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Promethean Fuzzy Model to Predict Diabetic Foot Ulcer

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Abstract

One of the most serious complications of diabetes is Diabetic foot. The incidence of diabetic foot increases equally on a rise of diabetic's increases and it is often ignored by people leading to a rise in major amputations. Diabetic foot disease diagnosis is done by using fuzzy logic and beneficial as it incorporates the knowledge and experience of physician into fuzzy sets and rules. In this paper, we propose a fuzzy expert system framework for diabetic foot which constructs large scale knowledge based diabetic foot system. The knowledge is constructed by using the fuzzification. Fuzzy verdict mechanism uses triangular membership function with mamdanis inference. Defuzzification method is adopted to convert the fuzzy values into crisp values.

Keywords*: amputation, diabetic foot ulcer, fuzzy inference system, neuropathy*

1. Introduction

Over a period, diabetics will affect the organs of human and based on the organs being affected, they are classified into four types of neuropathy and they are Peripheral Neuropathy affects arms, hands and toe. Organs like eyes, ears, chest and abdomen are affected by Focal Neuropathy. Proximal Neuropathy affects hip, buttocks and thighs. Autonomic Neuropathy affects lungs, sweat glands and heart.

1.1. Diabetic Foot Problems

Some of the complications of Diabetic Neuropathy are 1. Loss of Limbs Lower: leg or toe gets amputated because of infection caused due to the unnoticed ulcer.2. Charcot Joint: Swelling and insensitivity due to damage of nerve makes the joints to deteriorate. 3. Ulcer tract infections and urinary incontinence: Urinary bladder controlling nerve gets damage leading to infection. 4. Hypoglycaemia unawareness: High heart beat due to sugar drop. 5. Low blood pressure: Fainting due to pressure drop caused by nerve damage of blood circulation. 6. Digestive problem: 7. Sexual Dysfunction: Men (erectile) and women (lubrication) problem 8. Increase or decrease sweating: Temperature regulation due to damage of sweat gland.

People with diabetes are more prone to infection. They can also develop neuropathy (damaged nerves) or peripheral vascular disease (blocked arteries) of the legs and either can lead to foot ulceration. Infection and foot ulceration, alone or in combination, often lead to amputation. This happens to about 3000 people in Australia each year. Neuropathy and peripheral vascular disease can also cause distressing pain in the lower limbs.

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Table 1. Common Diabetic Foot Problems

Common Diabetic foot Problems								
Ref No	**Problem**	**Description**	**Diagram**		**Ref No**	**Problem**	**Description**	**Diagram**
[23]	Athlete foot	Cracking due to fungus which allows the germs to enter in the foot which leads to infection.			[28]	Blister	Unfitted shoe causes foot to rub some parts of shoes which causes blister.	
[24]	Fungal Infection of Nails	Nails become thick and discoloured due to fungus infection in nail which may lead to infection of nail.			[29]	Dry Skin	Germs enter through cracks in skin which are very dry.	
[25]	Calluses	Unfitted shoe and uneven weight distribution causes hard skin in foot.			[30]	Foot Ulcer	Infection due to both nerve and blood vessel damage	
[26]	Corns	Toes bone area will form a hard skin due to shoe pressure.			[31]	Hammertoes	Weakened muscles make the toe to bent and make it shorter.	
[27]	BUnion	Usage of high healed shoes result in more pressure in big toe which results in joining of big toe with second toe which is burning.			[32]	Ingrown Toenails	Nails which are not trimmed can enter or grow in to the skin which causes pain in the edges of nail	

2. Literature Review

Estimates the factors that independently contribute to Diabetic foot ulcer on lower extremity amputation in [4] and mortality rate with 644 subjects. Age, gender, diabetes duration, complication count and previous LEA ere determined as the risk variables for lower extremity amputation and mortality. The study also suggests that DFU prevention is the better way for survival and diminished morbidity with diabetic patients.

Foot shape of 2939 diabetic subjects were assessed [5] for hammer toes, claw toes, hallux limitus, hallux valgus, bony prominences, Charcot deformity, metatarsal heads, plantar callus, foot type, ankle mobility, muscle atrophy and neuropathy. Foot ulcers were found more in the locations on foot such as hallux and toes. Findings of the study revealed that foot deformities such as hammer/claw toes, bony prominences were the important risk factors for ulceration. Type 1 DM, greater duration of DM, insulin use, neuropathy, history of amputation, and history of ulceration were the demographic and general health parameters related to ulceration. Foot deformities like pes-cavus and pes-planus types are not that significant.

In [6] 130 patients with diabetic foot osteomyelitis were analyzed and found that 66.9% of the patients were healed with antibiotic treatment alone and 13.9% needed amputation. Study also found that mostly death, amputation and failure to heal were associated with the presence of MRSA. To predict osteomyelitis accurately the clinical practice includes ulcers with visible bone, sausage deformity or probing to bone. In the absence of severe infection and critical ischemic, medical treatment instead of surgery is practiced for osteomyelitis.

A review [7] is presented on advancement in wound dressing for diabetic patients. The main factors that delay diabetic wound repair are Diabetic neuropathy, peripheral vascular disease, and abnormal cellular and cytokine/chemokine activity. Study states that no existing dressing fulfils all the requirements associated with DFU treatment and the choice of the correct dressing depends on the wound type and stage, injury extension, patient condition and the tissues involved. Different types of wound dressings that can be used for DFU treatment differs on their application modes, materials, shape and on the methods employed for production. Dressing materials can include natural, modified and synthetic polymers, films, foams, hydrocolloids and hydrogels.

Patient and professional delay in patients with diabetic foot ulcers is discussed in [8]. Duration of patient delay, professional delay and the overall treatment delay were measured. The time interval between ulcer detection by the patient and the first consultation of a health care professional is defined as the patient delay. The time interval between the first consultation of a health care professional and the first consultation of a participating podiatrist is defined as the professional delay. Overall treatment delay is the sum of patient delay and professional delay. Results show that there is a substantial relationship between duration of professional delay, duration of treatment delay and duration of podiatric treatment.

Use Clustering and classification technique [9] to determine the regional peak plantar pressures of diabetic feet. Foot ulceration is highly associated with plantar pressure. Plantar pressure distribution helps to identify diabetic patients with high risk of foot ulcer and providing of suitable design insole. As the total number of cluster increases, the accuracy of clustering and classification between subsets of plantar pressure decreases. 93% was the success rate of for two clusters and 63% for ten clusters. This analysis discloses that the inconsistency of the regional peak plantar pressure distributions serves as a guide for the preventative assessment and prevention of diabetic foot ulcers in diabetic patients.

Nord-Trøndelag Health Survey (HUNT3), Norway [10] investigated the associated factors, healing time and the proportion of people with diabetes having foot ulcer. The study associated the following factors with diabetic foot ulcer are age, gender, waist circumference, insulin use and macro vascular complications. The study presented that 7.4% conveyed a history of diabetes-related foot ulcer requiring more than three weeks healing.

Inspected the association between site-specific peak plantar pressure (PPP) and ulcer risk. Peak pressure and the pressure–time integral were calculatedin [11]. Peak pressure is the highest pressure sensed within the mask. The pressure–time integral was calculated as the summation of the total peak pressure experienced in a given location per each time unit; it is a measure of pressure dosage. The study examining the association between baseline plantar pressure at a specific location beneath the foot and the subsequent development of a plantar ulcer at that same location. Results shows a significantly higher peak pressure at baseline for diabetic subjects who developed metatarsalhead ulcers, but this relationship did not hold for other locations beneath the foot like the heel and hallux, where higher baseline plantar pressure was not predictive of ulceration.

The prevalence of diabetic foot complications and three types of risk factors like demographic, diabetes specific and biological are identified [12]. Age, sex, race/ethnicity, education, income, and smoking comprise the demographic variables. Type of diabetes, duration of diabetes, insulin use, and hemoglobinA1c comprises the diabetes specific variables. Body mass index, systolic and diastolic blood pressure, low density lipoprotein cholesterol, triglycerides, history of micro vascular complications, history of macro vascular complications, and Charlson co morbidity index comprise the biological variables.

In predicting amputation and hospital length of stay in diabetic patients [13] with acute foot ulceration, baseline levels of acute-phase reactants like white blood cells (WBC), C-reactive protein(CRP), erythrocyte sedimentation rate (ESR) and increased Wagner grade were used.

[14] Identified the most causal sequence leading to foot ulceration and amputation in diabetic patients. The most common causal sequence leading to foot ulceration includes neuropathy, minor trauma, and deformity. The most frequent causal sequence leading to diabetes related amputation are minor trauma, ulceration, and faulty wound healing with neuropathy, ischaemia with gangrene and infection. Once an ulcer has developed, infection and peripheral arterial disease are the major causes of amputation. Trauma and wound infection were found to be consistent factors.

The independent variables to predict major lower extremity amputation, minor lower extremity amputation and non-amputation are Demographic characteristics, laboratory data, disease history, ankle brachial pressure index (ABI) and Wagner classification. Risk factors for LEA in different Wagner grades were further analyzed in [15]. The most of the recognized risk factors were only found in wagner grade 3.High grade of Wagner classification that is above grade 3 increases the risk of lower extremity amputation.

The study [16] evaluated the risk factors for amputations and the incidence of amputation among patients with diabetic foot ulcer (DFU). Common risk factors which influence amputation were peripheral vascular disease (PVD), white blood cell (WBC) counts, neutrophil granulocyte percentage, hemoglobin, triglyceride, cholesterol, LDL-C, HDL-C andserum sCRP.

3. Proposed Method

This paper proposes a model for predicting the risk DFU (Diabetic Foot Ulcer) using independent agents for different input parameters and a combination of fuzzy expert systems. The model has basically two parts. The first part consists of agents who respectively work on input parameters. The second part, Fuzzy system consists of multi-layered architecture consisting of three FISs (Fuzzy Inference Systems) in the first layer. The input of second layer has output from the first layer and this Fuzzy inference system used knowledge base to give the output.

System Architecture:

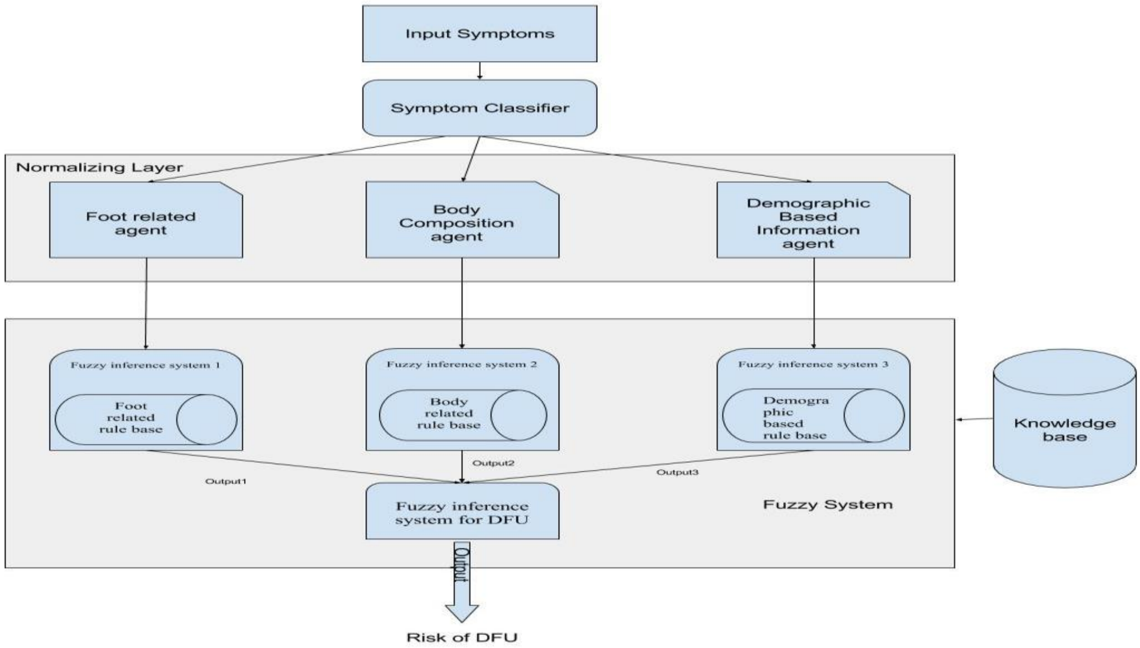

Figure 1. Overview of the Model

Basically, the model is supposed to take input from in the form of values consisting of factors like age, duration of diabetes, Systolic blood pressure, and diastolic blood pressure. These input parameters are categorized based on the keywords the agent sends the input values to proper fuzzy inference systems for calibration. This agent is known as symptom classification agent.

Symptom Classifier:

Based on algorithms discussed in survey done by Aggarwal [18] and classifiers discussed by Rajeswari [1], a classifier was implemented to select important attributes from a large set of attributes. By using data mining techniques and reducing the attributes, the accuracy of classifier can be significantly improved. The mentioned classifier was modified to separate input attributes in three different classes, namely: foot related, body related and demographic related. This classifier then sends the attributes to the respective agent.

Normalizing layer:

The system subsequently has three agents, namely, foot related agent, body composition agent and demographic based agent. Foot related agent is concerned with factors like condition of foot, callus of foot, etc. Second agent, Body composition agent takes care of the parameters like blood pressure, duration of diabetes, age, co-morbidity, etc and the third agent works on attitude of patient (whether the patient is favorable while taking the medications and therapies), knowledge of diabetes that patient has, etc. The agents have the task of converting the values to fuzzy value from crisp and also calibrating according to the fuzzy inference systems which will work on them. For example duration of diabetes is converted into an input which varies from zero to one. The values from these agents are transferred to respective fuzzy expert systems, which forms the first layer.

Fuzzy System:

The fuzzy inference systems in the first layer are named (Fuzzy Inference System one) FIS1, FIS2 and FIS3. Each of these systems has its own rule base, which is used to give an intermediate output. The rules are generated from a knowledge based taken from domain experts. This output is used as input for another fuzzy inference system which is used to give the output of risk of DFU. This forms the second layer of the fuzzy system.

Inference Systems:

Based on the rules and input, the risk of DFU is evaluated. These rules may have different weights and priorities depending on the importance of the factor in deciding the risk of Ulcer. For example, the weight of callus of foot is higher than age, because the risk is much higher for a person who has callus present than a person who has age greater the 45.

Mamdani Inference system was used for its intuitiveness and widespread acceptance. Centroid method is used for de-fuzzification. MATLAB FIS editor is used to select the various parameters. "AND" method used is minimum (min), "OR" method used is maximum (max), implication method used is minimum(min) and aggregation method used is maximum(max).

Fuzzy Inference System 1:

Table 2. FIS1

Fuzzy inference system 1			
MFN	**Membership function**	**MFN**	**Membership function**
Callus is present	$\mu_{present} = \begin{cases} \frac{9.5 - x}{9.5}, & 0 < x \leq 9.5 \\ 0, & x > 9.5 \end{cases}$	Sensory is Present	$\mu_{present} = \begin{cases} 0, & x < 1 \\ \frac{x - 1}{9}, & 1 < x \leq 10 \end{cases}$
Callus is absent	$\mu_{absent} = \begin{cases} 0, & x < 9.5 \\ \frac{x - 0.95}{0.05}, & 9.5 < x \leq 1 \end{cases}$	Sensory is Absent	$\mu_{absent} = \begin{cases} \frac{2 - x}{2}, & 0 < x \leq 2 \\ 0, & x > 2 \end{cases}$
Feet are cracked	$\mu_{cracked} = \begin{cases} \frac{0.777 - x}{0.777}, & 0 < x \leq 0.777 \\ 0, & x > 0.777 \end{cases}$	Ill fitting shoes	$\mu_{true} = \begin{cases} \frac{9.25 - x}{9.25}, & 0 < x \leq 9.25 \\ 0, & x > 9.25 \end{cases}$
Feet are healthy	$\mu_{healthy} = \begin{cases} 0, & x < 0.777 \\ \frac{x - 0.777}{0.223}, & 0.777 < x \leq 1 \end{cases}$	Proper shoes	$\mu_{false} = \begin{cases} 0, & x < 0.925 \\ \frac{x - 0.925}{0.075}, & 0.925 < x \leq 1 \end{cases}$

The input parameters considered are:

1. *Callus of foot:* The value indicates the severity of callus of on foot of the patients. The value varies from 0 to 10.
2. *Condition of feet:* This parameter has membership functions for cracked feet and healthy feet. The range is 0 to 1.
3. *Sensory loss to vibration:* Sensory loss to vibration is important factor in predicting the risk of DFU. The value varies from 0 to 1.
4. *Condition of footwear:* The footwear used by patient also taken in consideration to calculate risk of DFU. Range 0-10.

Fuzzy Inference System 2

Table 3. FIS2

Fuzzy inference system 2			
M.F.N	**Membership function**	**MFN**	**Membership function**
Diabetic duration: More than a decade	$\mu_{>10} = \begin{cases} 0, & x < 0.1046 \\ \frac{x - 0.1046}{0.8954}, & 0.1046 < x \leq 1 \end{cases}$	Systolic: Normal	$\mu_{underweight} = \begin{cases} 0, & x < 100 \\ \frac{x - 100}{10}, & 100 < x \leq 110 \\ \frac{120 - x}{10}, & 110 < x \leq 120 \\ 0, & 120 < x \end{cases}$
Diabetic duration: Less than a decade	$\mu_{<10} = \begin{cases} \frac{0.1046 - x}{0.1046}, & 0 < x \leq 0.1046 \\ 0, & 0.1046 < x \end{cases}$	Systolic:Pre-hypertension	$\mu_{pre-hyp} = \begin{cases} 0, & x < 120 \\ \frac{x - 120}{4.5}, & 120 < x \leq 124.5 \\ \frac{139 - x}{14.5}, & 124.5 < x \leq 139 \\ 0, & 139 < x \end{cases}$
Co-morbidity present	$\mu_{co-morbid} = \begin{cases} \frac{0.846 - x}{2}, & 0 < x \leq 0.846 \\ 0, & 0.846 < x \end{cases}$	Systolic: High stage 1	$\mu_{High1} = \begin{cases} 0, & x < 130 \\ \frac{x - 130}{16.7}, & 130 < x \leq 146.7 \\ \frac{159 - x}{12.3}, & 146.7 < x \leq 159 \\ 0, & 159 < x \end{cases}$
Absent	$\mu_{healthy} = \begin{cases} 0, & x < 0.846 \\ \frac{x - 0.846}{0.154}, & 0.846 < x \leq 1 \end{cases}$	Systolic: High stage 2	$\mu_{>High2} = \begin{cases} 0, & x < 160 \\ 1, & 160 < x \end{cases}$
BMI: Overweight	$\mu_{overweight} = \begin{cases} 0, & x < 22.5 \\ \frac{x - 22.5}{1.5}, & 22.5 < x \leq 24 \\ \frac{26 - x}{2}, & 24 < x \leq 26 \\ 0, & 26 < x \end{cases}$	Diastolic Normal	$\mu_{normal} = \begin{cases} 0, & x < 50 \\ \frac{x - 50}{30}, & 50 < x \leq 80 \\ 0, & 100 < x \end{cases}$
BMI: Medium	$\mu_{medium} = \begin{cases} 0, & x < 18 \\ \frac{x - 18}{3}, & 18 < x \leq 21 \\ \frac{23.5 - x}{2.5}, & 21 < x \leq 23.5 \\ 0, & 23.5 < x \end{cases}$	Diastolic Pre-hypertension	$\mu_{pre-hyp} = \begin{cases} 0, & x < 80 \\ \frac{x - 80}{4.5}, & 80 < x \leq 84.5 \\ \frac{90 - x}{5.5}, & 84.5 < x \leq 90 \\ 0, & 90 < x \end{cases}$
Age: Younger than 45	$\mu_{<45} = \begin{cases} \frac{0.252 - x}{0.252}, & 0 < x \leq 0.252 \\ 0, & 0.252 < x \end{cases}$	Diastolic High stage 1	$\mu_{High1} = \begin{cases} 0, & x < 90 \\ \frac{x - 90}{4.5}, & 90 < x \leq 94.5 \\ \frac{100 - x}{5.5}, & 94.5 < x \leq 100 \\ 0, & 100 < x \end{cases}$
Age: Older than 45	$\mu_{>45} = \begin{cases} 0, & x < 0.23 \\ \frac{x - 0.23}{0.77}, & 0.23 < x \leq 1 \end{cases}$	Diastolic High stage 2	$\mu_{>High2} = \begin{cases} 0, & x < 100 \\ 1, & 100 < x \end{cases}$

The input parameters considered are:

1. *Duration of diabetes:* The value indicates normalized value. The value varies from 0 to 1.
2. *Co-morbidity:* This parameter has membership functions for whether the patient has some other disease or not. The range is 0 to 1.
3. *BMI:* BMI is important factor in predicting the risk of DFU. The value varies from 16 to 26.
4. *Age:* The age of patient is also taken in consideration to calculate risk of DFU. The membership function based on whether the patient is older the 45 years or not. Range is 0-1.
5. *Systolic Blood Pressure:* This factor represents the upper limit of blood pressure. The range is 100 to 160.
6. *Diastolic Blood Pressure*: This factor represents the lower limit of blood pressure. The range is 50 to 100.

Fuzzy Inference System 3: -

Table 3. FIS3

Fuzzy inference system 3					
MFN	**Membership function**		**MFN**	**Membership function**
Occupation: Farmer	$\mu_{farmer} = \begin{cases} \frac{0.947 - x}{0.947}, & 0 < x \leq 0.947 \\ 0, & 0.947 < x \end{cases}$		Attitude: Unfavorable	$\mu_{unfavorable} = \begin{cases} \frac{0.763 - x}{0.763}, & 0 < x \leq 0.763 \\ 0, & 0.763 < x \end{cases}$
Government Employee	$\mu_{govemp} = \begin{cases} 0, & x < 0.807 \\ \frac{x - 0.807}{0.193}, & 0.807 < x \leq 1 \end{cases}$		Attitude: Favorable	$\mu_{favorable} = \begin{cases} 0, & x < 0.703 \\ \frac{x - 0.703}{0.297}, & 0.703 < x \leq 1 \end{cases}$
Area: Rural	$\mu_{rural} = \begin{cases} \frac{8.12 - x}{8.12}, & 0 < x \leq 8.12 \\ 0, & 8.12 < x \end{cases}$		Knowledge: Poor	$\mu_{poor} = \begin{cases} \frac{7.029 - x}{7.029}, & 0 < x \leq 7.029 \\ 0, & 7.029 < x \end{cases}$
Area: Urban	$\mu_{urban} = \begin{cases} 0, & x < 7.52 \\ \frac{x - 7.52}{2.48}, & 7.52 < x \leq 10 \end{cases}$		Knowledge: Good	$\mu_{good} = \begin{cases} 0, & x < 5.45 \\ \frac{x - 5.45}{4.55}, & 5.45 < x \leq 10 \end{cases}$

The input parameters considered are:

1. *Occupation:* The value indicates the occupation of the patients. The value varies from 0 to 1.
2. Area of residence: This parameter has membership functions for rural and urban. The range is 0 to 10.
3. Attitude towards treatment: Attitude of patient to get treatment is also taken in consideration and the value varies from 0 to 1.
4. Knowledge about diabetes: Knowledge possessed by patient is measured on the scale of 0-10.

w1 to w6 are the weight ages assigned depending upon the importance of factor.

Output 1 = (w1*Callus) + (w2*Cracked feet) + (w3*sensory loss feet) + (w4*ill-fitting shoes)

Output 2 = (w1*Diastolic bp) + (w2*Systolic bp) + (w3*age) + (w4*BMI) + (w5*co-morbidity) + (w6*diabetes duration)

Output 3 = (w1*Occupation) + (w2*areas) + (w3*attitude) + (w4*Knowledge)

3.1 Fuzzy Inference System 1

Fuzzy Rules: Each fuzzy inference system has its own rule base. The rules are derived from the knowledge gained from experts in the medical field. Some of the rules of first fuzzy system concerning about the body related issues are:

Rules in verbose format: If (callus of foot is present) and (Ill-fitting shoes is True) and (Dry feet is true) then (Risk_of_DFU is High)
If (callus of foot is present) and (Ill-fitting shoes is True) and (Sensory loss to vibration is present) then (Risk_of_DFU is High)
If (Ill-fitting shoes is True) and (Dry feet is true) and (Sensory loss to vibration is present) then (Risk_of_DFU is High)
If (Dry feet is true) and (Sensory loss to vibration is present)and (callus of foot is present) then (Risk_of_DFU is High)
If (callus of foot is present) and (Ill-fitting shoes is False) and (Dry feet is true) then (Risk_of_DFU is Medium)
If (callus of foot is present) and (Ill-fitting shoes is False) and (Sensory loss to vibration is present) then (Risk_of_DFU is Medium)
If (Ill-fitting shoes is True) and (Dry feet is False) and (Sensory loss to vibration is present) then (Risk_of_DFU is Medium)
If (Dry feet is true) and (Sensory loss to vibration is absent)and (callus of foot is present) then (Risk_of_DFU is Medium)
If (callus of foot is present) and (Ill-fitting shoes is true) and (Dry feet is false) then (Risk_of_DFU is Medium)
If (callus of foot is present) and (Ill-fitting shoes is true) and (Sensory loss to vibration is absent) then (Risk_of_DFU is Medium)
If (Ill-fitting shoes is True) and (Dry feet is True) and (Sensory loss to vibration is absent) then (Risk_of_DFU is Medium)
If (Dry feet is true) and (Sensory loss to vibration is present)and (callus of foot is absent) then (Risk_of_DFU is Medium)
If (callus of foot is present) and (Ill-fitting shoes is False) then (Risk_of_DFU is Low)
If (callus of foot is present) and(Dry feet is False) then (Risk_of_DFU is Low)
If (callus of foot is present) and(Sensory loss to vibration is Absent) then (Risk_of_DFU is Low)
If (Ill-fitting shoes is True) and(Dry feet is False) then (Risk_of_DFU is Low)
If (Dry feet is true) and (Sensory loss to vibration is Absent) then (Risk_of_DFU is Low)
If (Ill-fitting shoes is True) and (callus of foot is Absent) then (Risk_of_DFU is Low)
If (Dry feet is True) and (callus of foot is Absent) then (Risk_of_DFU is Low)
If (Sensory loss to vibration is Present) and(callus of foot is Absent) then (Risk_of_DFU is Low)

3.2. Fuzzy Inference System 2

Fuzzy Rules:

Each fuzzy inference system has its own rule base. The rules are derived from the knowledge gained from experts in the medical field. Some of the rules of first fuzzy system concerning about the body related issues are:

Rules in verbose format: If (Duration of Diabetes is high) and (Co- morbidity is Yes) and (BMI is high) and (age is high) then (Risk_of_DFU is High)
If (Duration of Diabetes is high) and (Co- morbidity is Yes) and (BMI is high) and (Systolic is high) then (Risk_of_DFU is High)
If (Duration of Diabetes is high) and (Co- morbidity is Yes) and (BMI is high) and (Diastolic is high) then (Risk_of_DFU is High)
If (Co- morbidity is Yes) and (BMI is high)and (age is high) and (Diastolic is high)then (Risk_of_DFU is High)
If (Co- morbidity is Yes) and (BMI is high)and (age is high) and (Systolic is high)then (Risk_of_DFU is High)
If (Duration of Diabetes is Low) and (Co- morbidity is No) and (BMI is high) and (age is high) then (Risk_of_DFU is medium)
If (Duration of Diabetes is Low) and (Co- morbidity is No) and (BMI is high) and (Systolic is high) then (Risk_of_DFU is medium)
If (Duration of Diabetes is low) and (Co- morbidity is no) and (BMI is high) and (Diastolic is high) then (Risk_of_DFU is medium)
If (Co- morbidity is no) and (BMI is low)and (age is high) and (Diastolic is high)then (Risk_of_DFU is medium)
If (Co- morbidity is no) and (BMI is low)and (age is high) and (Systolic is high)then (Risk_of_DFU is medium)
If (Duration of Diabetes is high) and (Co- morbidity is Yes) and (BMI is low) and (age is low) then (Risk_of_DFU is medium)
If (Duration of Diabetes is high) and (Co- morbidity is Yes) and (BMI is low) and (Systolic is low) then (Risk_of_DFU is medium)
If (Duration of Diabetes is high) and (Co- morbidity is Yes) and (BMI is low) and (Diastolic is low) then (Risk_of_DFU is medium)
If (Co- morbidity is Yes) and (BMI is high)and (age is low) and (Diastolic is low)then (Risk_of_DFU is medium)
If (Co- morbidity is Yes) and (BMI is high)and (age is low) and (Systolic is low)then (Risk_of_DFU is medium)
If (Duration of Diabetes is low) and (Co- morbidity is no) and (BMI is low) and (age is high) then (Risk_of_DFU is low)
If (Duration of Diabetes is low) and (Co- morbidity is no) and (BMI is low) and (Systolic is high) then (Risk_of_DFU is low)
If (Duration of Diabetes is low) and (Co- morbidity is no) and (BMI is low) and (Diastolic is high) then (Risk_of_DFU is low)
If (Co- morbidity is no) and (BMI is low)and (age is low) and (Diastolic is high)then (Risk_of_DFU is low)
If (Co- morbidity is no) and (BMI is low)and (age is low) and (Systolic is high)then (Risk_of_DFU is low)

3.3. Fuzzy Inference System 3

Fuzzy Rules:

Each fuzzy inference system has its own rule base. The rules are derived from the knowledge gained from experts in the medical field. Some of the rules of first fuzzy system concerning about the body related issues are:

Rules in Verbose format: If (Occupation is farmer) and (Area is rural) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is High)
If (Occupation is farmer) and(Area is rural) and (Attitude is unfavorable) then (Risk_of_DFU is High)
If (Area is rural) and (Attitude is unfavorable) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is High)
If (Attitude is unfavorable) and (Knowledge about Diabetes is poor) and(Occupation is farmer) then (Risk_of_DFU is High)
If (Occupation is farmer) and (Area is Urban) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is Medium)
If (Occupation is farmer) and(Area is Urban) and (Attitude is unfavorable) then (Risk_of_DFU is Medium)
If (Area is Urban) and (Attitude is unfavorable) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is Medium)
If (Attitude is favorable) and (Knowledge about Diabetes is poor) and(Occupation is farmer) then (Risk_of_DFU is Medium)
If (Area is Urban) and (Attitude is unfavorable) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is Medium)
If (Occupation is Non-farmer) and (Area is rural) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is Medium)
If (Occupation is Non-farmer) and(Area is Rural) and (Attitude is unfavorable) then (Risk_of_DFU is Medium)
If (Area is Rural) and (Attitude is favorable) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is Medium)
If (Attitude is unfavorable) and (Knowledge about Diabetes is good) and(Occupation is farmer) then (Risk_of_DFU is Medium)
If (Attitude is unfavorable) and (Knowledge about Diabetes is good) and(Area is Rural) then (Risk_of_DFU is Medium)
If (Occupation is Non-farmer) and (Area is Urban) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is low)
If (Occupation is Non-farmer) and(Area is Urban) and (Attitude is unfavorable) then (Risk_of_DFU is low)
If (Area is Urban) and (Attitude is favorable) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is low)
If (Attitude is favorable) and (Knowledge about Diabetes is good) and(Occupation is farmer) then (Risk_of_DFU is low)
If (Area is rural) and (Attitude is favorable) and(Knowledge about Diabetes is poor) then (Risk_of_DFU is low)
If (Attitude is favorable) and (Knowledge about Diabetes is good) and(Occupation is farmer) then (Risk_of_DFU is low)

3.4. Results

The following are control surfaces for first layer outputs. The 3D representation has two input parameters and the third parameter shows the value of risk.

3.4.1. Results for FIS 1

Table 5. Values of Output 1

Serial number	Callus of foot value	Condition of footwear	Condition of feet	Sensory loss to vibration	Risk of DFU	Risk of DFU (High, Med, Low)
1	2.8	1.46	0.22	5	0.86	High
2	7.35	1.46	0.22	5	0.843	
3	8.86	4.54	0.447	6.54	0.841	
4	0.945	9.46	0.447	6.54	0.543	Medium
5	8.56	9.46	0.174	4.23	0.5	
6	8.56	10	0.902	4.23	0.438	
7	6.74	7.31	0.917	10	0.464	
8	9.62	10	0.902	4.23	0.164	Low
9	10	10	0.841	10	0.13	
10	6.74	9	0.841	10	0.246	

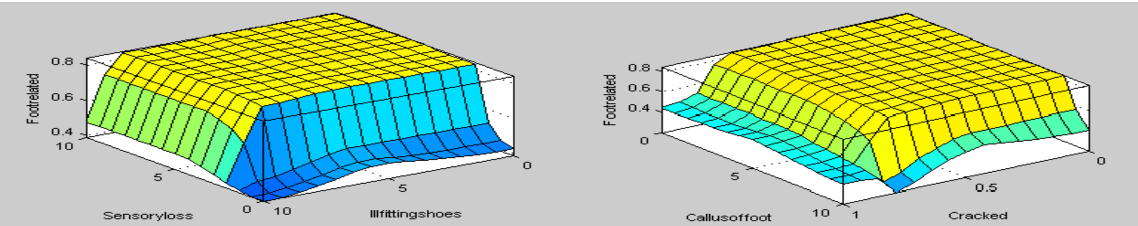

Figure 2. Control Surfaces of Sensory Loss to Vibration and Ill Fitting Shoes in First Figure and Control Surface of Callus of foot and Condition of feet in the Second Figure (Both Relating to Foot Fuzzy System)

The above figure consists of control surfaces created by input parameters from the FIS1. The first control surface has the input parameters are Ill fitting shoes and sensory loss to vibration. The graph is mostly showing risk as high because these inputs have a great effect if ulcer even if present in small values. Similarly, the second control surface has input parameters as callus and condition of feet (grading based on how much the feet are cracked). The graph shows low value if the callus is absent (*i.e.* having low value).

3.4.2. Results for FIS 2

Table 6. Values of Output 2

Serial number	Duration of diabetes	Co-morbidity	BMI	Age	Systolic Blood Pressure	Diastolic Blood Pressure	Risk of DFU	Risk of DFU (High, Medium, Low)
1	0.5	0.5	21	0.5	135	85	0.831	High
2	0.5	0.8133	16.42	0.5	135	85	0.807	
3	0.811	0.3072	24.13	0.5	109	105.1	0.856	
4	0.7744	0.5361	17.27	0.286	164.6	98.23	0.81	
5	0.811	0.994	24.13	0.5	109	105.1	0.5	Medium
6	0.07927	0.933	18.47	0.054	111.5	87.99	0.432	
7	0.06707	0.9337	21.6	0.5305	113.2	85.43	0.413	
8	0.07927	0.9337	18.47	0.054	108.1	77.74	0.182	Low
9	0.07927	0.9337	18.47	0.5305	112.4	111.9	0.25	
10	0.06707	0.9337	21.6	0.5305	112.4	111.9	0.164	

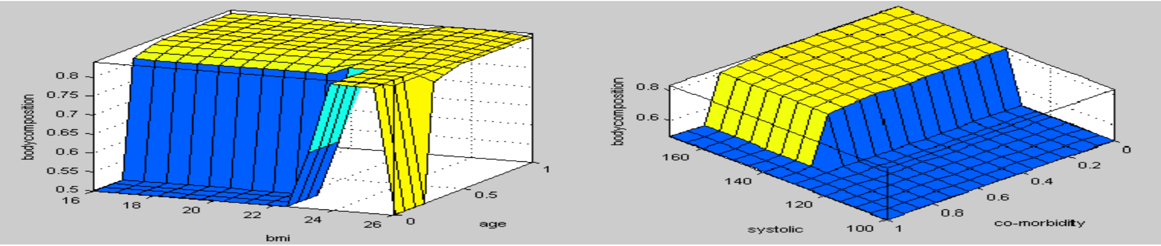

Figure 3. Control Surfaces of Age and BMI In First Figure and Control Surface of Systolic Blood Pressure and Co-Morbidity In the Second Figure (Both Relating To Body Fuzzy System)

The above shows control surfaces obtained after comparing input parameters from the FIS2 (*i.e.* Fuzzy Inference System relating to body). The first graph shows that the risk is low when the BMI (Body Mass Index) is low and sharply increases when BMI increases. The second control surface is plotted with co-morbidity, systolic blood pressure and risk on its axes. The graph shows low risk when the systolic blood pressure is low and co-morbidity is low.

3.4.3. Results for FIS 3

Table 7. Values of Output 3

Serial number	Occupation	Area	Attitude	Knowledge	Risk of DFU	Risk of DFU (High, Medium, Low)
1	0	0	0.727	2.24	0.741	High
2	0	0	0.715	0.517	0.787	
3	0.5	5	0.5	5	0.598	Medium
4	0.5	9	0.5	8.7	0.5	
5	0.5	0	0	2.24	0.624	
6	0.937	9	0.238	0	0.398	
7	0.937	9	0.552	4.77	0.408	
8	0.144	2.97	0.413	1.32	0.621	
9	0.937	9	0.238	0	0.398	
10	0.937	9	0.971	1.78	0.161	Low

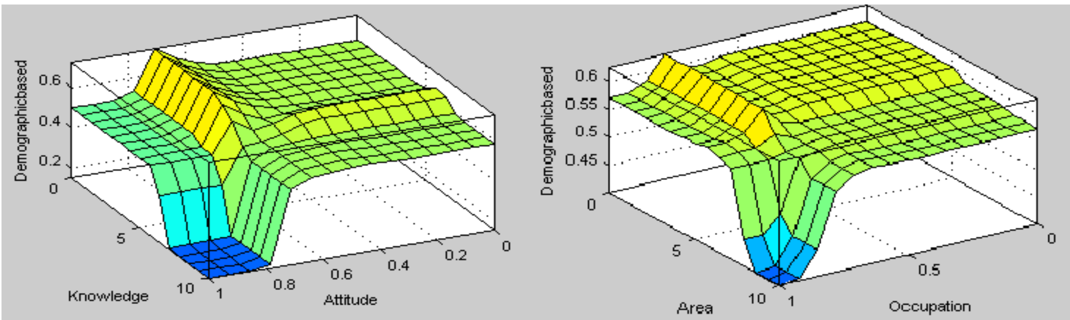

Figure 4. Control Surfaces of Knowledge and Attitude in First Figure and Control Surface of Area and Occupation in the Second Figure (Both Relating To Demographic Fuzzy System)

Above figure contains two control surfaces. The first surface is plotted with Knowledge of patient, Attitude of patient and the risk. Surface dips down when the knowledge of patient is good (*i.e*. the value is greater than 7) and attitude is tending to favorable. The second control surface comprises of area of residence, occupation and risk. Similar to the first control surface, the graph dips down if the input parameters are good and shows higher risk if the inputs are indicating high risk of ulcer.

3.5. Second Layer Fuzzy Inference System

The fuzzy inference system of the second layer takes input from the first layer namely, the output of FIS 1(Foot related inference system), FIS 2(Body related inference system), FIS 3(Demographic based inference system) and finally gives the Risk of DFU. The system gives output as severe risk, Moderate risk and Low risk.

If (Foot related is high) and (Body composition is high) and (Demographic information is high) then (Risk_of_DFU is Severe)
If (Foot related is high) and (Body composition is Medium) and (Demographic information is high) then (Risk_of_DFU is Severe)
If (Foot related is high) and (Body composition is high) and (Demographic information is Medium) then (Risk_of_DFU is Severe)
If (Foot related is Medium) and (Body composition is high) and (Demographic information is high) then (Risk_of_DFU is Severe)
If (Foot related is medium) and (Body composition is medium) and (Demographic information is high) then (Risk_of_DFU is Moderate)
If (Foot related is medium) and (Body composition is low) and (Demographic information is high) then (Risk_of_DFU is Moderate)
If (Foot related is medium) and (Body composition is medium) and (Demographic information is Medium) then (Risk_of_DFU is Moderate)
If (Foot related is low) and (Body composition is medium) and (Demographic information is high) then (Risk_of_DFU is Moderate)
If (Foot related is low) and (Body composition is medium) and (Demographic information is medium) then (Risk_of_DFU is Moderate)
If (Foot related is low) and (Body composition is low) and (Demographic information is medium) then (Risk_of_DFU is low)
If (Foot related is low) and (Body composition is medium) and (Demographic information is low) then (Risk_of_DFU is low)
If (Foot related is medium) and (Body composition is low) and (Demographic information is low) then (Risk_of_DFU is low)
If (Foot related is low) and (Body composition is low) and (Demographic information is low) then (Risk_of_DFU is low)

Table 8. Results for Second Layer Inference System

Serial number	FIS 1	FIS 2	FIS 3	Risk of DFU	Risk of DFU (Severe, Moderate, Low)
1	0.789	0.223	0.102	0.814	Severe
2	0.789	0.38	0.102	0.749	
3	0.741	0.314	0.09	0.822	
4	0.414	0.881	0.641	0.456	Moderate
5	0.414	0.881	0.271	0.5	
6	0.307	0.813	0.645	0.463	
7	0.2	0.9	0.63	0.19	Low
8	0.3	0.8	0.73	0.234	

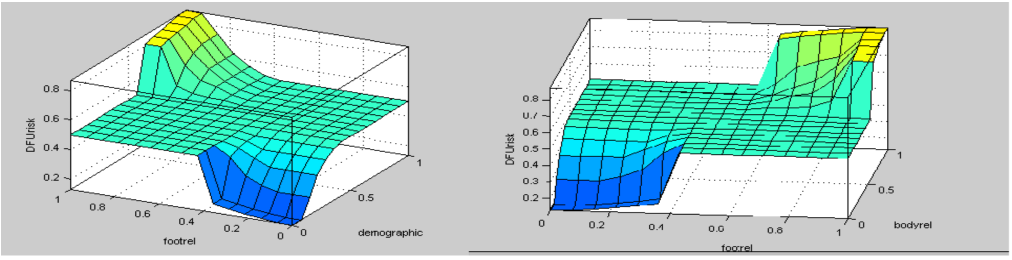

Figure 5. Control Surfaces of Foot Input and Demographic In First Figure and Control Surface of Foot and Body Related In the Second Figure, Both Inputs from The First Layer

Figure5 displays two control surfaces which were plotted as a result from the second layer. The first control surface is plotted with foot related (output from FIS1) values, demographic (output from FIS3) values and risk of DFU. The graph shows a dip when the values from both the other axes are low and the value increase when the input from either axes increases. The second figure represents a similar kind of control surface. The graph has foot related values on one axis, body related (output from FIS2) values on other axis and risk on the third axis. The graph shows low risk when the value from other axis is low.

3.6. Diabetic Foot Classifications

The well-established widely used Wagner wound classification system, the new University of Texas (UT) diabetic wound classification system PEDIS classification. All the wound classification systems are easy to use among health care providers, and both can provide a guide to planning treatment strategies. The Wagner system assesses ulcer depth and the presence of osteomyelitis or gangrene by using the following grades: grade 0 (pre- or post-ulcerative lesion), grade 1 (partial/ full thickness ulcer), grade 2 (probing to tendon or capsule), grade 3 (deep with osteitis), grade 4 (partial foot gangrene), and grade 5 (whole foot gangrene). The UT system assesses ulcer depth, the presence of wound infection, and the presence of clinical signs of lower-extremity ischemia. This system uses a matrix of grade on the horizontal axis and stage on the vertical axis. The grades of the UT system are as follows: grade 0 (pre- or post-ulcerative site that has healed), grade 1 (superficial wound not involving tendon, capsule, or bone), grade 2 (wound penetrating to tendon or capsule) and grade 3 (wound penetrating bone or joint). Within each wound grade there are four stages: clean wounds (stage A), non-ischemic infected wounds (stage B), ischemic non infected wounds (stage C), and ischemic infected wounds (stage D). Perfusion, extent, depth, infection and sensation are the components of interest in the PEDIS classification.

Table 9. Comparison with Wagner Foot Classification with Regimen

Comparison with Wagner foot classification with Regimen			
Risk of DFU	Wagner foot classification	Regimen (Treatment/Control)	Clinical Cure rate
Severe	Grade > 3	Ceftobiprole/ Vincomycin	86.2/81.8
		Clinafloxacin / Piperacillin - tazobactam	51.7/48
Moderate	Grade 1 and 2	Moxifloxacin / Piperacillin - tazobactam	67.6/61
		Daptomycin / Vincomycin	66/70
Mild	Grade 0	Pexiganan topical / Ofloxacan	86.8/90.4
		Piperacillin - tazobactam / Ampicillin - Sulbactam	81.3/83.1

3.7. Conclusion

This paper proposes a model for predicting the risk DFU (Diabetic Foot Ulcer) using independent agents for different input parameters and a combination of fuzzy expert systems. To describe the severity of diabetic foot ulcer, the proposed system uses [17] Wagner foot classification system. If the wagner grade >= 3, then the risk of DFU-severe and if the grades are 1 and 2, then the risk of DFU is moderate and grade 0 illustrates the risk of DFU as mild. From the study [18] , Ceftobiprole/ Vincomycin and Clinafloxacin / Piperacillin - tazobactam are the treatment/ control used for severe foot ulcer with a clinical cure rate of 86.2/81.8 and 51.7/48. Moxifloxacin / Piperacillin - tazobactam and Daptomycin / Vincomycin are the treatment/ control used for Moderate foot ulcer with a clinical cure rate of 67.6/61and 66/70. Pexiganan topical / Ofloxacan and Piperacillin - tazobactam / Ampicillin - Sulbactam are the treatment/ control used for Mild foot ulcer with a clinical cure rate of 86.8/90.4 and 81.3/83.1.

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