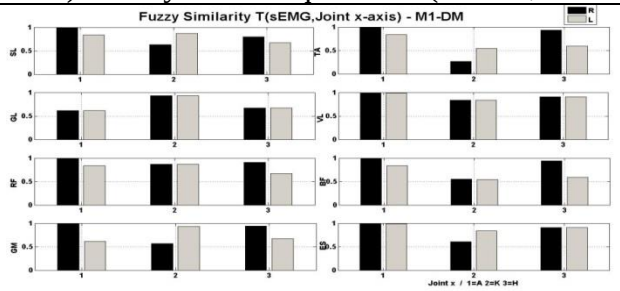
T (sEMG left, joint y left)

	A	K	H
SL	0.3037	0.3409	0.2752
TA	0.1717	0.3780	0.3780
GL	0.3037	0.3089	0.2752
VL	0.1261	0.2188	0.2571
RF	0.1500	0.2188	0.2571
BF	0.1450	0.2188	0.2571
GM	0.2434	0.3579	0.3579
ES	0.3037	0.6038	0.4795

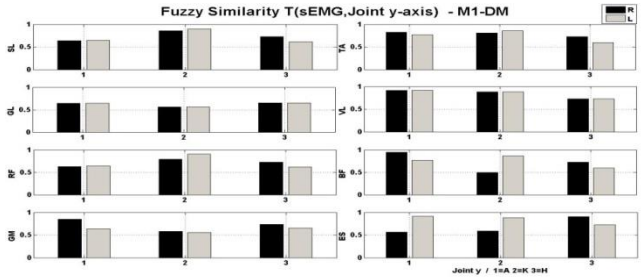
T (sEMG left, joint z left)

	A	K	H
SL	0.1937	0.3865	0.5100
TA	0.1870	0.3266	0.3920
GL	0.1937	0.3865	0.5100
VL	0.1173	0.3865	0.4736
RF	0.1173	0.3865	0.4736
BF	0.1562	0.3865	0.4736
GM	0.1937	0.3865	0.4736
ES	0.1937	0.3865	0.5100

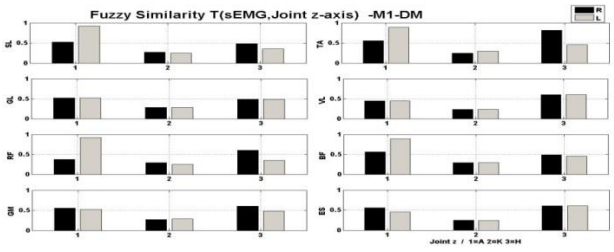
a) Fuzzy Result Equation T (sEMG, Joints)



b) Fuzzy Similarity T (sEMG, Joint x axis)



c) Fuzzy Similarity T (sEMG, Joint y axis)



d) Fuzzy Similarity T (sEMG, Joint z axis)

Conclusions for Case 1 M1-DM:

vGRF analysis from table 12

- vGRF is very similar to the control group, with wider stance approx. 10-15%. Left limb presents a bigger delay with respect to his right.
- On the Fuzzy similarity chart, this delay is reflected as value differences mainly in phase 4 Pre-Swing (50-60%) and Initial Swing (60-70%).

Muscle analysis Table 13:

- Both muscles SL are delayed about 15% with respect to the same muscle from healthy control group (HCG).
- Left TA shows, at the end, a difference with respect to its respective right side.
- Left GL reaches its max values before his right limb and before HCG.
- Left RF is delayed about 10% with respect to his right side.
- Right BF is delayed about 10% with respect to left BF.
- Note: Left ES signal had a sensor failure.

Joint angles analysis Table 14:

- Muscles delay/weakness is observed as lower angle variations mainly in the y-axis

Fuzzy results analysis from table 15:

  - Shows the most affected muscles/joint with respect to the Sagittal Plane are:
    - Muscle / Joint Ankle are: SL, GL, RF, and ES.
    - Muscle / Joint Knee are: GL, BF, GM, and ES.
    - Muscle / Joint Hip are: SL,TA,GL, BF, and GM

General results from Tables 12-15

- Suggests that the left limb is more affected than right limb

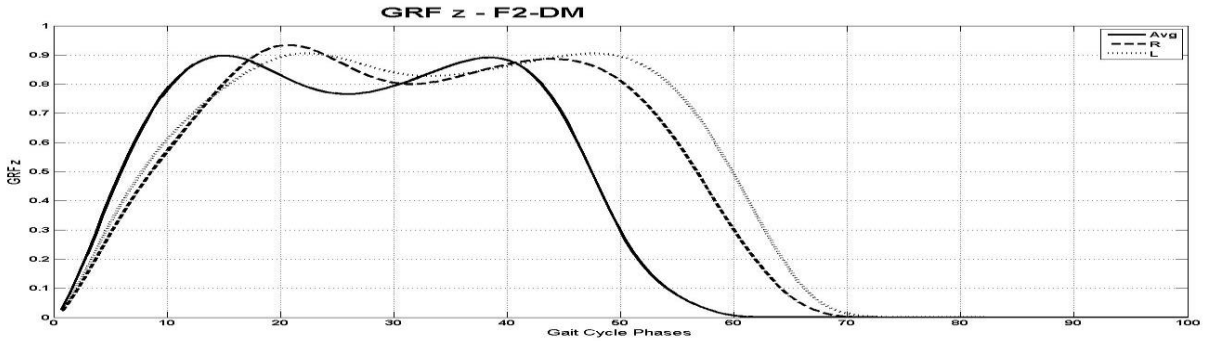
Case study 2 Fuzzy logic method differential analysis: Subject M2-DM

The anthropometric data from this subject is shown in Table 16 a), including the average z-axis ground reaction forces of all strides (Table 12 b), and the fuzzy similarity with respect to healthy control group (Table 12c) using the equation indicated in Fig 17.

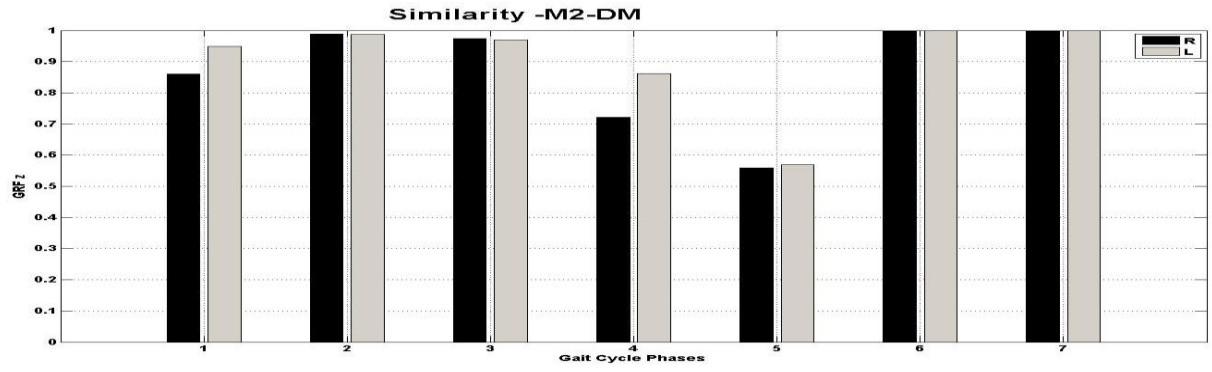
Table 16 Case study for M2-DM a) Anthropometric data, b) vGRF, and c) Fuzzy Similarity

Anthropometric Data						
Age (Years)	Gender	Height (cm)	BMI (Kg/m^2)	DM Years	DM Type	Brisk walking speed (m/s)
52	Male	164	33.87	6	2	0.6

a) Anthropometric data



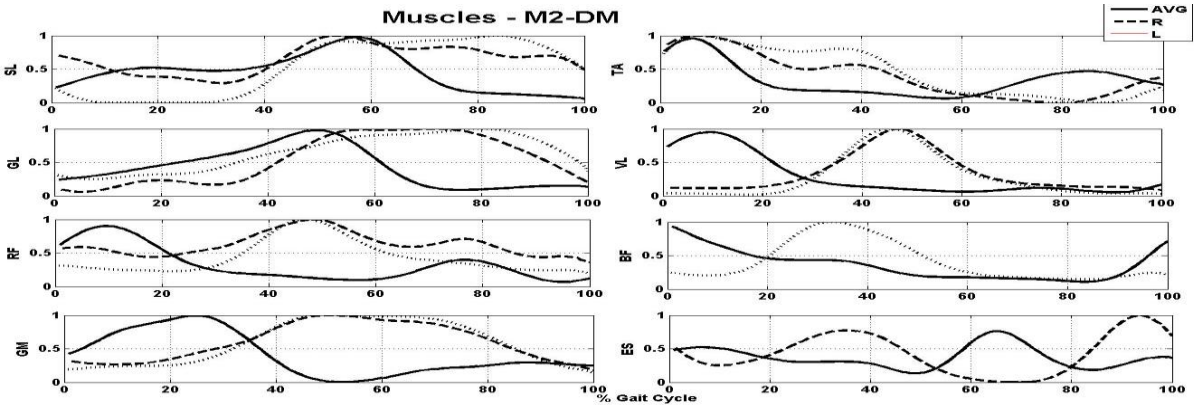
b) vGRF



c) Fuzzy similarity vGRF

The sEMG average muscles of both sides, and the sEMG muscles healthy control group are charted in Table 17a, the fuzzy set equation R (sEMG, Gait phases) for both limbs are shown in table 17b, and the Fuzzy Similarity is indicated in Table 17c.

Table 17 Case study for M2-DM a) sEMG averaged, b) Fuzzy set equations R (sEMG, Gait phases), and Fuzzy similarity between Fuzzy set R with respect to healthy control group



a) sEMG averaged

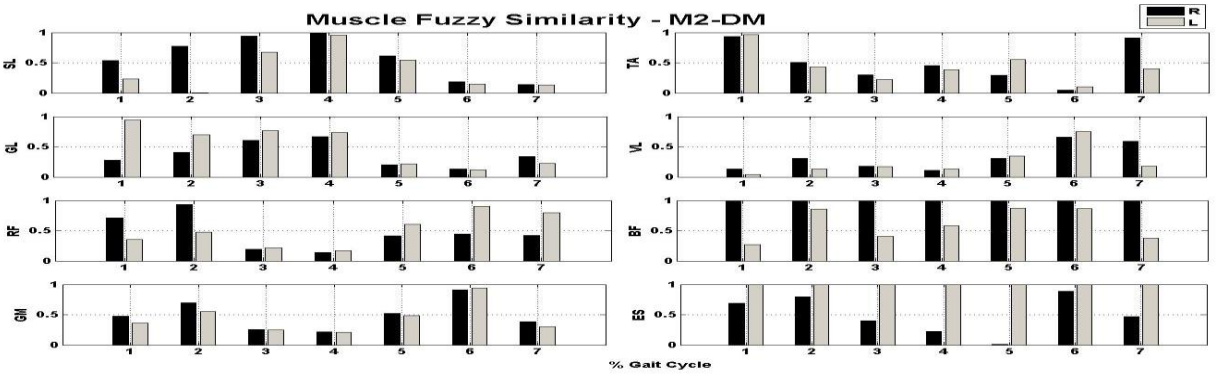
R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.6236	0.3822	0.5987	0.9438	0.8109	0.7660	0.5593
TA	0.9555	0.7065	0.4685	0.1524	0.0658	0.0228	0.2876
GL	0.0778	0.1931	0.5067	0.9739	0.9924	0.8733	0.3524
VL	0.1178	0.1751	0.7642	0.5961	0.2501	0.1528	0.1022
RF	0.5735	0.4918	0.8530	0.7729	0.6102	0.6171	0.3735
BF							
GM	0.2854	0.3755	0.8251	0.9565	0.8881	0.6290	0.2435
ES	0.3511	0.4564	0.6110	0.1078	0.0073	0.3055	0.7844

R (sEMG left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.0787	0.0035	0.4282	0.8997	0.9100	0.9670	0.6094
TA	0.9270	0.8351	0.6332	0.1787	0.1244	0.0453	0.1278
GL	0.2647	0.3270	0.6398	0.8818	0.9274	0.9685	0.5238
VL	0.0358	0.0754	0.7896	0.5103	0.2204	0.0753	0.0311
RF	0.2867	0.2508	0.7749	0.6522	0.4160	0.3028	0.1968
BF	0.2164	0.5602	0.7927	0.3046	0.1860	0.1527	0.1837
GM	0.2176	0.2953	0.8337	0.9846	0.9531	0.6464	0.1896
ES							

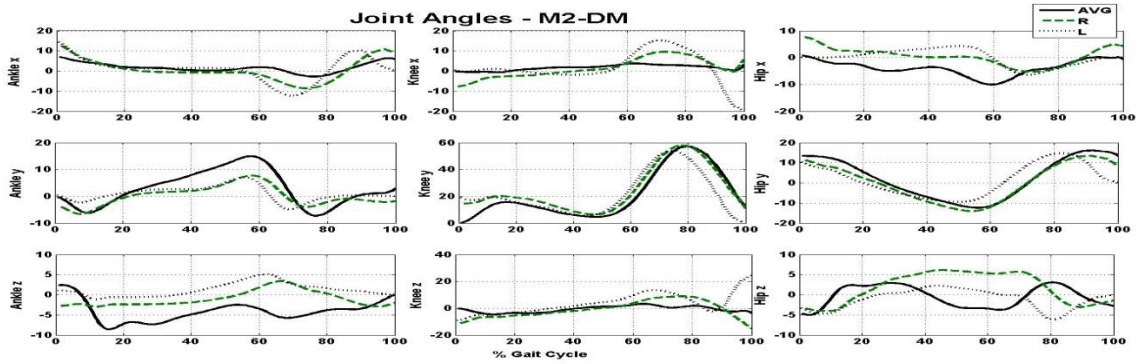
b) Fuzzy set for each limb: R (sEMG, Gait phases)



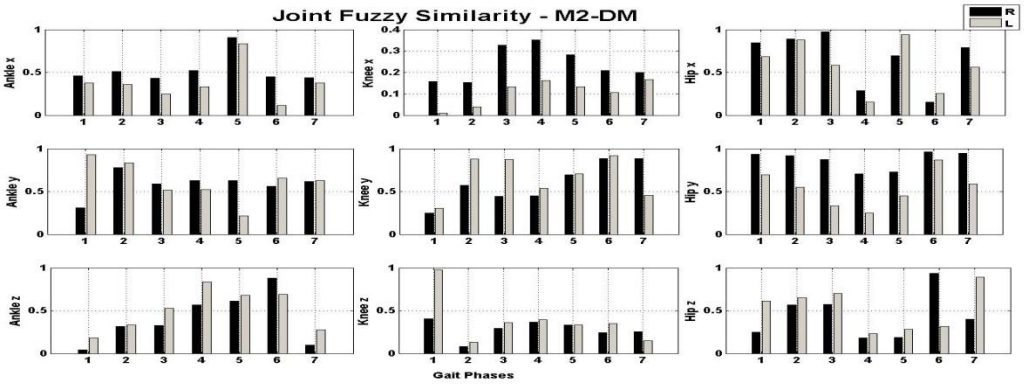
c) Fuzzy similarity

The averaged Joint angles for this subject are charted with the HCG in Table 18a, the fuzzy similarity between them are charted in Table 18b, and the fuzzy set equation S(Joint axis, Gait Phases) for each side and each axis are represented in Table 18c.

Table 18 Case study for M2-DM a) Averaged Joint Angles, b) Fuzzy Similarity Joint angles, and c) Fuzzy set equations for each axis: S (Joints, Gait phases)



a) Joint Angles



b) Fuzzy Similarity Joint angles

S (Joint x right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.5051	0.2885	0.2262	0.2187	0.1119	0.0579	0.4456
K	0.0392	0.1691	0.2448	0.3211	0.4897	0.5463	0.3385
H	0.4488	0.3004	0.2245	0.1960	0.0587	0.0406	0.3132

S (Joint x left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.6138	0.4081	0.3907	0.3431	0.0847	0.2307	0.5234
K	0.6596	0.6650	0.6019	0.7011	1.0451	1.0736	0.4073
H	0.2609	0.3038	0.3952	0.3666	0.0892	0.0663	0.2229

S (Joint y right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0263	0.1202	0.1992	0.2958	0.2117	0.0876	0.1109
K	0.2936	0.3312	0.2098	0.2527	0.5454	0.8165	0.4963
H	0.5940	0.4116	0.1223	0.0126	0.1650	0.4949	0.6541

S (Joint y left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0783	0.1286	0.1754	0.2477	0.0730	0.0747	0.1134
K	0.2417	0.2160	0.1062	0.2106	0.5344	0.6634	0.2005
H	0.4422	0.2471	0.0465	0.0358	0.2679	0.5501	0.4067

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0089	0.0097	0.0261	0.0736	0.1313	0.0833	0.0135
K	0.0845	0.1298	0.1785	0.2262	0.2903	0.3132	0.1481
H	0.0070	0.1012	0.2357	0.2417	0.2369	0.1610	0.0400

S (Joint z left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0384	0.0103	0.0421	0.1088	0.1183	0.0653	0.0385
K	0.0331	0.0764	0.1469	0.2087	0.2894	0.2192	0.2496
H	0.0464	0.1162	0.1924	0.1860	0.1565	0.0538	0.1126

c) Fuzzy set equations: S (Joints, Gait phases)

The Fuzzy Result Equation (Fig. 17) is calculated and the results are shown in Table 19a, and finally the fuzzy similarity with respect to the HCG is obtained and charted on Table 19b-d.

Table 19 Case study for M2-DM: a) Fuzzy Result Equation T (sEMG, Joints), and Fuzzy Similarity T (sEMG, Joints) with respect to the HCG in b) x-axis, c) y-axis, and d) z-axis

T (sEMG right, joint x right)

	A	K	H
SL	0.5051	0.5463	0.4488
TA	0.5051	0.2876	0.4488
GL	0.3524	0.5463	0.3132
VL	0.2262	0.3211	0.2245
RF	0.5051	0.5463	0.4488
BF	0.5051	0.5463	0.4488
GM	0.2885	0.5463	0.3004
ES	0.4456	0.3385	0.3511

T (sEMG right, joint y right)

	A	K	H
SL	0.2958	0.7660	0.5940
TA	0.1992	0.3312	0.5940
GL	0.2958	0.8165	0.4949
VL	0.2958	0.2527	0.1751
RF	0.2958	0.6171	0.5735
BF	0.2958	0.8165	0.6541
GM	0.2958	0.6290	0.4949
ES	0.1992	0.4963	0.6541

T (sEMG right, joint z right)

	A	K	H
SL	0.1313	0.3132	0.2417
TA	0.0736	0.1785	0.2357
GL	0.1313	0.3132	0.2417
VL	0.1313	0.2501	0.2417
RF	0.1313	0.3132	0.2417
BF	0.1313	0.3132	0.2417
GM	0.1313	0.3132	0.2417
ES	0.0833	0.3055	0.2357

T (sEMG right, joint x left)

	A	K	H
SL	0.5234	0.9670	0.3952
TA	0.6138	0.6650	0.3952
GL	0.5234	0.9685	0.3952
VL	0.3907	0.6019	0.3952
RF	0.3907	0.6522	0.3952
BF	0.4081	0.6019	0.3952
GM	0.3907	0.9531	0.3952
ES	0.6138	1.0736	0.3952

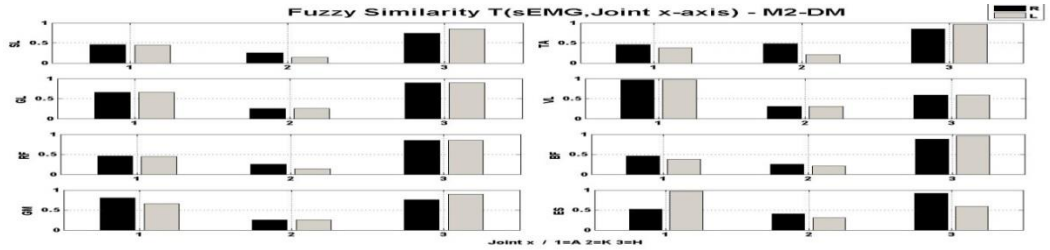
T (sEMG right, joint y left)

	A	K	H
SL	0.2477	0.6634	0.5501
TA	0.1787	0.2417	0.4422
GL	0.2477	0.6634	0.5501
VL	0.2477	0.2204	0.2204
RF	0.2477	0.4160	0.3028
BF	0.2477	0.2164	0.2471
GM	0.2477	0.6464	0.5501
ES	0.2477	0.6634	0.5501

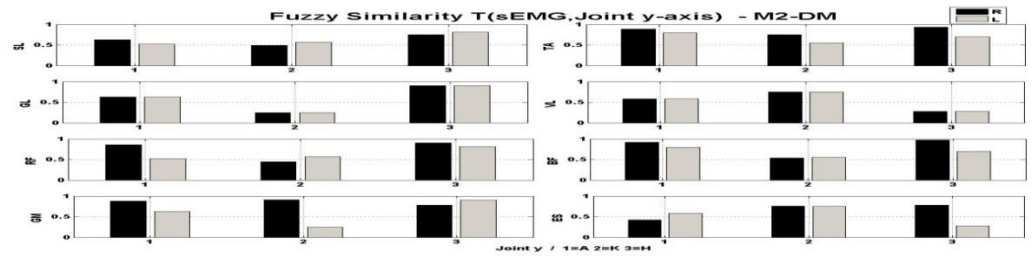
T (sEMG right, joint z left)

	A	K	H
SL	0.1183	0.2894	0.1924
TA	0.1183	0.1787	0.1924
GL	0.1183	0.2894	0.1924
VL	0.1183	0.2204	0.1924
RF	0.1183	0.2894	0.1924
BF	0.1183	0.2087	0.1924
GM	0.1183	0.2894	0.1924
ES	0.1183	0.2894	0.1924

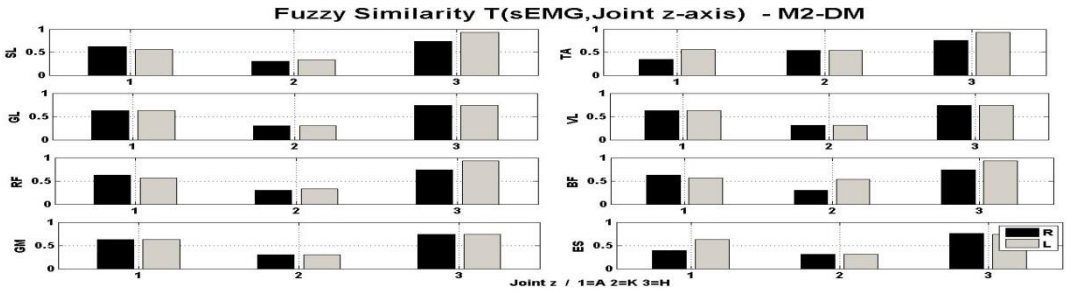
a) Fuzzy Result Equation T (sEMG, Joints)



b) Fuzzy Similarity T (sEMG, Joint x axis)



c) Fuzzy Similarity T (sEMG, Joint y axis)



d) Fuzzy Similarity T (sEMG, Joint z axis)

Conclusions for Case 2 M2-DM:

vGRF analysis from table 16

- This subject shows vGRF in a very similar shape to the control group with a wider stance of approx. 12-18%. The left limb presents a wider stance with respect to his right.
- On the Fuzzy similarity chart this delay is reflected as values differences in phases: 1 Loading response (0-10%), 4 Pre-Swing (50-60%), and 5 Initial Swing (60-70%).

Muscle analysis from Table 17:

- Almost all muscle present delay and variant values to follow healthy control group signal.
- Left and right VL and RF muscle has a delay of almost 30%
- Left SL has slower activity than right SL
- Note: Sensor failure in right BF and left ES

Joint analysis from Table 18:

- Muscles delay/weakness are present mainly in the left limb and observed as angle variations in the 3-axis of all planes.

Fuzzy results analysis from Table 19:

- Shows the most affected muscles/joint with respect to the Sagittal Plane are:
    - Muscle / Joint Ankle are: SL, GL, VL, RF, and ES.
    - Muscle / Joint Knee are: SL, TA, GL, RF, BF, and GM.
    - Muscle / Joint Hip are: VL, and ES.

General results from Tables 16-19

- Suggests that the left limb is more affected than right limb

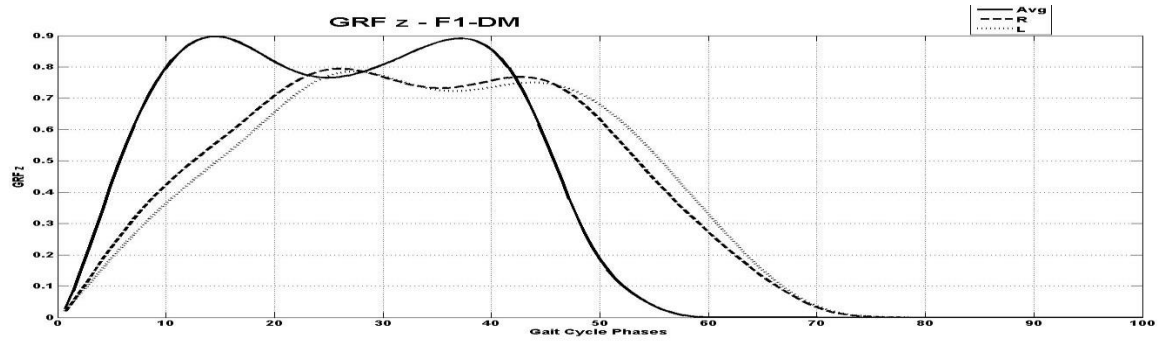
Case study 3 Fuzzy logic method differential analysis: Subject F1-DM

The anthropometric data from this subject is shown in Table 20a, including the average z-axis ground reaction forces of all strides (Table 20b), and the fuzzy similarity with respect to healthy control group (Table 20c) using the equation indicated in Fig 17.

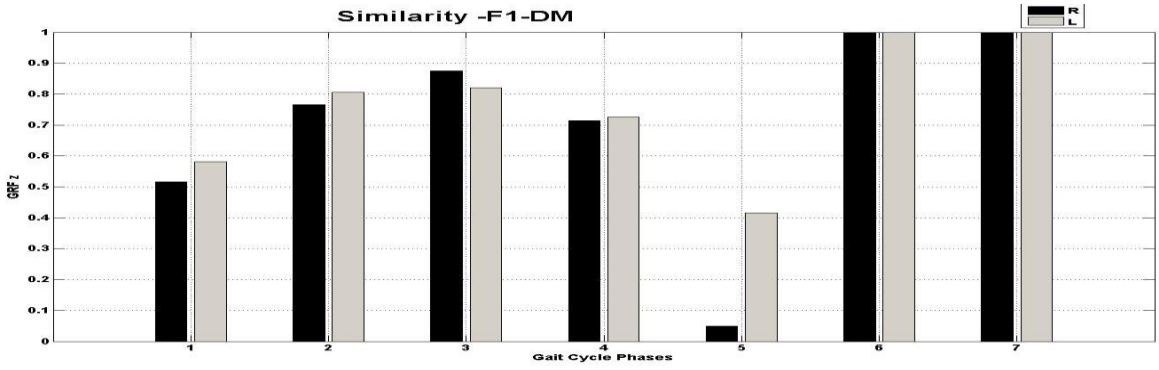
Table 20 Case study for F1-DM a) Anthropometric data, b) vGRF, and c) Fuzzy Similarity

Anthropometric Data						
Age (Years)	Gender	Height (cm)	BMI (Kg/m^2)	DM Years	DM Type	Brisk walking speed (m/s)
60	Female	155	39.75	22	2	0.4

a) Anthropometric data



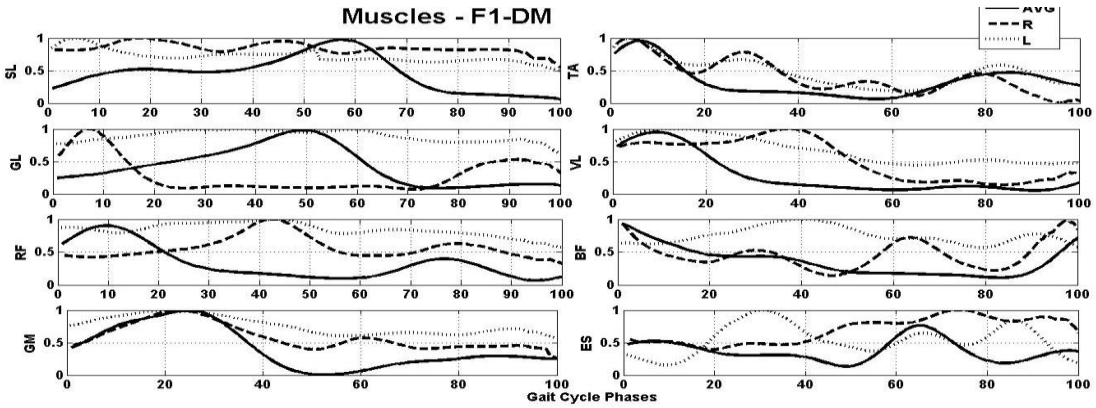
b) vGRF



c) Fuzzy similarity vGRF

The sEMG average muscles of both sides, and the sEMG muscles healthy control group are charted in Table 21a, the fuzzy set equation R (sEMG, Gait phases) for both limbs are shown in table 21b, and the Fuzzy Similarity in Table 21c.

Table 21 Case study for F1-DM a) sEMG averaged, b) Fuzzy set equations R (sEMG, Gait phases), and Fuzzy similarity between Fuzzy set R with respect to healthy control group



a) sEMG averaged

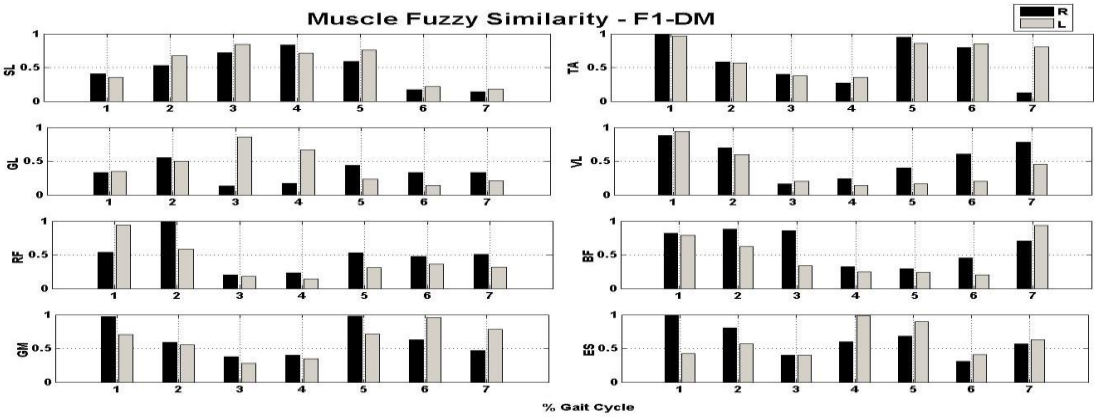
R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.8242	0.9299	0.8790	0.7879	0.8388	0.8210	0.5508
TA	0.9062	0.6188	0.3514	0.2558	0.2122	0.3493	0.0388
GL	0.8543	0.2614	0.1087	0.1127	0.0893	0.3497	0.3550
VL	0.7705	0.8004	0.8263	0.2829	0.1911	0.1648	0.2218
RF	0.4328	0.5214	0.8286	0.4735	0.4821	0.5795	0.3112
BF	0.6531	0.4235	0.2766	0.5439	0.5531	0.2907	0.6791
GM	0.5775	0.9074	0.5503	0.5271	0.4564	0.4349	0.2979
ES	0.5174	0.4515	0.6046	0.8034	0.9258	0.8900	0.6475

R (sEMG left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.942	0.735	0.753	0.670	0.654	0.654	0.435
TA	0.921	0.634	0.370	0.194	0.260	0.514	0.255
GL	0.807	0.935	0.973	0.971	0.859	0.805	0.562
VL	0.931	0.937	0.671	0.470	0.465	0.502	0.383
RF	0.848	0.894	0.947	0.799	0.830	0.761	0.492
BF	0.630	0.774	0.937	0.716	0.680	0.649	0.516
GM	0.840	0.962	0.762	0.611	0.648	0.656	0.494
ES	0.215	0.641	0.604	0.477	0.570	0.671	0.232

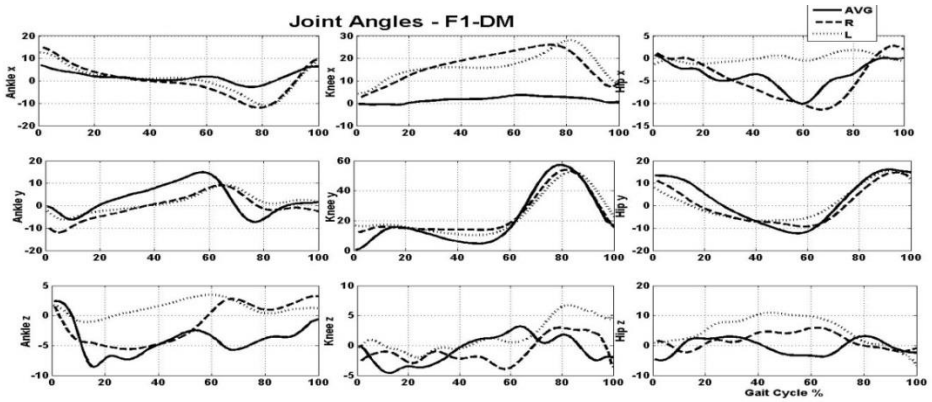
b) Fuzzy set for each limb: R (sEMG, Gait phases)



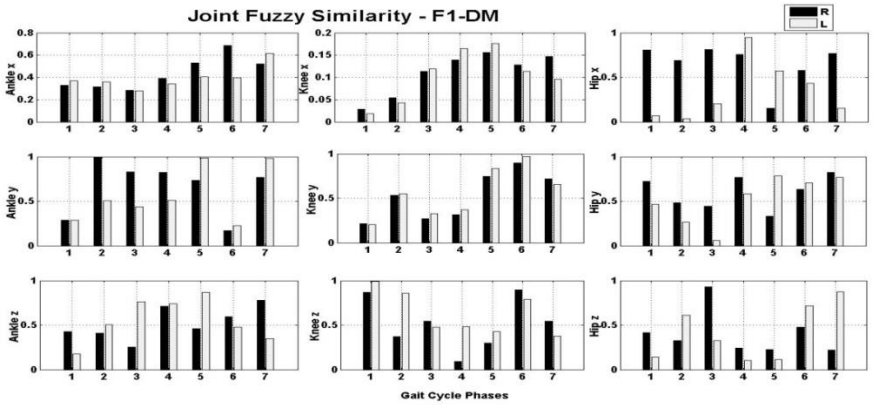
c) Fuzzy similarity

The averaged Joint angles for this subject are chart with the HCG in Table 22a, the fuzzy similarity between them are charted in Table 22b, and the fuzzy set equation S(Joint axis, Gait Phases) for each side and each axis are presented in Table 22c.

Table 22 Case study for F1-DM a) Averaged Joint Angles, b) Fuzzy Similarity Joint angles, and c) Fuzzy set equations for each axis: S (Joints, Gait phases)



a) Joint Angles



b) Fuzzy Similarity Joint angles

S (Joint x right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.7051	0.4678	0.3420	0.2911	0.1912	0.0381	0.3758
K	0.2205	0.4754	0.7062	0.8177	0.8909	0.8908	0.4631
H	0.4734	0.3883	0.1870	0.0750	0.0131	0.1517	0.5144

S (Joint y right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0242	0.1538	0.2806	0.3891	0.4569	0.2900	0.2344
K	0.3389	0.3551	0.3428	0.3591	0.5053	0.8025	0.6141
H	0.4595	0.2167	0.0619	0.0116	0.0401	0.3017	0.5706

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0901	0.0126	0.0202	0.0926	0.1745	0.1586	0.1779
K	0.0295	0.0273	0.0288	0.0075	0.0286	0.0846	0.0685
H	0.0680	0.0586	0.1454	0.1780	0.1940	0.0821	0.0221

S (Joint x left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.6294	0.4096	0.3486	0.3350	0.2514	0.0662	0.3193
K	0.3460	0.6024	0.6736	0.6894	0.7870	1.0031	0.7078
H	0.0266	0.0092	0.0464	0.0536	0.0480	0.1134	0.0612

S (Joint y left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0244	0.0778	0.1483	0.2419	0.3313	0.2170	0.1839
K	0.3578	0.3455	0.2864	0.3055	0.4531	0.7438	0.6704
H	0.2966	0.1177	0.0084	0.0152	0.0947	0.3379	0.5298

S (Joint z left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0366	0.0156	0.0607	0.0962	0.0922	0.0452	0.0479
K	0.0337	0.0119	0.0252	0.0397	0.0408	0.0959	0.0994
H	0.1985	0.2926	0.4115	0.4161	0.3793	0.2396	0.1149

c) Fuzzy set equations: S (Joints, Gait phases)

The Fuzzy Result Equation (Fig. 17) is calculated and the results are shown in Table 23a, and finally the fuzzy similarity with respect to the HCG is obtained and charted on Table 23b-d.

Table 23 Case study for F1-DM: a) Fuzzy Result Equation T (sEMG, Joints), and Fuzzy Similarity T (sEMG, Joints) with respect to the HCG in b) x-axis, c) y-axis, and d) z-axis

T (sEMG right, joint x right)

	A	K	H
SL	0.7051	0.8388	0.5144
TA	0.7051	0.4754	0.4734
GL	0.7051	0.3550	0.4734
VL	0.7051	0.7062	0.4734
RF	0.4678	0.7062	0.4328
BF	0.6531	0.5531	0.5144
GM	0.5775	0.5503	0.4734
ES	0.5174	0.8909	0.5144

T (sEMG right, joint y right)

	A	K	H
SL	0.4569	0.8025	0.5508
TA	0.2900	0.3551	0.4595
GL	0.2900	0.3550	0.4595
VL	0.2829	0.3551	0.4595
RF	0.4569	0.5795	0.4328
BF	0.4569	0.6141	0.5706
GM	0.4564	0.4564	0.4595
ES	0.4569	0.8025	0.5706

T (sEMG right, joint z right)

	A	K	H
SL	0.1779	0.0846	0.1940
TA	0.1745	0.0846	0.1940
GL	0.1779	0.0846	0.1127
VL	0.1779	0.0846	0.1911
RF	0.1779	0.0846	0.1940
BF	0.1779	0.0846	0.1940
GM	0.1779	0.0846	0.1940
ES	0.1779	0.0846	0.1940

T (sEMG left, Joint x left)

	A	K	H
SL	0.6294	0.6736	0.1134
TA	0.6294	0.6024	0.1134
GL	0.6294	0.8050	0.1134
VL	0.6294	0.6710	0.1134
RF	0.6294	0.7870	0.1134
BF	0.6294	0.6894	0.1134
GM	0.6294	0.6736	0.1134
ES	0.4096	0.6710	0.1134

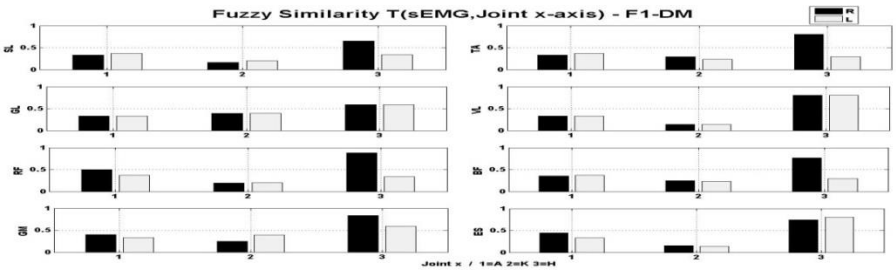
T (sEMG left, Joint y left)

	A	K	H
SL	0.3313	0.6540	0.4350
TA	0.2600	0.5140	0.3379
GL	0.3313	0.7438	0.5298
VL	0.3313	0.5020	0.3830
RF	0.3313	0.7438	0.4920
BF	0.3313	0.6490	0.5160
GM	0.3313	0.6560	0.4940
ES	0.3313	0.6710	0.3379

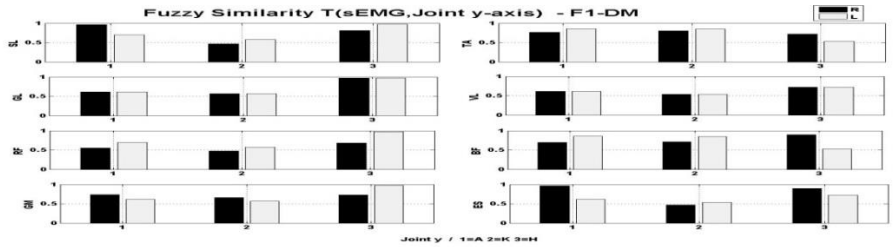
T (sEMG left, Joint z left)

	A	K	H
SL	0.0962	0.0994	0.4161
TA	0.0962	0.0994	0.3700
GL	0.0962	0.0994	0.4161
VL	0.0962	0.0994	0.4161
RF	0.0962	0.0994	0.4161
BF	0.0962	0.0994	0.4161
GM	0.0962	0.0994	0.4161
ES	0.0962	0.0994	0.4161

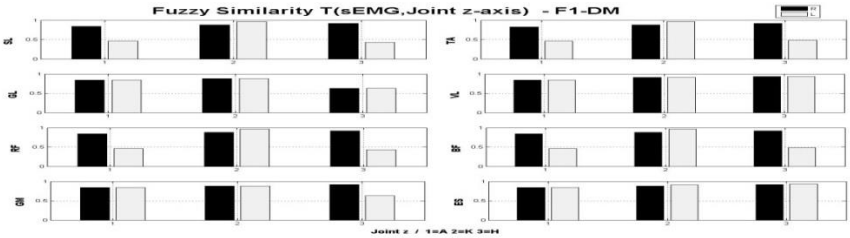
a) Fuzzy Result Equation T (sEMG, Joints)



b) Fuzzy Similarity T (sEMG, Joint x axis)



c) Fuzzy Similarity T (sEMG, Joint y axis)



d) Fuzzy Similarity T (sEMG, Joint z axis)

Conclusions for Case 3 F1-DM:

vGRF analysis from table 20

- This subject shows his vGRF very similar to the control group with a wider stance approx. 13-16%, and less magnitude.
- On the Fuzzy similarity chart this delay is reflected as values differences in phases from 1 Loading response (0-10%) to 5 Initial Swing (60-70%).

Muscle analysis from Table 21:

- Almost all muscles present delay and variant oscillation waves values to follow HCG signal.
- Both SL muscles present very slow movement in Phase 1, 2, 5, 6 and 7
- Both TA muscles present instabilities in amplitude
- Both RF muscles presents a delay of almost 30%
- Both ES presents signal instability as oscillations

Joint analysis from Table 22:

- Muscles delay/weakness mainly in both limbs are observed as angle variations in the sagittal plane, and amplitude angles variations in plane x and z.

Fuzzy results analysis from Table 23:

- Shows the most affected muscles/joint with respect to the Sagittal Plane are:
    - Muscles / Joint Ankle most affected are: VL, RF
    - Muscles / Joint Knee most affected are: SL, GL, VL, RF, GM, and ES
    - Muscles / Joint Hip most affected are: TA,VL, RF, BF

General results from Tables 20-23

- Suggests that both limbs are affected, but the right limb presents many signal instability in amplitude as sinusoidal waves

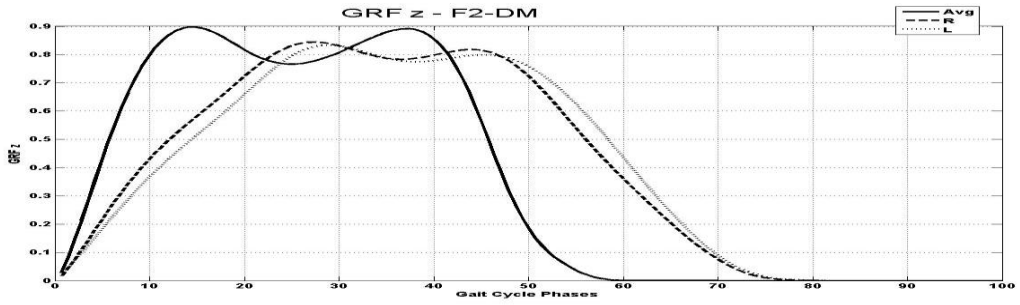
Case study 4 Fuzzy logic method differential analysis: Subject F2-DM

The anthropometric data from this subject is shown in Table 24a, including the average z-axis ground reaction forces of all strides (Table 24b), and the fuzzy similarity with respect to healthy control group (Table 24c) using the equation indicated in Fig 17.

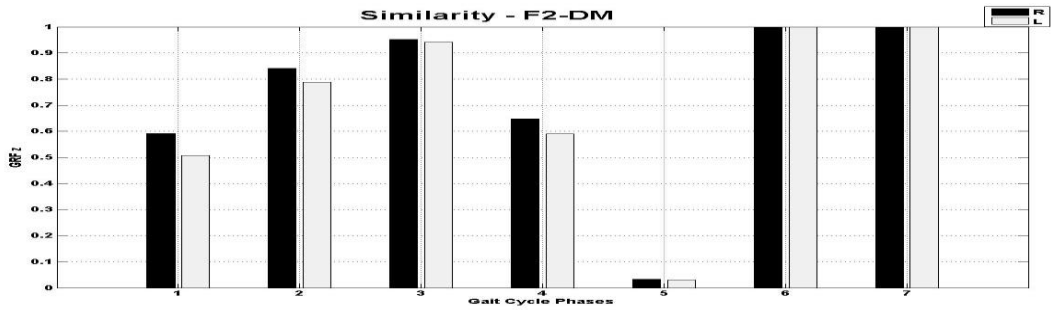
Table 24 Case study for F2-DM a) Anthropometric data, b) vGRF, and c) Fuzzy Similarity

Anthropometric Data						
Age (Years)	Gender	Height (cm)	BMI (Kg/m^2)	DM Years	DM Type	Brisk walking speed (m/s)
56	Female	154	29.9	2	2	0.5

a) Anthropometric data



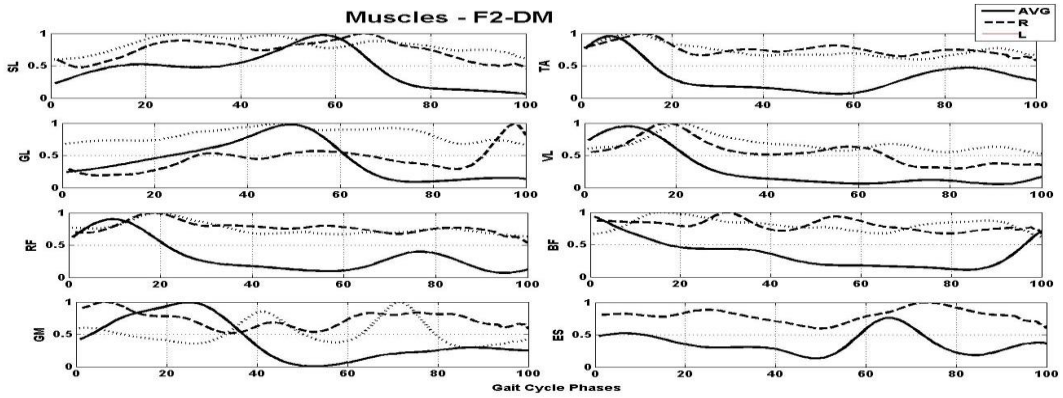
b) vGRF



c) Fuzzy similarity vGRF

The sEMG average muscles of both sides, and the sEMG muscles healthy control group are charted in Table 25a, the fuzzy set equation R (sEMG, Gait phases) for both limbs are shown in table 25b, and the Fuzzy Similarity in Table 25c.

Table 25 Case study for F2-DM a) sEMG averaged, b) Fuzzy set equations R (sEMG, Gait phases), and Fuzzy similarity between Fuzzy set R with respect to healthy control group



a) sEMG averaged

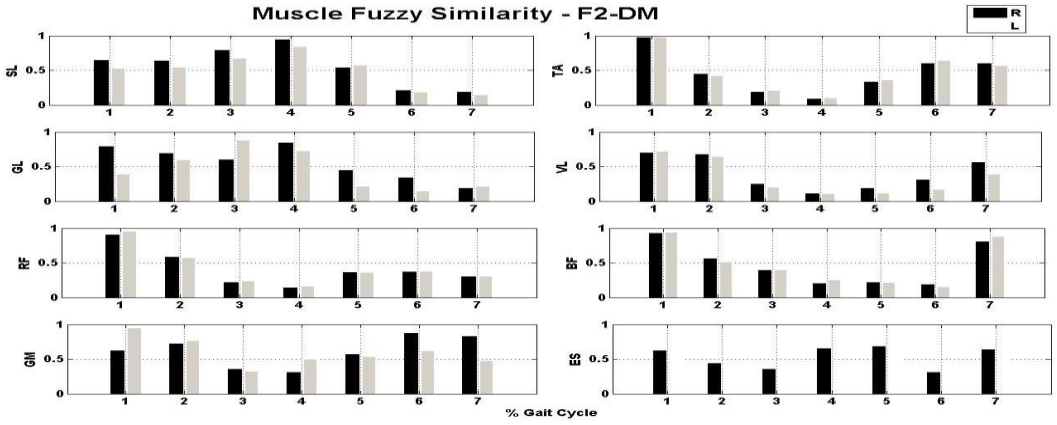
R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.5223	0.7760	0.7992	0.8916	0.9314	0.6871	0.4193
TA	0.8691	0.8098	0.7470	0.7834	0.6699	0.7289	0.5253
GL	0.2226	0.3250	0.5003	0.5507	0.4504	0.3402	0.6390
VL	0.6136	0.8292	0.5364	0.6180	0.4076	0.3229	0.3100
RF	0.7231	0.9010	0.7806	0.7825	0.6976	0.7484	0.5220
BF	0.8592	0.8608	0.8113	0.8800	0.7499	0.6986	0.5964
GM	0.9573	0.7438	0.5906	0.6755	0.8151	0.7889	0.5239
ES	0.8167	0.8342	0.6839	0.7445	0.9327	0.8912	0.5758

R (sEMG left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.6292	0.9015	0.9348	0.7967	0.8666	0.7739	0.5208
TA	0.9081	0.8453	0.6731	0.6801	0.6155	0.6831	0.5552
GL	0.7120	0.7793	0.9467	0.8954	0.9137	0.7556	0.5430
VL	0.6353	0.8709	0.6716	0.5991	0.6488	0.5880	0.4361
RF	0.7680	0.9129	0.7052	0.6754	0.6995	0.7323	0.5088
BF	0.7513	0.9359	0.7950	0.7074	0.7425	0.8519	0.5484
GM	0.5628	0.4100	0.6465	0.4214	0.8627	0.4259	0.3027
ES	0.9676	0.9529	0.9674	0.9776	0.9788	0.9336	0.7366

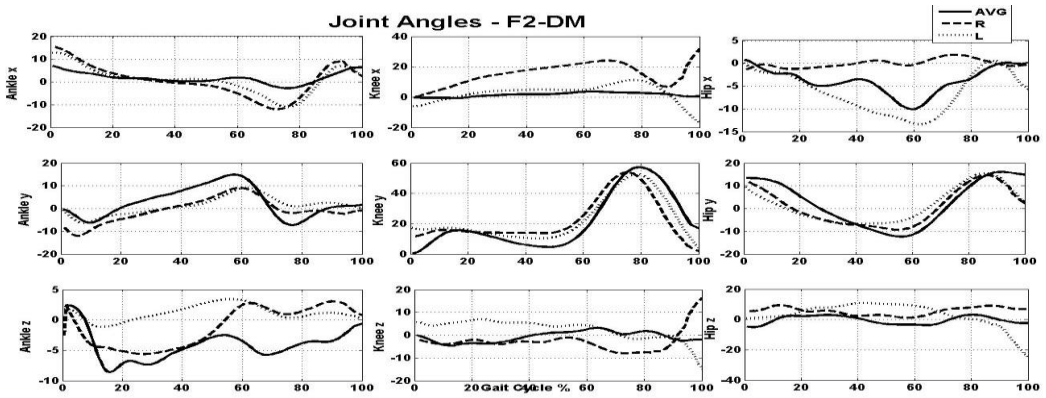
b) Fuzzy set for each limb: R (sEMG, Gait phases)



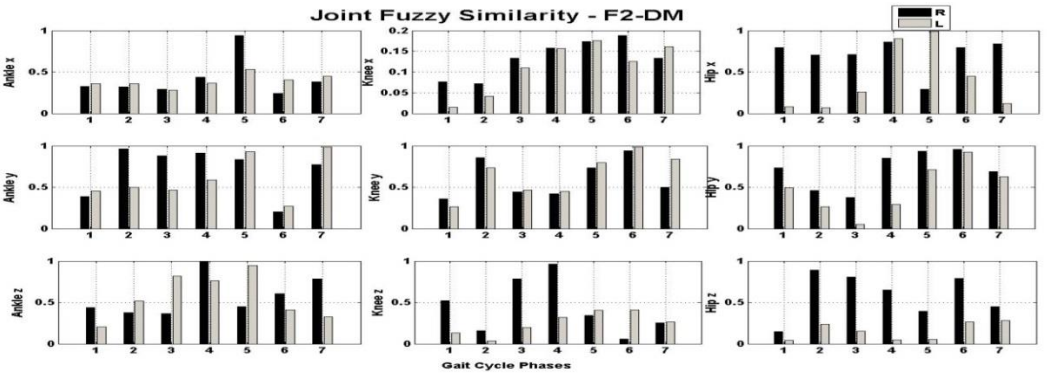
c) Fuzzy similarity sEMG

The averaged Joint angles for this subject are charted with the HCG in Table 26a, the fuzzy similarity between them are charted in Table 26b, and the fuzzy set equation S(Joint axis, Gait Phases) for each side and each axis are presented in Table 26c.

Table 26 Case study for F2-DM a) Averaged Joint Angles, b) Fuzzy Similarity Joint angles, and c) Fuzzy set equations for each axis: S (Joints, Gait phases)



a) Joint Angles



b) Fuzzy similarities between joint angles

S (Joint x right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.7133	0.4603	0.3340	0.2586	0.1077	0.1073	0.5130
K	0.0815	0.3580	0.5976	0.7178	0.7957	0.6059	0.5111
H	0.4798	0.3790	0.1643	0.0488	0.0249	0.3305	0.4702

S (Joint y right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0326	0.1601	0.2976	0.4315	0.4032	0.2421	0.2324
K	0.2038	0.2224	0.2108	0.2686	0.5157	0.6784	0.2196
H	0.4671	0.2069	0.0525	0.0076	0.1287	0.4565	0.4778

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0917	0.0116	0.0292	0.1313	0.1781	0.1556	0.1764
K	0.0652	0.0646	0.0670	0.0855	0.0331	0.0045	0.1478
H	0.1902	0.2002	0.1088	0.0668	0.1126	0.2171	0.2232

S (Joint x left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.6426	0.4102	0.3460	0.3123	0.1898	0.0640	0.4389
K	0.4139	0.6146	0.7246	0.7221	0.7873	0.9078	0.4223
H	0.0307	0.0189	0.0591	0.0510	0.0847	0.1184	0.0483

S (Joint y left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0385	0.0773	0.1572	0.2792	0.3131	0.1818	0.1769
K	0.2731	0.2599	0.2001	0.2540	0.4737	0.7111	0.3709
H	0.3149	0.1192	0.0073	0.0302	0.1688	0.4411	0.4354

S (Joint z left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0433	0.0160	0.0651	0.0992	0.0759	0.0388	0.0452
K	0.2615	0.2801	0.2651	0.2556	0.2366	0.1840	0.1422
H	0.6582	0.7537	0.8768	0.8710	0.8013	0.6522	0.3543

c) Fuzzy set equations: S (Joints, Gait phases)

The Fuzzy Result Equation (Fig. 17) is calculated and the results are shown in Table 27a, and finally the fuzzy similarity with respect to the HCG is obtained and charted on Table 27b-d.

Table 27 Case study for F2-DM: a) Fuzzy Result Equation T (sEMG, Joints), and Fuzzy Similarity T (sEMG, Joints) with respect to the HCG in b) x-axis, c) y-axis, and d) z-axis

T (sEMG right, Joint x right)

	A	K	H
SL	0.5223	0.7957	0.4798
TA	0.7133	0.7178	0.4798
GL	0.5130	0.5507	0.4702
VL	0.6136	0.6180	0.4798
RF	0.7133	0.7178	0.4798
BF	0.7133	0.7499	0.4798
GM	0.7133	0.7957	0.4798
ES	0.7133	0.7957	0.4798

T (sEMG right, Joint y right)

	A	K	H
SL	0.4315	0.6784	0.4671
TA	0.4315	0.6784	0.4778
GL	0.4315	0.4504	0.4778
VL	0.4315	0.4076	0.4671
RF	0.4315	0.6784	0.4778
BF	0.4315	0.6784	0.4778
GM	0.4315	0.6784	0.4778
ES	0.4315	0.6784	0.4778

T (sEMG right, Joint z right)

	A	K	H
SL	0.1781	0.1478	0.2232
TA	0.1781	0.1478	0.2232
GL	0.1781	0.1478	0.2232
VL	0.1781	0.1478	0.2232
RF	0.1781	0.1478	0.2232
BF	0.1781	0.1478	0.2232
GM	0.1781	0.1478	0.2232
ES	0.1781	0.1478	0.2232

T (sEMG left, Joint x left)

	A	K	H
SL	0.6292	0.7873	0.1184
TA	0.6426	0.6831	0.1184
GL	0.6426	0.7873	0.1184
VL	0.6353	0.6716	0.1184
RF	0.6426	0.7323	0.1184
BF	0.6426	0.8519	0.1184
GM	0.5628	0.7873	0.1184
ES	0.6426	0.9078	0.1184

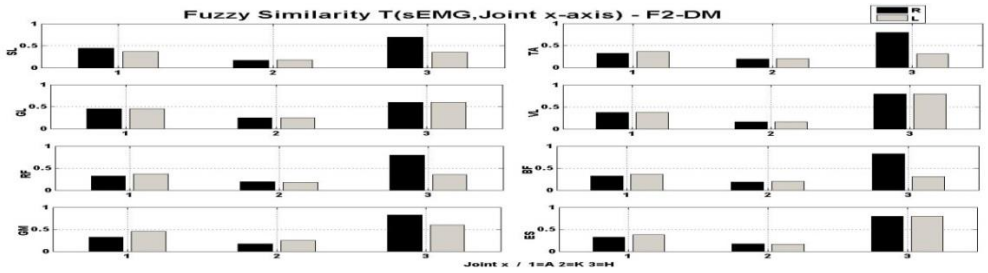
T (sEMG left, Joint y left)

	A	K	H
SL	0.3131	0.7111	0.4411
TA	0.3131	0.6831	0.4411
GL	0.3131	0.7111	0.4411
VL	0.3131	0.5880	0.4411
RF	0.3131	0.7111	0.4411
BF	0.3131	0.7111	0.4411
GM	0.3131	0.4737	0.4259
ES	0.3131	0.7111	0.4411

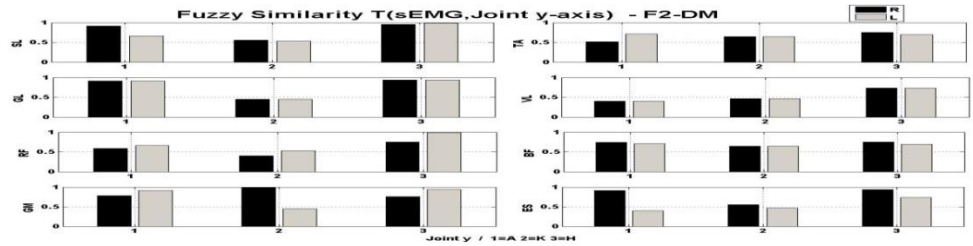
T (sEMG left, Joint z left)

	A	K	H
SL	0.0992	0.2801	0.8768
TA	0.0992	0.2801	0.7537
GL	0.0992	0.2801	0.8768
VL	0.0992	0.2801	0.7537
RF	0.0992	0.2801	0.7537
BF	0.0992	0.2801	0.7950
GM	0.0992	0.2801	0.8013
ES	0.0992	0.2801	0.8768

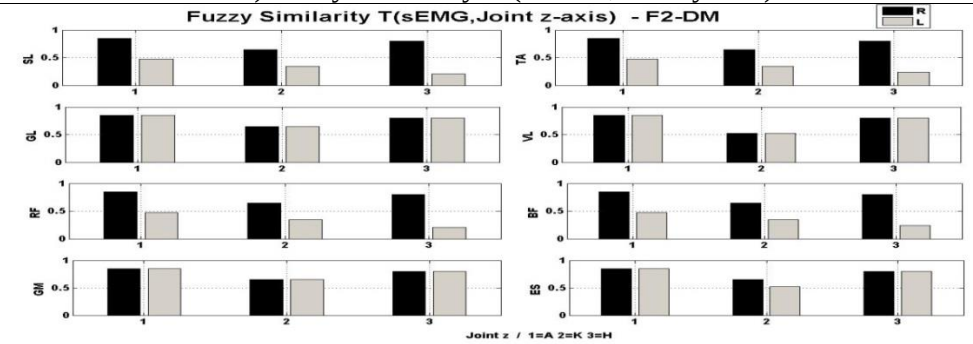
a) Fuzzy Result Equation T (sEMG, Joints)



b) Fuzzy Similarity T (sEMG, Joint x axis)



c) Fuzzy Similarity T (sEMG, Joint y axis)



c) Fuzzy Similarity T (sEMG, Joint z axis)

Conclusions for Case 4 F2-DM:

vGRF analysis from table 20

- This subject shows his vGRF to be very similar to the control group with a wider stride approx. 16-18% with the HCG.
- On the Fuzzy similarity chart this delay is reflected as values differences in phases from 1 Loading response (0-10%), 4 Pre Swing (50-60%), and 5 Initial Swing (60-70%).

Muscle analysis from Table 21:

- Almost all muscles present delay and very slow amplitude values to follow HCG signal.
- Both SL muscles present very slow movement in Phase 1, 2, 5, 6 and 7.
- Both TA and Both VL muscles present instabilities in amplitude.
- Both RF and BF present very small amplitude changes.
- Note: Sensor failure in left ES.

Joint analysis from Table 22:

- Muscles delay/weakness mainly in both limbs is observed as angle variations in the sagittal plane, with less range of motion.

Fuzzy results analysis from Table 23:

- Shows the most affected muscles/joint with respect to the Sagittal Plane are:
    - Muscles / Joint Ankle most affected are: TA and VL
    - Muscles / Joint Knee most affected are all 8 eight of them except GM
    - Muscles / Joint Hip most affected are: RF, and BF

General results from Tables 20-23

- Suggests that both limbs are affected. As a main observation, the sEMG has very small changes in amplitude and smaller range of motion

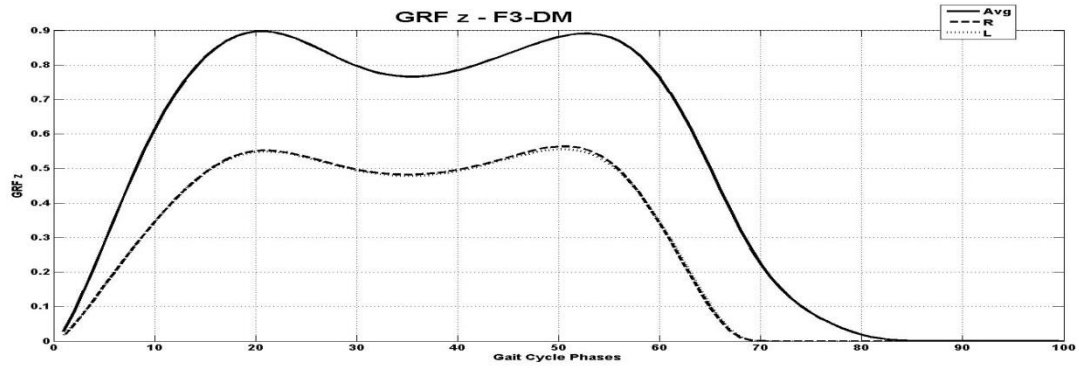
Case study 5 Fuzzy logic method differential analysis: Subject F3-DM

The anthropometric data from this subject is shown in Table 28a, including the average z-axis ground reaction forces of all strides (Table 28b), and the fuzzy similarity with respect to healthy control group (Table 28c) using the equation indicated in Fig 17.

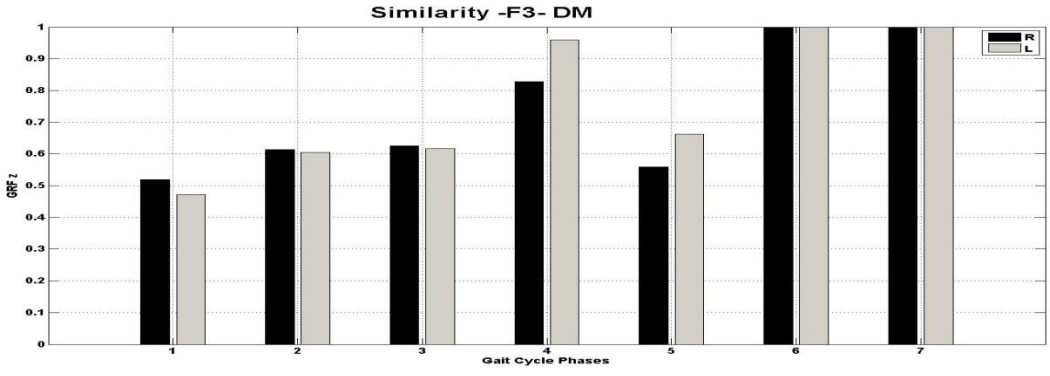
Table 28 Case study for F3-DM a) Anthropometric data, b) vGRF, and c) Fuzzy Similarity

Anthropometric Data						
Age (Years)	Gender	Height (cm)	BMI (Kg/m^2)	DM Years	DM Type	Brisk walking speed (m/s)
47	Female	146	29.22	3	2	0.85

a) Anthropometric data



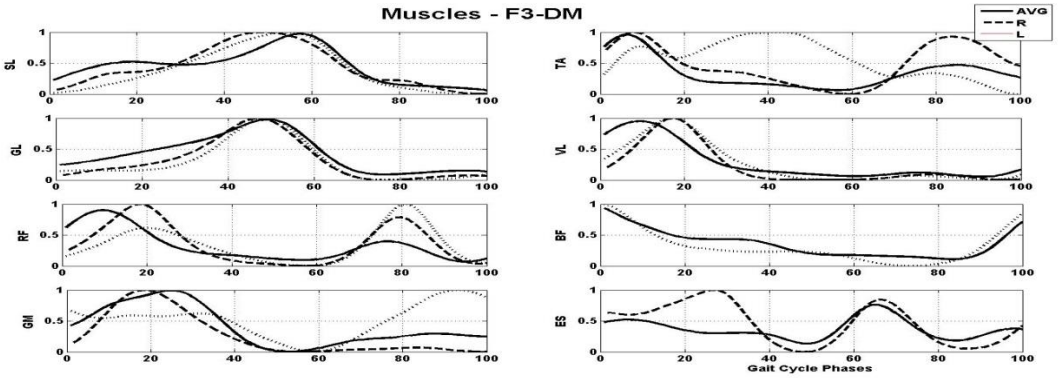
b) vGRF



c) Fuzzy similarity vGRF

The sEMG average muscles of both sides, and the sEMG muscles healthy control group are charted in Table 29a, the fuzzy set equation R (sEMG, Gait phases) for both limbs are shown in table 29b, and the Fuzzy Similarity in Table 29c.

Table 29 Case study 5 for F3-DM a) sEMG averaged, b) Fuzzy set equations R (sEMG, Gait phases), and Fuzzy similarity between Fuzzy set R with respect to healthy control group



a) sEMG averaged

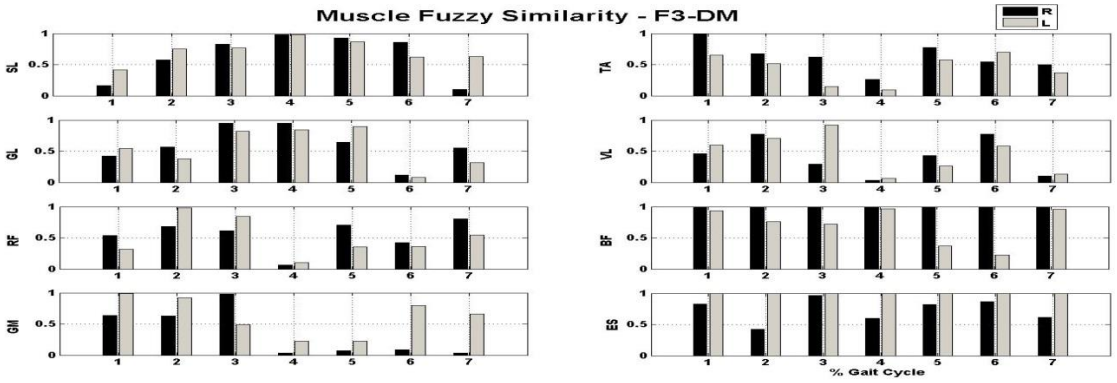
R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.0539	0.2862	0.7639	0.9622	0.5361	0.1225	0.0083
TA	0.8977	0.5331	0.2256	0.0182	0.1737	0.8023	0.6365
GL	0.1199	0.2656	0.7944	0.6199	0.1304	0.0135	0.0655
VL	0.4035	0.7222	0.0395	0.0026	0.0330	0.0775	0.0176
RF	0.4287	0.7640	0.1038	0.0073	0.1802	0.6480	0.1274
BF	NaN	NaN	NaN	NaN	NaN	NaN	NaN
GM	0.3782	0.8479	0.2062	0.0073	0.0320	0.0590	0.0212
ES	0.6180	0.8520	0.2528	0.2911	0.7738	0.2362	0.2255

R (sEMG left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.1398	0.3720	0.8272	0.9279	0.5749	0.2293	0.0500
TA	0.5857	0.6989	0.9636	0.7013	0.3889	0.3082	0.1182
GL	0.1533	0.1772	0.6852	0.7740	0.2260	0.0089	0.0381
VL	0.5223	0.7968	0.1460	0.0044	0.0202	0.0584	0.0235
RF	0.2530	0.5334	0.2000	0.0116	0.0898	0.7531	0.2872
BF	0.8530	0.3659	0.2320	0.1849	0.0597	0.0296	0.4598
GM	0.5851	0.5829	0.4264	0.0471	0.1048	0.5510	0.9491
ES	NaN	NaN	NaN	NaN	NaN	NaN	NaN

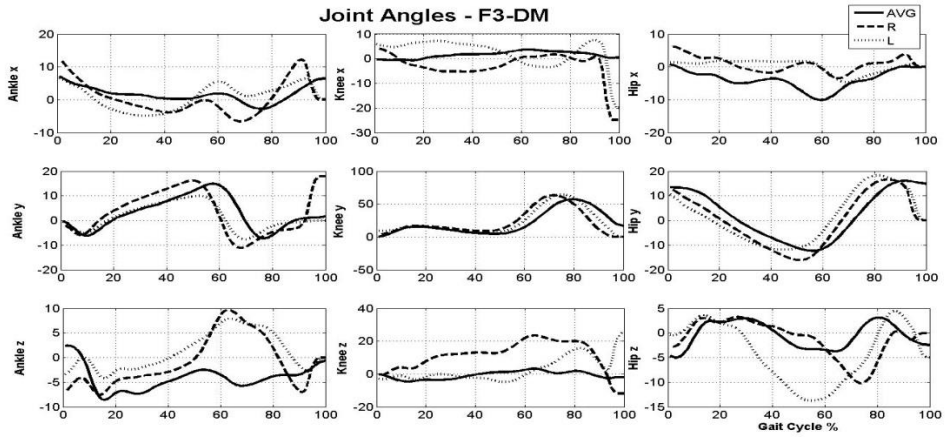
b) Fuzzy set for each limb: R (sEMG, Gait phases)



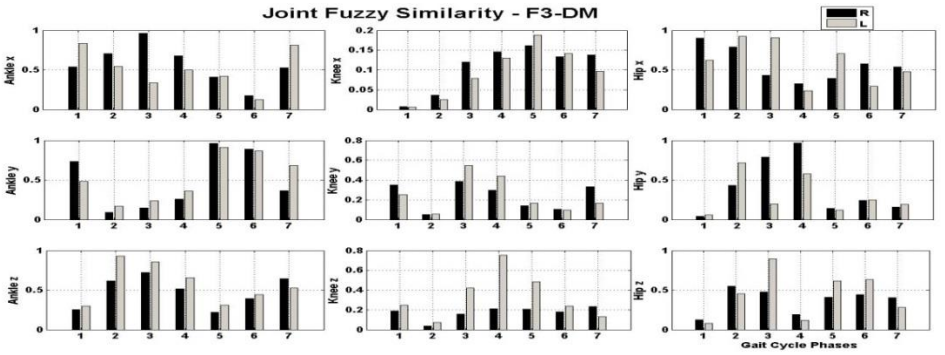
c) Fuzzy similarity sEMG

The averaged Joint angles for this subject are charted with the HCG in Table 30a, the fuzzy similarity between them are charted in Table 30b, and the fuzzy set equation S(Joint axis, Gait Phases) for each side and each axis are presented in Table 30c.

Table 30 Case study for F3-DM a) Averaged Joint Angles, b) Fuzzy Similarity Joint angles, and c) Fuzzy set equations for each axis: S (Joints, Gait phases)



a) Joint Angles



b) Fuzzy similarities between joint angles

S (Joint x right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.4330	0.2081	0.1016	0.1683	0.0417	0.1500	0.3712
K	0.9132	0.7100	0.6654	0.7754	0.8561	0.8532	0.4923
H	0.3444	0.2116	0.0996	0.1738	0.0332	0.1521	0.2126

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0528	0.0499	0.1101	0.2515	0.3646	0.2407	0.0893
K	0.1800	0.2610	0.3277	0.3851	0.4614	0.4234	0.1608
H	0.2271	0.3233	0.2826	0.2264	0.1080	0.0765	0.2473

S (Joint y right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.1537	0.3261	0.5335	0.4979	0.0773	0.1061	0.3767
K	0.0963	0.2041	0.1357	0.2772	0.6818	0.7090	0.1119
H	0.6553	0.4155	0.1068	0.0421	0.3163	0.7056	0.6250

S (Joint y left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.1014	0.1810	0.3396	0.3594	0.0877	0.0821	0.2024
K	0.1357	0.1845	0.0964	0.1867	0.5696	0.7953	0.2220
H	0.4787	0.2492	0.0270	0.0747	0.3602	0.6969	0.5278

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0528	0.0499	0.1101	0.2515	0.3646	0.2407	0.0893
K	0.1800	0.2610	0.3277	0.3851	0.4614	0.4234	0.1608
H	0.2271	0.3233	0.2826	0.2264	0.1080	0.0765	0.2473

S (Joint z left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0624	0.0332	0.0931	0.1985	0.2594	0.2135	0.0729
K	0.1366	0.1390	0.1250	0.1098	0.1975	0.3199	0.2871
H	0.3522	0.3926	0.1502	0.0051	0.0715	0.2711	0.3528

c) Fuzzy set equations: S (Joints, Gait phases)

The Fuzzy Result Equation (Fig. 17) is calculated and the results are shown in Table 31a, and finally the fuzzy similarity with respect to the HCG is obtained and charted on Table 31b-d.

Table 31 Case study for F3-DM: a) Fuzzy Result Equation T (sEMG, Joints), and Fuzzy Similarity T (sEMG, Joints) with respect to the HCG in b) x-axis, c) y-axis, and d) z-axis

T (sEMG right, Joint x right)

	A	K	H
SL	0.2081	0.7754	0.2116
TA	0.4330	0.8977	0.3444
GL	0.2081	0.6654	0.2116
VL	0.4035	0.7100	0.3444
RF	0.4287	0.7100	0.3444
BF	0.4330	0.9132	0.3444
GM	0.3782	0.7100	0.3444
ES	0.4330	0.7738	0.3444

T (sEMG right, Joint y right)

	A	K	H
SL	0.5335	0.5361	0.3163
TA	0.3767	0.7090	0.7056
GL	0.5335	0.2772	0.2656
VL	0.3261	0.2041	0.4155
RF	0.3261	0.6480	0.6480
BF	0.5335	0.7090	0.7056
GM	0.3261	0.2041	0.4155
ES	0.3261	0.6818	0.6180

T (sEMG right, Joint z right)

	A	K	H
SL	0.3646	0.4614	0.2862
TA	0.2407	0.4234	0.3233
GL	0.2515	0.3851	0.2826
VL	0.0775	0.2610	0.3233
RF	0.2407	0.4234	0.3233
BF	0.3646	0.4614	0.3233
GM	0.1101	0.2610	0.3233
ES	0.3646	0.4614	0.3233

T (sEMG right, Joint x left)

	A	K	H
SL	0.2390	0.8668	0.2532
TA	0.2794	0.9636	0.2532
GL	0.2286	0.7740	0.2532
VL	0.2794	0.7968	0.2475
RF	0.2530	0.7531	0.2475
BF	0.2794	0.8530	0.2475
GM	0.2794	0.6998	0.2532
ES	0.2794	1.0451	0.2532

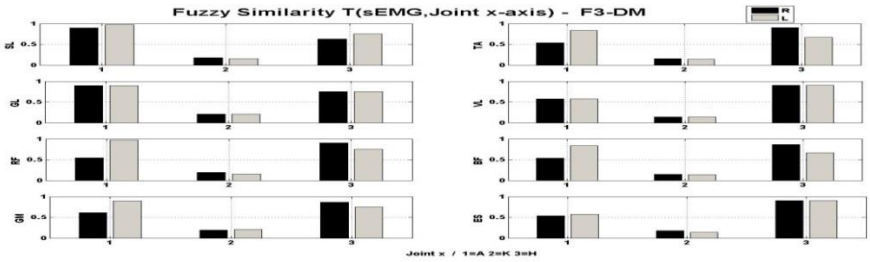
T (sEMG right, Joint y left)

	A	K	H
SL	0.3594	0.5696	0.3602
TA	0.3594	0.3889	0.4787
GL	0.3594	0.2260	0.2260
VL	0.1810	0.1845	0.4787
RF	0.2024	0.7531	0.6969
BF	0.2320	0.2220	0.4787
GM	0.3396	0.5510	0.5510
ES	0.3594	0.7953	0.6969

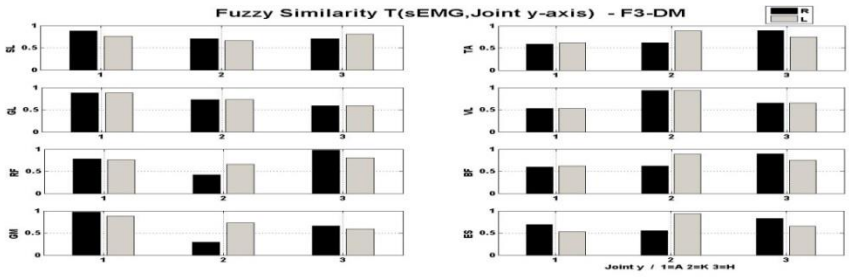
T (sEMG right, Joint z left)

	A	K	H
SL	0.2594	0.2293	0.3720
TA	0.2594	0.3082	0.3926
GL	0.2260	0.1975	0.1772
VL	0.0931	0.1390	0.3926
RF	0.2135	0.3199	0.3926
BF	0.1849	0.2871	0.3659
GM	0.2135	0.3199	0.3926
ES	0.2594	0.3199	0.3926

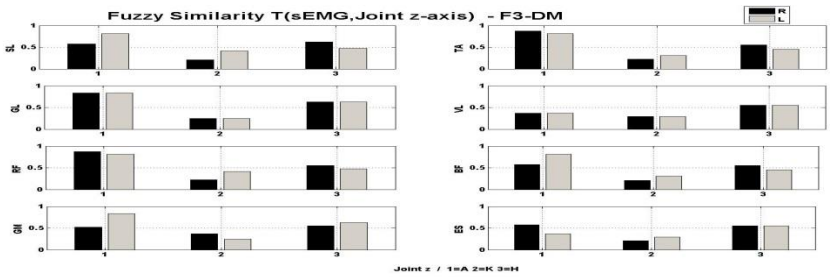
a) Fuzzy Result Equation T (sEMG, Joints)



b) Fuzzy Similarity T (sEMG, Joint x axis)



c) Fuzzy Similarity T (sEMG, Joint y axis)



c) Fuzzy Similarity T (sEMG, Joint z axis)

Conclusions for Case 5 F3-DM:

vGRF analysis from table 28

- This subject shows his vGRF to be very similar in shape but almost half in amplitude of the control group with a lower stride approx. 15-17% less.

- On the Fuzzy similarity chart this delay is reflected as value differences in phases from 1 Loading response (0-10%) , 2 Mid Stance (10-30%), 3 Terminal Stance (30-50%) ,and 5 Initial Swing (60-70%).

Muscle analysis from Table 28:

- Left TA muscle presents a delay of almost 30%.

- Both VL muscles present a delay of 10%

- Both RF muscles present two high peak amplitudes.

- Left GM presents a big delay of 70%

- Note: Sensor failure in left ES

Joint analysis from Table 30:

- Muscles delay/weakness mainly in both limbs is observed as angle variations in the sagittal plane, with less range of motion in ankle

Fuzzy results analysis from Table 31:

- Shows the most affected muscles/joint with respect to the Sagittal Plane are:
    - Muscles / Joint Ankle most affected are: TA, VL, BF, and ES.
    - Muscles / Joint Knee most affected are: TA, RF, BF, GM, and ES.
    - Muscles / Joint Hip most affected are: GL, and VL

General results from Tables 28-31

- Suggests that the left limb is slightly more affected then the right limb

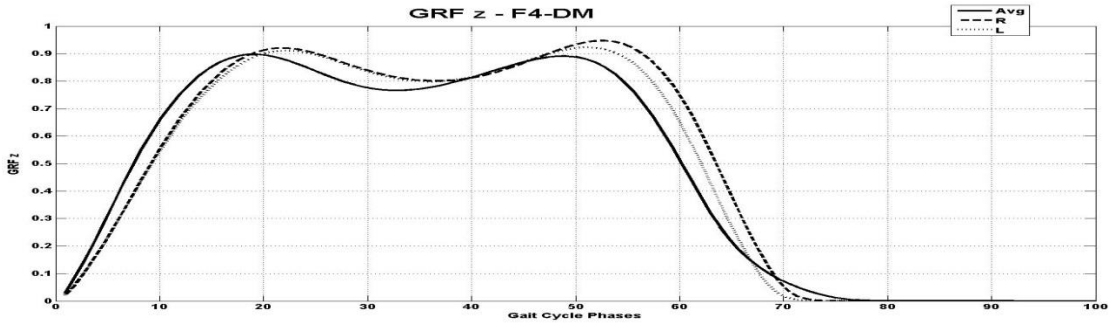
Case Study 6 Fuzzy logic method differential analysis: Subject F4-DM

The anthropometric data from this subject is shown in Table 32a, including the average z-axis ground reaction forces of all strides (Table 32b), and the fuzzy similarity with respect to healthy control group (Table 32c) using the equation indicated in Fig 17.

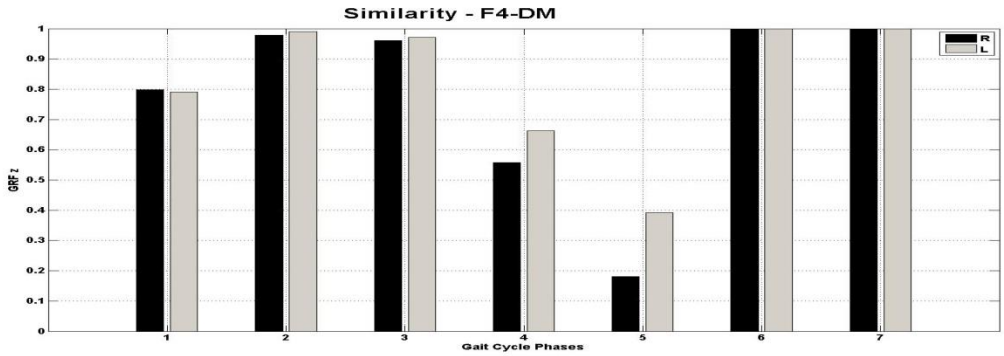
Table 32 Case study for F4-DM a) Anthropometric data, b) vGRF, and c) Fuzzy Similarity

Anthropometric Data						
Age (Years)	Gender	Height (cm)	BMI (Kg/m^2)	DM Years	DM Type	Brisk walking speed (m/s)
26	Female	161	38.84	4	2	0.85

a) Anthropometric data



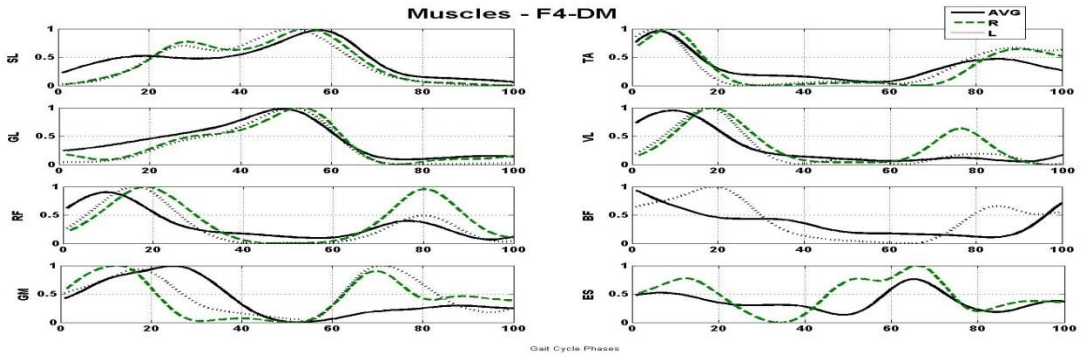
b) vGRF



c) Fuzzy similarity vGRF

The sEMG average muscles of both sides, and the sEMG muscles healthy control group are charted in Table 33a, the fuzzy set equation R (sEMG, Gait phases) for both limbs are shown in table 33b, and the Fuzzy Similarity in Table 33c.

Table 33 Case study for F4-DM a) sEMG averaged, b) Fuzzy set equations R (sEMG, Gait phases), and Fuzzy similarity between Fuzzy set R with respect to healthy control group



a) sEMG averaged

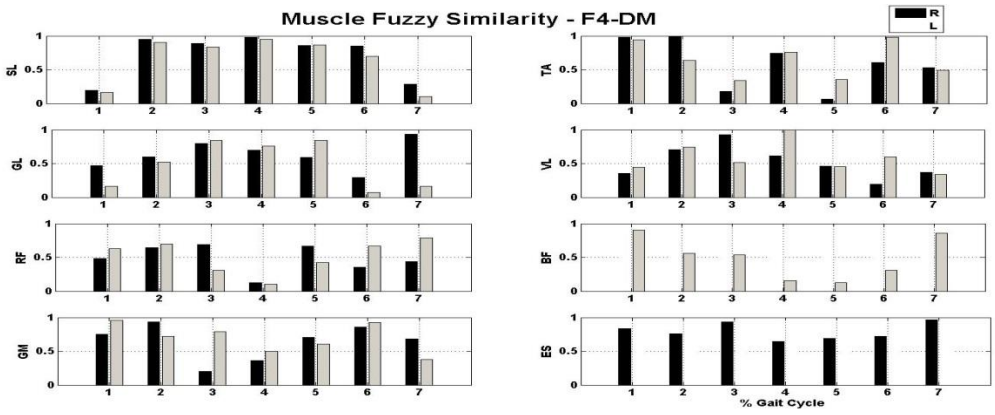
R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.0643	0.4692	0.7125	0.9647	0.5831	0.1216	0.0226
TA	0.8766	0.3642	0.0255	0.0513	0.0152	0.2666	0.5994
GL	0.1320	0.2799	0.6645	0.9308	0.3399	0.0342	0.1114
VL	0.3080	0.7911	0.1246	0.0415	0.1659	0.5067	0.0641
RF	0.3872	0.8174	0.1156	0.0143	0.1695	0.7761	0.3565
BF	NaN	NaN	NaN	NaN	NaN	NaN	NaN
GM	0.7910	0.5750	0.0431	0.0770	0.6575	0.5898	0.4304
ES	0.6085	0.4769	0.2602	0.7532	0.9230	0.3789	0.3547

R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.0559784	0.44745	0.75582	0.8991	0.430959	0.100191	0.00826
TA	0.9466303	0.22756	0.047462	0.05232	0.078936	0.447997	0.64287
GL	0.0464389	0.24731	0.701789	0.8557	0.239915	0.00814	0.01934
VL	0.3898898	0.754	0.069586	0.0684	0.034814	0.168286	0.05818
RF	0.5034152	0.75315	0.051635	0.01171	0.107596	0.412666	0.12513
BF	0.7187762	0.85596	0.173776	0.02856	0.020709	0.424962	0.55964
GM	0.6203171	0.74559	0.165028	0.10551	0.764591	0.739306	0.23637
ES	NaN	NaN	NaN	NaN	NaN	NaN	NaN

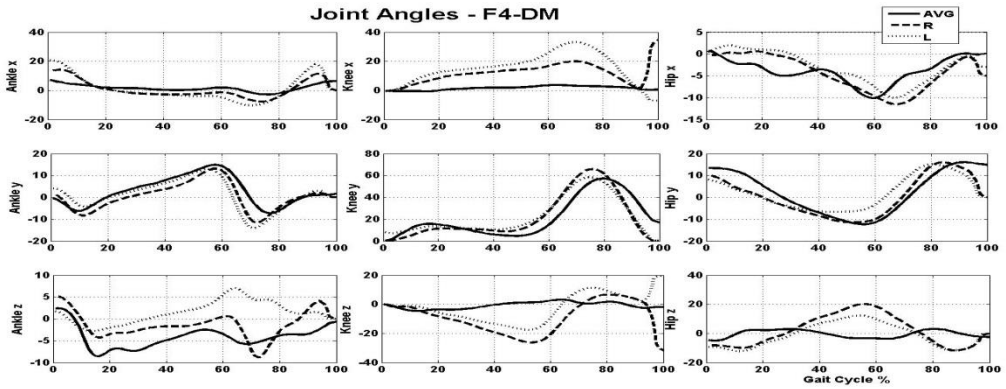
b) Fuzzy set for each limb: R (sEMG, Gait phases)



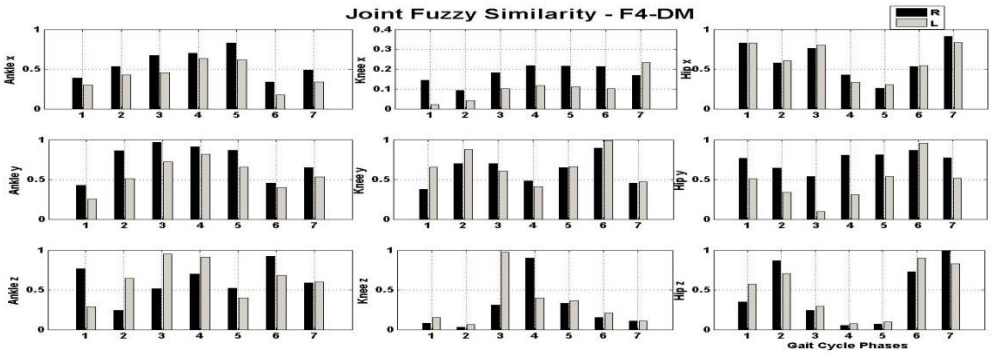
c) Fuzzy similarity sEMG

The averaged Joint angles for this subject are charted with the HCG in Table 34a, the fuzzy similarity between them are charted in Table 34b, and the fuzzy set equation S(Joint axis, Gait Phases) for each side and each axis are presented in Table 34c.

Table 34 Case study 6 for F4-DM a) Averaged Joint Angles, b) Fuzzy Similarity Joint angles, and c) Fuzzy set equations for each axis: S (Joints, Gait phases)



a) Joint Angles



b) Joint Angles

S (Joint x right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.6005	0.2776	0.1456	0.1630	0.1224	0.0767	0.4035
K	0.0428	0.2783	0.4409	0.5183	0.6392	0.5357	0.4012
H	0.4603	0.4625	0.3016	0.1322	0.0219	0.1406	0.3622

S (Joint x left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.7856	0.3474	0.2139	0.1805	0.0624	0.1493	0.5771
K	0.2916	0.6261	0.7878	0.9613	1.2628	1.1191	0.2911
H	0.4595	0.4393	0.2873	0.1717	0.0258	0.1430	0.3316

S (Joint y right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.1985	0.1781	0.3484	0.5176	0.2924	0.1082	0.2772
K	0.0277	0.1339	0.1323	0.2367	0.5823	0.8031	0.2009
H	0.4886	0.2878	0.0755	0.0072	0.1486	0.5480	0.5335

S (Joint y left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.3300	0.3025	0.4651	0.5755	0.2200	0.1236	0.3376
K	0.1116	0.1678	0.1530	0.2776	0.5695	0.7132	0.2079
H	0.3231	0.1520	0.0136	0.0285	0.2242	0.4982	0.3583

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.2740	0.1268	0.1547	0.1855	0.1528	0.0873	0.2353
K	0.4065	0.3210	0.1685	0.0912	0.2883	0.4870	0.3430
H	0.0805	0.1554	0.5498	0.7776	0.6177	0.2359	0.0997

S (Joint z left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.0604	0.0199	0.0838	0.1427	0.1997	0.1379	0.0833
K	0.2193	0.1646	0.0542	0.0331	0.2627	0.3624	0.3497
H	0.0495	0.1262	0.4646	0.5951	0.4553	0.1911	0.1213

c) Fuzzy set equations: S (Joints, Gait phases)

The Fuzzy Result Equation (Fig. 17) is calculated and the results are shown in Table 35a, and finally the fuzzy similarity with respect to the HCG is obtained and charted on Table 35b-d.

Table 35 Case study for F4-DM: a) Fuzzy Result Equation T (sEMG, Joints), and Fuzzy Similarity T (sEMG, Joints) with respect to the HCG in b) x-axis, c) y-axis, and d) z-axis

T (sEMG right, Joint y right)

	A	K	H
SL	0.5176	0.5823	0.2878
TA	0.2772	0.2666	0.5335
GL	0.5176	0.3399	0.2799
VL	0.1985	0.5067	0.5067
RF	0.2772	0.7761	0.5480
BF	0.5176	0.8031	0.5480
GM	0.2924	0.5898	0.5480
ES	0.5176	0.5823	0.4886

T (sEMG right, Joint z right)

	A	K	H
SL	0.1855	0.3210	0.7776
TA	0.2740	0.4065	0.2359
GL	0.1855	0.2883	0.7776
VL	0.2740	0.4870	0.2359
RF	0.2740	0.4870	0.2359
BF	0.2740	0.4870	0.7776
GM	0.2740	0.4870	0.6177
ES	0.2740	0.4065	0.7532

T (sEMG right, Joint z right)

	A	K	H
SL	0.1855	0.3210	0.7776
TA	0.2740	0.4065	0.2359
GL	0.1855	0.2883	0.7776
VL	0.2740	0.4870	0.2359
RF	0.2740	0.4870	0.2359
BF	0.2740	0.4870	0.7776
GM	0.2740	0.4870	0.6177
ES	0.2740	0.4065	0.7532

T (sEMG right, Joint x left)

	A	K	H
SL	0.3474	0.8991	0.4393
TA	0.7856	0.4480	0.4595
GL	0.2473	0.8557	0.2873
VL	0.3899	0.6261	0.4393
RF	0.5034	0.6261	0.4595
BF	0.7188	0.6261	0.4595
GM	0.6203	0.7646	0.4595
ES	0.7856	1.2628	0.4595

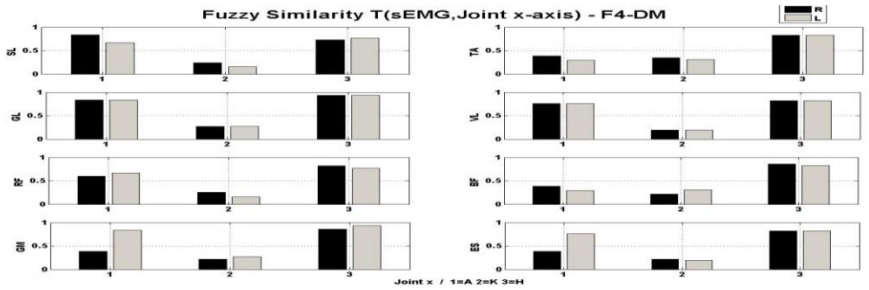
T (sEMG right, Joint y left)

	A	K	H
SL	0.5755	0.4310	0.2242
TA	0.3376	0.4480	0.4480
GL	0.5755	0.2776	0.2242
VL	0.3300	0.1683	0.3231
RF	0.3300	0.4127	0.4127
BF	0.3376	0.4250	0.4250
GM	0.3300	0.7132	0.4982
ES	0.5755	0.7132	0.4982

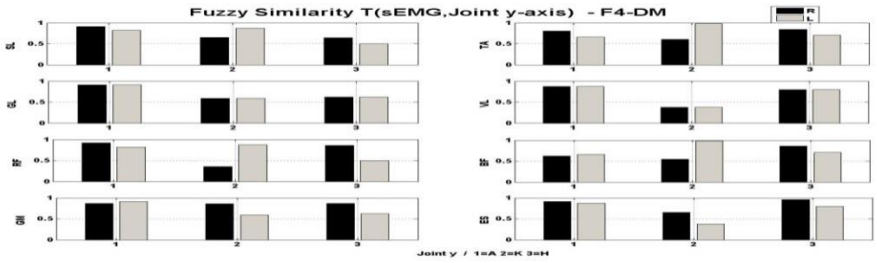
T (sEMG right, Joint z left)

	A	K	H
SL	0.1997	0.2627	0.5951
TA	0.1379	0.3624	0.1911
GL	0.1997	0.2399	0.5951
VL	0.1379	0.2193	0.1683
RF	0.1379	0.3624	0.1911
BF	0.1379	0.3624	0.1911
GM	0.1997	0.3624	0.4553
ES	0.1997	0.3624	0.5951

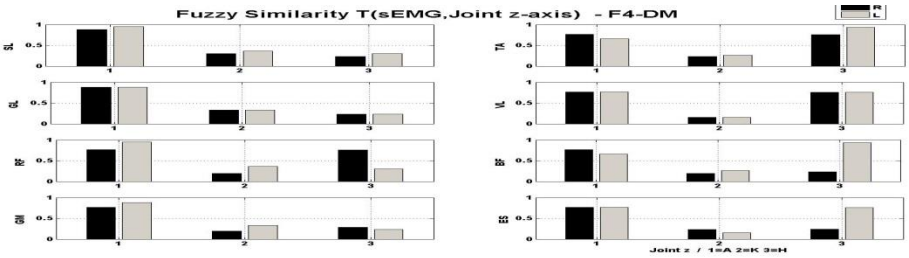
a) Fuzzy Result Equation T (sEMG, Joints)



b) Fuzzy Similarity T (sEMG, Joint x axis)



c) Fuzzy Similarity T (sEMG, Joint y axis)



d) Fuzzy Similarity T (sEMG, Joint z axis)

Conclusions for Case 6 F4-DM:

vGRF analysis from table 32

- This subject shows his vGRF to be very similar in shape and amplitude with the control group chart, with a lower stride of approx. 4-7% less.
- On the Fuzzy similarity chart this delay is reflected as values differences in phases from 1 Loading response (0-10%), 4 Pre Swing (50-60%), and 5 Initial Swing (60-70%).

Muscle analysis from Table 33:

- Both VL muscles present a delay of aprox. 10%.
- Both RF and both BF muscles present a delay of aprox. 10%, and amplitude variations.
- Both RF muscles present two high peak amplitudes.
- Both GM muscles present amplitude oscillations.
- Note: Sensors failure in left ES and right BF

Joint analysis from Table 34:

- Muscles delay/weakness mainly in both limbs is observed as angle variations in the sagittal plane, with less range of motion in the ankle and hip. A higher range of motion is observed in the knees.

Fuzzy results analysis from Table 35:

- Shows the most affected muscles/joint with respect to the Sagittal Plane are:
    - Muscles / Joint Ankle most affected are: TA, and BF.
    - Muscles / Joint Knee most affected are present in all muscles.
    - Muscles / Joint Hip most affected are: SL, RF, BF, GM and ES

General results from Tables 32-35

- Suggests that the right side is slightly more affected that left side

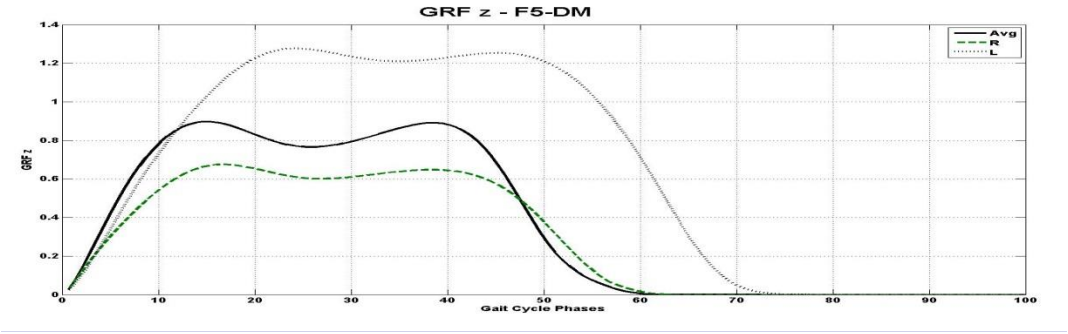
Case Study 7 Fuzzy logic method differential analysis: Subject F5-DM

The anthropometric data from this subject is shown in Table 36a, including the average z-axis ground reaction forces of all strides (Table 36b), and the fuzzy similarity with respect to the healthy control group (Table 36c) using the equation indicated in Fig 17.

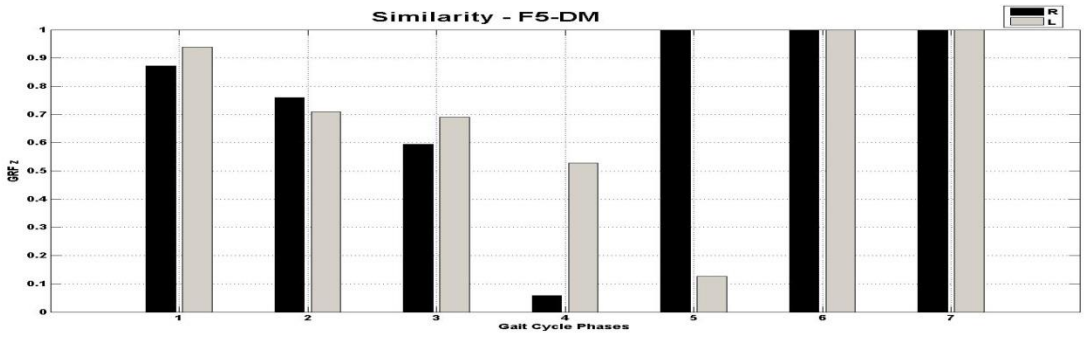
Table 36 Case study for F5-DM a) Anthropometric data, b) vGRF, and c) Fuzzy Similarity

Anthropometric Data						
Age (Years)	Gender	Height (cm)	BMI (Kg/m^2)	DM Years	DM Type	Brisk walking speed (m/s)
34	Female	168	50.06	4	2	0.7

a) Anthropometric data



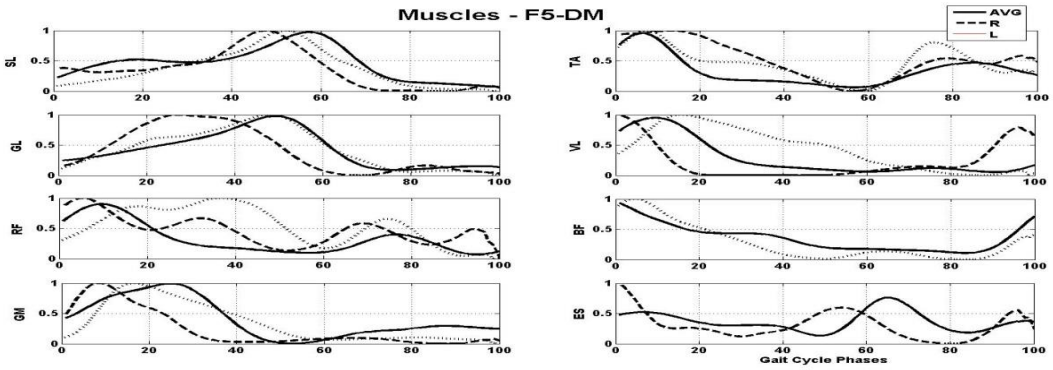
b) vGRF



c) Fuzzy similarity vGRF

The sEMG average muscles of both sides, and the sEMG muscles healthy control group are charted in Table 37a, the fuzzy set equation R (sEMG, Gait phases) for both limbs are shown in table 37b, and the Fuzzy Similarity in Table 37c.

Table 37 Case study 7 for F5-DM a) sEMG averaged, b) Fuzzy set equations R (sEMG, Gait phases), and Fuzzy similarity between Fuzzy set R with respect to healthy control group



a) sEMG averaged

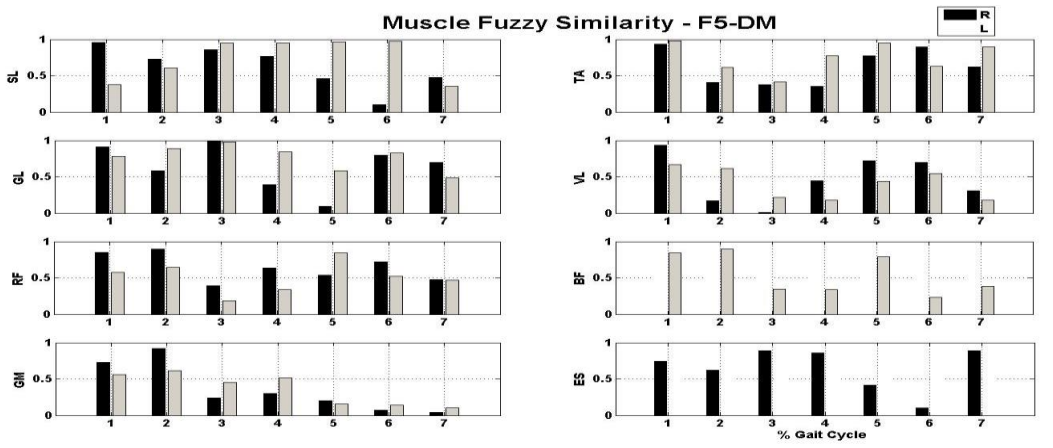
R (sEMG right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.350	0.362	0.736	0.725	0.232	0.015	0.038
TA	0.956	0.874	0.371	0.025	0.174	0.489	0.508
GL	0.257	0.807	0.836	0.255	0.019	0.092	0.083
VL	0.817	0.098	0.001	0.030	0.107	0.144	0.565
RF	0.945	0.586	0.432	0.174	0.472	0.383	0.330
BF	NaN	NaN	NaN	NaN	NaN	NaN	NaN
GM	0.818	0.583	0.051	0.063	0.094	0.048	0.029
ES	0.686	0.225	0.272	0.561	0.262	0.028	0.329

R (sEMG left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
SL	0.127	0.302	0.664	0.898	0.483	0.147	0.028
TA	0.913	0.587	0.340	0.054	0.213	0.698	0.353
GL	0.220	0.530	0.847	0.770	0.345	0.095	0.058
VL	0.588	0.916	0.608	0.381	0.175	0.055	0.030
RF	0.460	0.816	0.897	0.330	0.301	0.523	0.073
BF	0.949	0.536	0.112	0.060	0.128	0.031	0.187
GM	0.332	0.875	0.461	0.109	0.072	0.096	0.065
ES	NaN	NaN	NaN	NaN	NaN	NaN	NaN

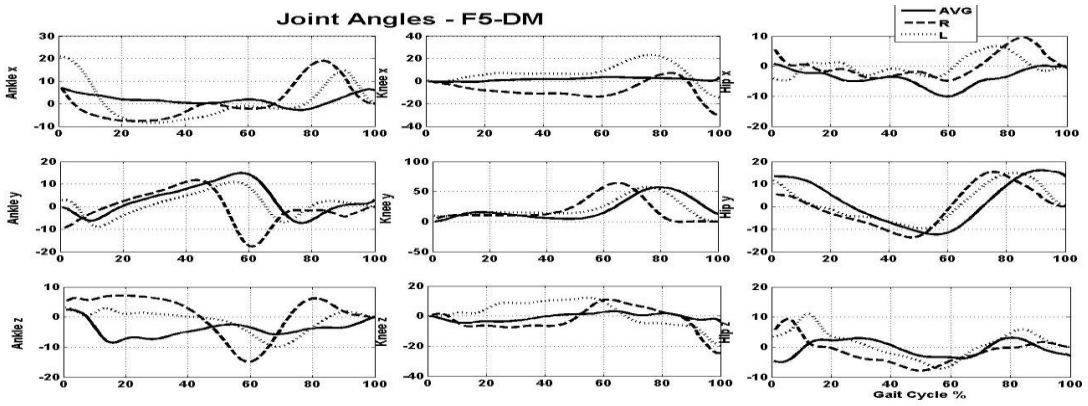
b) Fuzzy set for each limb: R (sEMG, Gait phases)



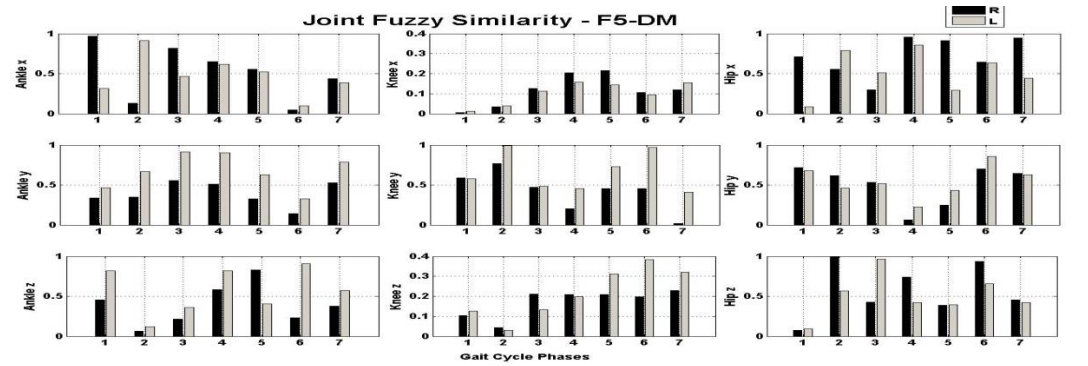
c) Fuzzy similarity sEMG

The averaged Joint angles for this subject are charted with the HCG in Table 38a, the fuzzy similarity between them are charted in Table 38b, and the fuzzy set equation S(Joint axis, Gait Phases) for each side and each axis are presented in Table 38c.

Table 38 Case study for F5-DM a) Averaged Joint Angles, b) Fuzzy Similarity Joint angles, and c) Fuzzy set equations for each axis: S (Joints, Gait phases



a) Joint Angles



b) Joint Angles

S (Joint x right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.2257	0.0194	0.1191	0.1758	0.1825	0.5800	0.4463
K	0.9311	0.7316	0.6284	0.5527	0.6394	1.0772	0.5638
H	0.2705	0.1478	0.0686	0.0543	0.0770	0.4076	0.3740

S (Joint x left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.7413	0.1346	0.0455	0.1846	0.1943	0.2714	0.5059
K	0.4923	0.6684	0.7145	0.7237	0.9676	1.2025	0.4353
H	0.0326	0.2116	0.1180	0.0660	0.2854	0.4136	0.1754

S (Joint y right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.2501	0.4429	0.6056	0.2425	0.1092	0.3496	0.3388
K	0.1238	0.1460	0.1979	0.5656	0.8277	0.3294	0.0083
H	0.4560	0.2756	0.0746	0.1342	0.4875	0.6835	0.4447

S (Joint y left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.1813	0.1024	0.3086	0.4254	0.2120	0.1500	0.2293
K	0.1265	0.1924	0.1933	0.2501	0.5170	0.6987	0.1815
H	0.4321	0.2073	0.0718	0.0398	0.2779	0.5552	0.4346

S (Joint z right, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.4605	0.4829	0.3736	0.0757	0.0966	0.4111	0.3642
K	0.3290	0.2400	0.2499	0.3956	0.4601	0.3837	0.1637
H	0.3841	0.1789	0.0578	0.0321	0.1140	0.1837	0.2200

S (Joint z left, Gait Phases)

	P1	P2	P3	P4	P5	P6	P7
A	0.2566	0.2560	0.2224	0.1591	0.0325	0.1040	0.2419
K	0.2699	0.3291	0.3934	0.4156	0.3063	0.1986	0.1166
H	0.3137	0.3153	0.1298	0.0183	0.1129	0.2621	0.2391

c) Fuzzy set equations: S (Joints, Gait phases)

)

The Fuzzy Result Equation (Fig. 17) is calculated and the results are shown in Table 39a, and finally the fuzzy similarity with respect to the HCG is obtained and charted on Table 39b-d.

Table 39 Case study for F5-DM: a) Fuzzy Result Equation T (sEMG, Joints), and Fuzzy Similarity T (sEMG, Joints) with respect to the HCG in b) x-axis, c) y-axis, and d) z-axis

T (sEMG right, Joint x right)

	A	K	H
SL	0.2257	0.6284	0.2705
TA	0.4890	0.9311	0.4076
GL	0.2257	0.7316	0.2570
VL	0.4463	0.8170	0.3740
RF	0.3830	0.9311	0.3830
BF	0.5800	1.0772	0.4076
GM	0.2257	0.8180	0.2705
ES	0.3290	0.6860	0.3290

T (sEMG right, Joint y right)

	A	K	H
SL	0.6056	0.5656	0.3500
TA	0.4429	0.3294	0.4890
GL	0.6056	0.2550	0.2756
VL	0.3388	0.1440	0.4560
RF	0.4429	0.4720	0.4720
BF	0.6056	0.8277	0.6835
GM	0.4429	0.1460	0.4560
ES	0.3290	0.5610	0.4560

T (sEMG right, Joint z right)

	A	K	H
SL	0.3736	0.3956	0.3500
TA	0.4829	0.3837	0.3841
GL	0.4829	0.2570	0.2570
VL	0.4605	0.3290	0.3841
RF	0.4829	0.4601	0.3841
BF	0.4829	0.4601	0.3841
GM	0.4829	0.3290	0.3841
ES	0.4605	0.3956	0.3841

T (sEMG right, Joint x left)

	A	K	H
SL	0.1943	0.7237	0.2854
TA	0.7413	0.6980	0.4136
GL	0.2200	0.7237	0.2854
VL	0.5880	0.6684	0.2116
RF	0.4600	0.7145	0.4136
BF	0.7413	0.5360	0.2116
GM	0.3320	0.6684	0.2116
ES	0.7413	1.2025	0.4136

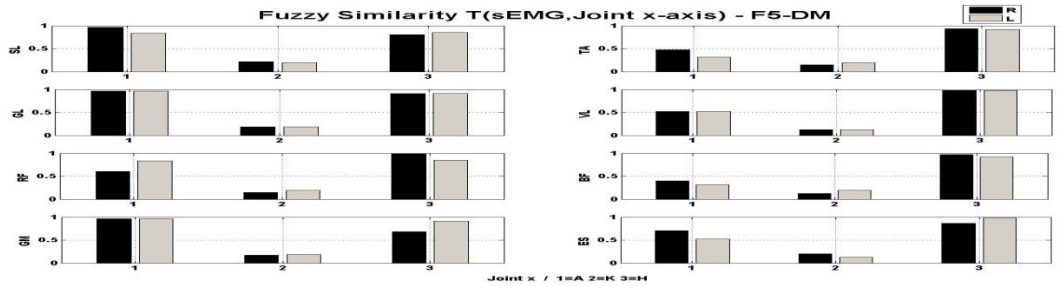
T (sEMG right, Joint y left)

	A	K	H
SL	0.4254	0.4830	0.2779
TA	0.3086	0.6980	0.5552
GL	0.4254	0.3450	0.2779
VL	0.3810	0.2501	0.4321
RF	0.3300	0.5230	0.5230
BF	0.1870	0.1924	0.4321
GM	0.3086	0.1933	0.3320
ES	0.4254	0.6987	0.5552

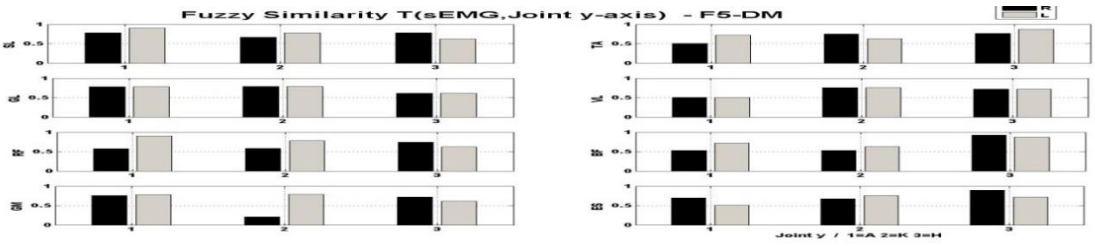
T (sEMG right, Joint z left)

	A	K	H
SL	0.2560	0.4156	0.3020
TA	0.2566	0.3400	0.3153
GL	0.2560	0.4156	0.3153
VL	0.2566	0.3934	0.3153
RF	0.2566	0.3934	0.3153
BF	0.2566	0.3291	0.3153
GM	0.2566	0.3934	0.3153
ES	0.2566	0.4156	0.3153

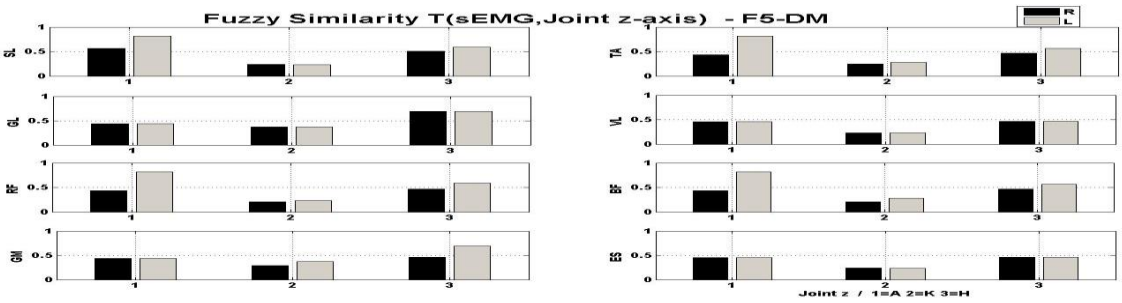
a) Fuzzy Result Equation T (sEMG, Joints)



b) Fuzzy Similarity T (sEMG, Joint x axis)



c) Fuzzy Similarity T (sEMG, Joint y axis)



d) Fuzzy Similarity T (sEMG, Joint z axis)

Conclusions for Case 7 F5-DM:

vGRF analysis from table 36

- This subject shows his vGRF to be very similar in shape and amplitude in amplitude of the control group in the right side, but a very wide stride in the left vGRF
- On the Fuzzy similarity chart this delay is reflected as value differences in phases from 2 Mid Stance (10-30%), 3 Terminal Stance (30-50%), 4 Pre Swing (50-60%), 5 Initial Swing (60-70%), and 6 Mid Swing (70-85%)

Muscle analysis from Table 37:

- Both TA muscles present amplitude oscillations.
- Almost all right limb muscles signals are 10% led and left side 10% lag with respect to HCG, with exception of GM that both are ahead of HCG.
- Both RF muscles present two amplitude oscillations.
- Note: Sensors failure in left ES and right BF

Joint analysis from Table 38:

- Muscles delay/weakness mainly in both limbs is observed as angle variations in the sagittal plane, with less range of motion in left side, and more on the right joints.

Fuzzy results analysis from Table 39:

- Shows the most affected muscles/joint with respect to the Sagittal Plane are:
    - Muscles / Joint Ankle most affected are: TA, VL, RF, BF and ES.
    - Muscles / Joint Knee most affected are: RF, BF, and GM
    - Muscles / Joint Hip most affected are: SL, GL, VL, RF, and GM.

General results from Tables 36-39

- Suggests a big difference between the right limb always more stronger than the left side limb always less stronger than HCG.

5.2 Final consolidated results of three methods

Three methods to evaluate DM subjects have been explained in this research:

1. The **Monofilament test (SWM)** to detect foot sensation. Using a monofilament of 10 gr testing in five areas as indicate in Fig. 8a. The results are explained and tabulated in section 4.2.3

2. **Muscle energy expenditure analysis** using Dynamic transition-to-fatigue muscle fatigue during brisk walking. Data from surface electromyography (sEMG) muscle activity from instrument Delsys®, and analyzed in frequency domain with segmented (windows) data based on MDF (section 4.2.6). All cases studies results explained in section 4.27

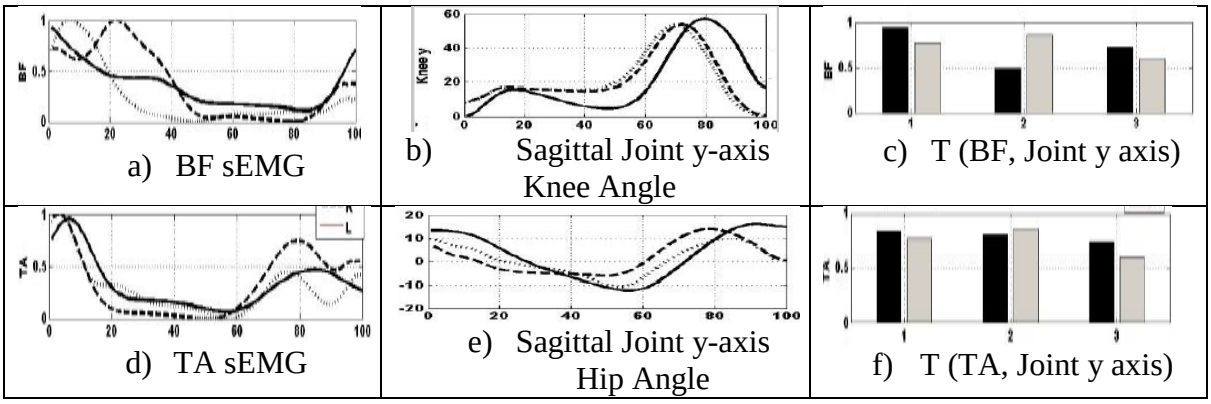
3. **Natural Fuzzy logic method for differential analysis in muscle/joint activation pattern**. During this test, data signal are drawn from three instruments: Ground Reaction Forces (GRF) form instrumented treadmill BERTEC®, surface electromyography (sEMG) muscle activity from instrument Delsys®, and joint angles from the instrument Lima Smart Goniometer (Section 4.3). All information is processed and analyzed with case studies results shown in section 4.3.3

In this section all results are compared side by side to obtain general suggestions for for each DM subjects.

The consolidated results for case 1 M1-DM

- The Monofilament test (SWM) method report:
    - No detection of any poor foot sensation, and he passed satisfactory all test with the 10 gram monofilament.
- Transition-to-fatigue results suggest that muscle faceted during brisk walking are:
    - Two soft transitions detected: one in right **BF**, and another in left limb **TA**.
- Natural Fuzzy logic method concludes the most affected muscle/joint in sagittal plane are:
    - Muscle / Joint Ankle are: SL, GL, RF, and ES.
    - Muscle / Joint Knee are: GL, **BF**, GM, and ES.
    - Muscle / Joint Hip are: SL,**TA**,GL, BF, and GM

Table 40 Muscle comparative analysis for case 1M1-DM: BF a-c, and TA d-f.



Consistent (significant) results could be observed from the Transition-to-fatigue results and results from the Natural Fuzzy Logic (NFL) method mainly in the right BF and left TA. Table 40a-c shows how the right BF muscle is delayed approx. 15-20 % with respect to the HCG signal (a). A similarity T value lower than .5 in the right BF/knee (b), and a lower and led knee range of motion (c).Table 40d-f shows a decrease in amplitude in the left TA (d), Lower left T

value TA/Hip (f) , and lower hip range of motion (e). All results suggest that the left limb is more affected than right limb.

The consolidated results for case 2 M2-DM

- The Monofilament test (SWM) method report:
    - Monofilament test (SWM) failed all areas, and one callus for eacht foot.
- Transition-to-fatigue results suggest that muscle faceted during brisk walking are:
    - Three soft transition-to-fatigues are detected: right **VL**, left **SL** and left VL.

      The Subject present frequently loss balances during brisk walking test.
- Natural Fuzzy logic method concludes the most affect muscle/joint in sagittal plane :
    - Muscle / Joint Ankle are: **SL**, GL, **VL**, RF, and ES.
    - Muscle / Joint Knee are: **SL**, TA, GL, RF, BF, and GM.
    - Muscle / Joint Hip are: **VL**, and ES.

Table 41 Muscle comparative analysis for case 2 M2-DM: VL a-c, and SL d-f.

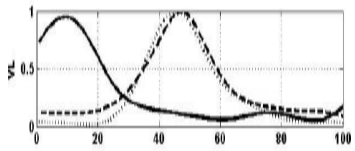
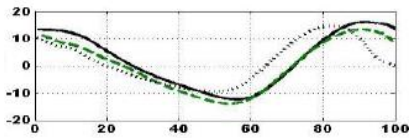
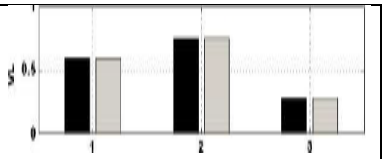
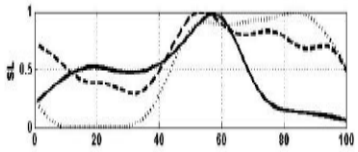
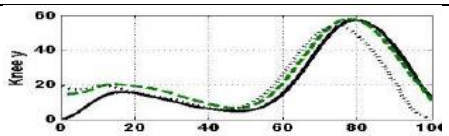
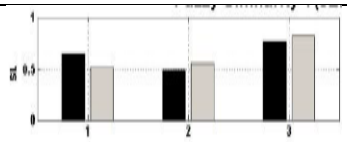
 a) VL sEMG from Table 21a	 b) Sagittal Joint y-axis Hip Angle from Table 22a	 c) T (VL, Joint y axis) from Table 23c
 d) SL sEMG from Table 21a	 e) Sagittal Joint y-axis Knee Angle from Table 22a	 f)T (SL, Joint y axis) from Table 23c

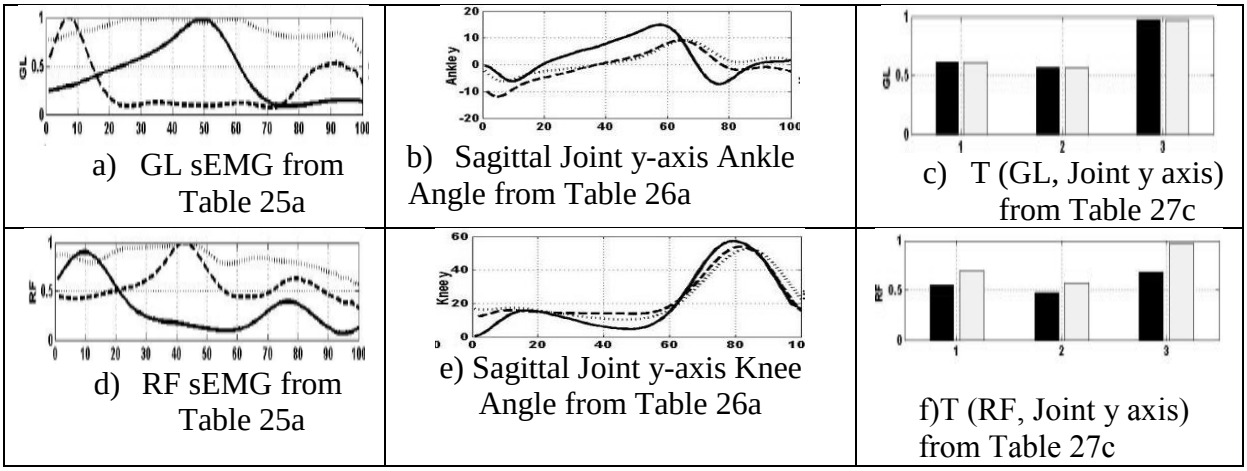
Table 41a-c shows how the both VL muscles are delayed approx. 20-25 % with respect to the HCG signal (a). A similarity T value lower than .5 in the both VL/Hip (b), and a lower hip range of motion (c).Table 41d-f shows an unstable amplitude for left SL (d), Lower left T value

for VL/Knee and VL/ankle (f) , and lower knee range of motion (e). All results suggest that the left limb is more affected than right limb.

The consolidated results for case 3 F1-DM

- The Monofilament test (SWM) method report:
    - Failed all test, no physical callus were detected.
- Transition-to-fatigue test results suggested that muscles affected during brisk walking:
    - Four soft and five fast transition-to-fatigues are detected during very slow brisk walking speed of 0.40 m/s, the slowest from this DM group.
    - The high muscles fatigue suggested during brisk walking are: One in the right limb **GL** muscle and the others in the left limb are: **SL**, **TA**, **RF** and **ES**. Slow muscles fatigue is detected on the right limb: **SL**, TA, and BF. And in left limb the GL.
- Natural Fuzzy logic method concludes that most affected muscles/joints in Sagittal Plane:
    - Muscles / Joint Ankle more affected are: VL, **RF**
    - Muscles / Joint Knee more affected are: **SL**, **GL**, VL, RF, GM, and **ES**
    - Muscles / Joint Hip more affected are: **TA**,VL, RF, BF

Table 42 Muscle comparative analysis for case 3 F1-DM: GL a-c, and RF d-f.



a) GL sEMG from Table 25a

b) Sagittal Joint y-axis Ankle Angle from Table 26a

c) T (GL, Joint y axis) from Table 27c

d) RF sEMG from Table 25a

e) Sagittal Joint y-axis Knee Angle from Table 26a

f)T (RF, Joint y axis) from Table 27c

Table 42a-c shows how the right GL muscles are led approx. 40-45 % with respect to the HCG signal (a). A similarity T value close to .5 in the both GL/Ankle and GL/Knee (b), and a

lower knee range of motion (c).Table 42d-f shows an erratic amplitude for both RF muscles signal (d), Lower left T value RF/right Knee and VL/ right ankle (f) , and lower knee range of motion (e).

All results suggest that both limbs are affected, but the right limb presents many signal instability in amplitude as sinusoidal waves. The three methods seems to complement each other, adding more information about subject beahviors during the tests.

The consolidated results for case 4 F2-DM

- The Monofilament test (SWM) method report:
    - Five failed area tests, no physical callus were detected.
- Transition-to-fatigue test results suggested that muscles affected during brisk walking are:
    - On the left limb only: **TA**, **BF**, and **VL**.
- Natural Fuzzy logic method concludes that most affected muscles/joints in Sagittal Plane:
    - Muscles / Joint Ankle more affected are: **TA** and **VL**
    - Muscles / Joint Knee more affected are all 8 eight of them except GM
    - Muscles / Joint Hip more affected are: RF, and **BF**

Table 43 Muscle comparative analysis for case 4 F2-DM: TA a-c, and VL d-f.

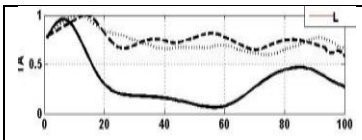
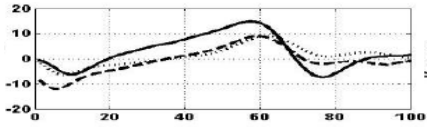
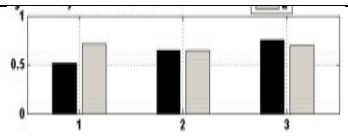
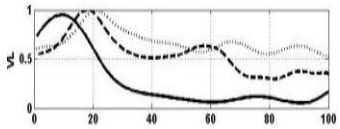
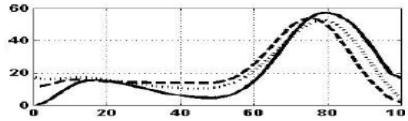
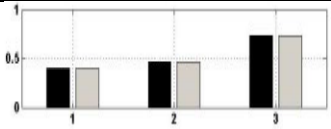
 a) TA sEMG from Table 29a	 b) Sagittal Joint y-axis Ankle Angle from Table 30a	 d) T (TA, Joint y axis) from Table 31c
 e) VL sEMG from Table 29a	 e) Sagittal Joint y-axis Knee Angle from Table 30a	 f)T (VL, Joint y axis) from Table 31c

Table 43a-c shows how the both TA muscles very small and unstable amplitude, with a delay of approx. 10-12 % with respect to the HCG signal (a). A similarity T value close to.5 in the TA/Ankle (b), and a lower ankle and knee range of motions (c).Table 43 d-f shows unstable amplitude for VL muscles (d), low T value in both sides of VL/ Knee and VL/ ankle (f), and lower knee range of motion (e).

All results suggest that both limbs are affected. As a main observation the sEMG has very small changes in amplitude and smaller range of motion. The three methods seems to complement each other, adding more information about subject beahviors during the tests.

The consolidated results for case 5 F3-DM

- The Monofilament test (SWM) method report:
    - No physical calluses were found on sole areas.
    - Monofilament test failed: one right foot (1M), and three on left foot (1M, 3M).
- Transition-to-fatigue test results suggested that muscles affected during brisk walking:
    - Slow weaknesses: two in left limb (**GL** and **ES**), and one in the right **BF**.
- Natural Fuzzy logic method concludes that most affected muscles/joints in Sagittal Plane:
    - Muscles / Joint Ankle more affected are: TA, VL, **BF**, and **ES**.
    - Muscles / Joint Knee more affected are: TA, RF, BF, GM, and **ES**.
    - Muscles / Joint Hip more affected are: **GL**, and VL

Table 44 Muscle comparative analysis for case 5 F3-DM: GL a-c, and ES d-f.

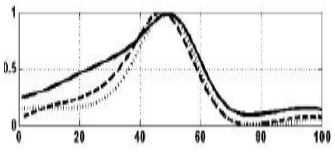
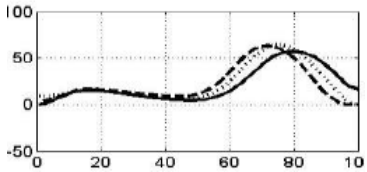
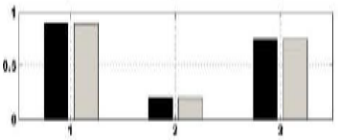
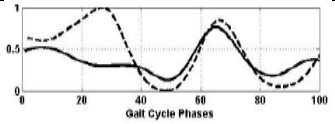
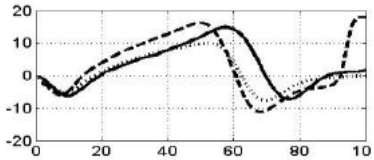
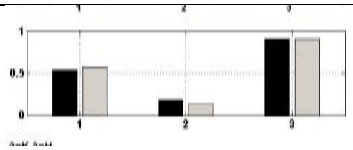
 a) GL sEMG from Table 29a	 b) Sagittal Joint y-axis Knee Angle from Table 30a	 c) T (GL, Joint y axis) from Table 31c
 d) ES sEMG from Table 29a	 e) Sagittal Joint y-axis Ankle Angle from Table 30a	 f)T (ES, Joint y axis) from Table 31c

Table 44a-c shows how the both GL muscles with a stretch wide wave (a). A similarity T value lower than .5 in the GL/Ankle (c), and a bigger ankle range of motion (b).Table 44 d-f shows an unstable amplitude for right ES (d), Low T value on both side for ES/ Knee and ES/

ankle (f) , and lower ankle range of motion in the left limb (e). General results suggest that the left limb is slightly more affected then the right limb.

The consolidated results for case 6 F4-DM

- The Monofilament test (SWM) method report:
    - No physical calluses were found on sole areas. She passed all tests
- Transition-to-fatigue test results suggested that muscles affected during brisk walking:
    - One muscle present fast weakness in the left limb BF. And two slow transition-to-fatigues in the right limb: VL and ES.
- Natural Fuzzy logic method concludes that most affected muscles/joints in Sagittal Plane:
    - Muscles / Joint Ankle more affected are: TA, and BF.
    - Muscles / Joint Knee more affected are present in all muscles.
    - Muscles / Joint Hip more affected are: SL, RF, BF, GM, and ES

Table 45 Muscle comparative analysis for case 6 F4-DM: VL a-c, and ES d-f.

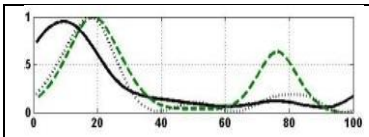
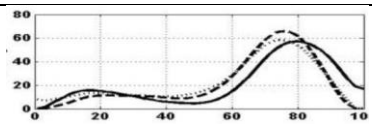
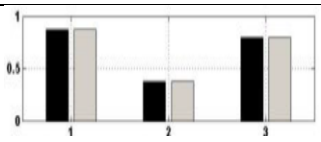
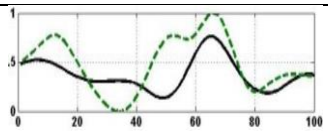
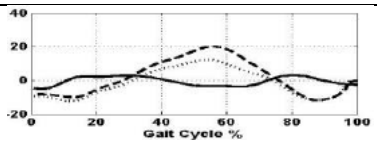
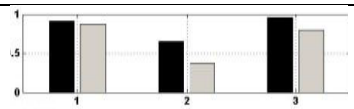
 a) VL sEMG from Table 33a	 b) Sagittal Joint y-axis Knee Angle from Table 34a	 c) T (VL, Joint y axis) from Table 35c
 d) ES sEMG from Table 33a	 e) Sagittal Joint y-axis Hip Angle from Table 34a	 f)T (ES, Joint y axis) from Table 35c

Table 45a-c shows how the both GL muscles with a stretch wide wave, a delayed of 10%, and an peak amplitude in the right limb (a). A similarity T value lower than .5 in the VL/Knee (c), and a bigger knee range of motion in the right knee (b).Table 45 d-f shows an erratic amplitude for right ES (d), lower left T value for ES/ left Knee (f) , and bigger Hip range of

motion (e). General results suggest that the right side is slightly more affected that left side. The three methods seem to complement each other on the results obtained.

The consolidated results for case 7 F5-DM

- The Monofilament test (SWM) method report:
    - No physical calluses were found on sole areas. She passed all tests.
- Transition-to-fatigue test results suggested that muscles affected during brisk walking:
    - Five slow muscles weakness are reported: one in right limb (RF), and four left limb: VL, RF, BF and GM.
- Natural Fuzzy logic method concludes that most affected muscles/joints in Sagittal Plane:
    - Muscles / Joint Ankle more affected are: TA, VL, RF, BF and ES.
    - Muscles / Joint Knee more affected are: RF, BF, and GM
    - Muscles / Joint Hip more affected are: SL, GL, VL, RF, and GM.

Table 46 Muscle comparative analysis for case 7 F4-DM: RF a-c, and TA d-f.

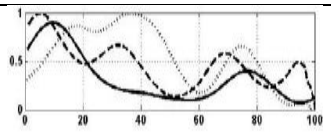
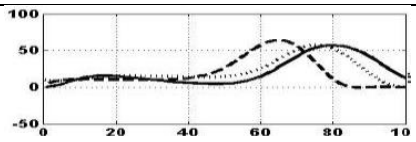
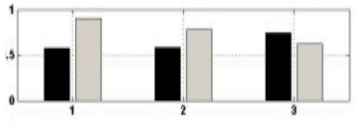
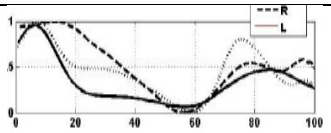
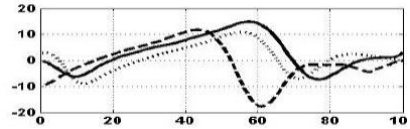
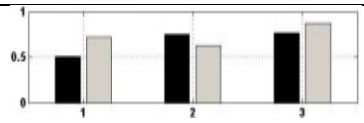
 a) RF sEMG from Table 37a	 b) Sagittal Joint y-axis Knee Angle from Table 38a	 c) T (RF, Joint y axis) from Table 39c
 d) TA sEMG from Table 37a	 e) Sagittal Joint y-axis Ankle Angle from Table 38a	 e) T (TA, Joint y axis) from Table 39c

Table 46a-c shows how the both RF muscles with erratic amplitude, and a delayed of approx. 10% (a). A similarity T value close than .5 in the RF/right Knee, and RF/right Ankle (c), and a bigger knee range of motion in the right side, and lower en the left knee (b).Table 46 d-f shows an instable amplitude for both TA (d), Lower left T value for TA/ right Ankle (f) , and

slower Ankle range of motion (e). General results suggest right side is slightly more affected that left side.

5.3 General conclusions

Two new methods based on information obtained during brisk walking are presented in this research; to help monitoring the Diabetic Mellitus type 2 in seven affected subjects:

- Transition-to-Fatigue limb muscle detection as a value for muscle energy consumption (Section 4.2)

- Natural fuzzy differential analysis to establish variances in the muscle/joint activation pattern and energy consumption on some limb muscles during brisk walking.(Section 4.3)

The results are then compared with the most popular physical method used the Semmes-Weinstein monofilament test (section 4.2.3), and a final suggestions are given to 7 DM subjects. The three methods seems to complement each other, adding more information about subject muscles behavior.

These results can be used as an additional exercise feedback besides the traditional blood sugar tracking (Section 3.1), adding more information over which muscles/joint of each limb need more attention to improve and help in BG control for DM type 2 subjects.

Chapter 6 Discussion and Contribution

Usually the most common method to visualize human muscle energy expenditure is based in thermal methods [129], or metabolic observations [130-131]. Thermal methods detect mechanical energy liberation during simulated muscle contractions. Metabolic detect calorimetry consumption as indirect parameter as oxygen uptake [130], or body fat using x-ray[131]. On this dissertation the new non-invasive method the **Dynamic muscle energy expenditure analysis** (Section 4.2.6), use a completely new different approach detecting muscle transition-to-fatigue. The same results were consistent with the second method **Natural fuzzy logic method for differential analysis in muscle/joint activation pattern** (Section 4.3) using a **Infer T equation muscles/joint in DM patients** (Section 4.3)**.** These results show more detailed information that describes the association, interaction or interconection between elements of muscle activities with the joint angles. And boths results methods were consolitaed with the traditional (from 1950) Semmes-Weinstein monofilament test widely used by physician.

Future work is promising for these novelty methods, that can be applied to study others body muscle beside the muscle limbs, and other illness besides DM.

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Curriculum Vita

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Jorge Garza-Ulloa earned his Bachelor of Engineering degree in Electronics and Communications Engineering Monterrey in 1977 from the Instituto Tecnologico de Monterrey, N.L. Mexico. He received his Master of Science degree in Electrical and Computer Engineering in 1980 from the University of Massachusetts at Amherst. In spring 2010 he joined the doctoral program.

Dr. Garza-Ulloa has been the recipient of numerous honors and awards including a University of Texas at El Paso Graduate School Research Award, Research Schellenger Foundation, and funds for his research from Stern Foundation.

While pursuing his degree, Dr. Garza-Ulloa worked as a research associate for the department of Electrical and Computer Engineering, and taught courses for the ECE UTEP department. He was a team leader and winner in the 2012 Camino Real Ventura International Competition.

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