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Research Article

Smart Wound Hydration Monitoring Using Biosensors and Fuzzy Inference System

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Skin wounds either minor or chronic may heal up with different time durations. But, this time duration of healing could not be easily predicted as healing is affected by different factors, e.g., age, nutrition, medication, and surroundings. Despite these factors, wound characteristic also plays a role in the healing process. Wound characteristics include wound size, wound type, internal and external wound environment, body temperature, body oxygenation, wound hydration, and infection. Therefore, monitoring of wound healing also required careful consideration of wound characteristics. Although the healthcare domain contains many applications for detection and monitoring of diseases, the wound care domain requires efficient techniques and sensing systems for the identification of wound biomarkers such as temperature, blood pressure, oxygen, and infection status of wound using biosensors. In the current research, we provide a wound care solution based on a biosensor-based sensing system to measure basic biomarkers, considered as major wound characteristics, i.e., body temperature and body oxygenation, and design a fuzzy inference system to predict their effect on wound hydration, which ultimately recommends necessary actions to boost healing.

1. Introduction

Skin wounds either minor or chronic heal up with time. This time duration may vary for minor and chronic wounds. Minor wounds may take less time for healing while chronic wound may take longer duration for complete healing. But this is not a static phenomenon, i.e., minor skin wound may also take longer duration to heal up as the healing process is affected by many factors, i.e., environment, age, nutrition, and medication. Despite these, wound local characteristic may also have an effect on healing. Wound characteristics are wound location, wound environment (external and internal), wound type, wound density, wound hydration, body temperature, oxygenation level, and infection. Traditional wound care requires regular clinical visit. However, current era technology invention demands more easy and efficient wound monitoring based on sensors [1], devices, analysis modules, and patients [2] at patient site rather than clinical-centric wound monitoring.

Although there is no clear definition for wound environment, it could be defined as surroundings outside wound area and surroundings beneath wound area. So, skin wound environment can technically be categorized into two major types, external environment and internal environment. External environment means surroundings that are outside the wound area, and internal environment means surroundings which are under the wound area. Any change in external environment indirectly affects internal wound environment [3]. External environment included surrounding temperature, humidity, air quality, pressure, dust particles, hydration gases (oxygen, carbon dioxide), etc., while internal environment included body temperature, skin

moisture level, body oxygenation, and infection. All these internal factors affect wound healing.

In recent times, many wearables are being used in healthcare domain. Such wearables help in diagnosis of disease by taking body characteristics as the input. However, these wearables should be be smart enough to read data from patient body and analyze its values for disease monitoring and drug response and assess clinical trial efficacy [4]. Many healthcare solutions used sensor-based systems to detect various medical conditions; although these systems had many benefits, e.g., low cost and easy access, they also faced many concerns e.g., noisy input, lightning conditions effect on sensor data, and sound algorithms for data analysis [5].

To monitor wound healing process, it is necessary to measure wound characteristics (most important biomarkers) and analyze these factors to ensure internal environment holding positive values to boost up healing process. In current research, we proposed an approach to measure major biomarkers with a biosensor attached with a Arduino microcontroller and analyzed their effect on hydration level using the fuzzy inference system. The proposed system can be implemented to recommend necessary actions to boost wound healing.

The rest of the paper is structured as follows: Section 2 describes related research work done in field of skin wound healing, effects of internal/external environment on wound healing, and wound characteristic effect; Section 3 describes the wound characteristics and their role in skin wound healing of the proposed system. This section also describes the structure and configuration of the proposed biometric sensing system and the proposed fuzzy inference system; Section 4 provides details of the experiments and their results and discussion to show the performance testing and outcomes of the proposed approach; and Section 5 presents a conclusion of the proposed research.

2. Literature Review

Information technology plays a significant role in providing solutions of daily life problems faced in almost all domains. To facilitate the medical domain, many researchers proposed healthcare applications for monitoring and control of different diseases. In this section, we will discuss such health care applications especially focusing on different diseases of skin and their solutions.

Keast et al. [6] designed a framework, namely, MEASURE for wound assessment; this framework can be used to design efficient systems for wound assessment. In their proposed framework, they provided a description of clinical aspects of wound care and provided good literature discussion of clinical wound terms, concepts, wound care practice standards and guidelines. All wound concepts and discussion of their framework provide efficient basis for development of wound assessment system design. The basic purpose of their framework is improvement in accuracy and reliability of wound assessment tools and techniques.

An IoT-based application was proposed by Meena and Indumathi [7] which can detect skin cancer. This application is efficient in comparison with the bioscopy method. They used a combination of support vector machine and digital image processing for image classification. Their classification method is based on particle swarm optimization algorithm. This efficient algorithm has the capability to differentiate cancer skin from normal one. In order to validate working of the proposed approach, they did experiments and obtained 97% accurate results. They sent database details to the IoT platform through the ESP8266 Wi-Fi module, from where these details can be shared at Twitter with doctors and the user and also through the Thingspeak IoT platform by using mail ids. Their system assured secure transmission by using MYSQL queries along with application user interface (API) key.

Salvo et al. [8] studied the role of biomedical sensors in wound healing. They discussed that patient life is affected by acute and chronic wounds. Healing process of wound goes through a huge number of biochemical processes; therefore, biomedical sensors can be used to monitor wound healing and detect infections. In their proposed research, they highlighted the role of biosensors in different phases of wound healing. The study showed that these sensors can monitor and allow wound healing process, and it facilitates the patient to improve his/her health by personal care at home.

Guinovart et al. [9] designed an IoT-based wearable potentiometric sensor for monitoring pH of wounds. Their proposed device consists of a screen-printed pH potentiometric sensor which was embedded into bandages. They used fabrication of sensor as an electro polymerized polyaniline (PANi) conducting polymer for pH sensing, which they combined with the screen printing fabrication methodology for the implementation of both the reference and the working electrodes. Their proposed pH bandage sensor displays a response over relevant pH range (5.5–8), with a noteworthy selectivity in the presence of physiological levels of most common ions. The sensor used in the proposed methodology displays good resiliency, repeatability, and reproducibility. Results showed that the device was successfully evaluated.

RoyChoudhury et al. [10] used a uric acid biosensor-based wearable device to monitor wound healing. This device is capable of identifying UA levels of wounds. UA serves as biomarker, which acts as a strong factor in wound healing. They used immobilization techniques for electrochemical analyses to show that the entrapped enzyme in a cationic polymer (PVA-SbQ) matrix can provide an enhanced response. They did experiments by which they obtained stable response at body temperature, so their proposed biosensor shows the potential of continuous wound monitoring. Their study concluded that detection of UA from wound fluid provides a way for evolving a dressing-embedded biosensor system in wound care on a wearable platform.

3. Wound Healing Background

Different clinical researchers defined wound healing as a biological process of human body, which is carried out through four precisely and highly programmed phases:

hemostasis, inflammation, proliferation, and remodeling. It is necessary that all these phases go in sequences for successful healing completion. But, it is not always possible as many factors interfere with one or more phases, thus causing improper or impaired wound healing [11].

Some characteristics of wound may significantly affect wound healing, e.g., wound size, wound type, wound location, wound hydration, wound temperature, oxygenation, necrotic tissue, and maceration. In this section, we will highlight the role of a major biomarker in healing process as shown in Figure 1.

3.1. Wound Healing Phases. Wound healing is composed of four ordered stages as discussed below:

(1) *Stage 1.* Hemostasis is first stage of wound healing which starts immediately after the wound occurs; in this phase, blood vessels compress and decrease blood flow at injury site. To prevent blood flow, blood clots are formed which ultimately prevent further blood loss.

(2) *Stage 2.* Inflammation causes opening of blood vessels around the wound to deliver fresh nutrients and oxygen into the wound for healing. This increased oxygen level triggers the macrophage, a white blood cell, to enter the wound, fight infection, supervise the healing process, and send messengers, called growth factors, needed to heal the wound. Macrophage is the clear fluid around the wound.

(3) *Stage 3.* The third stage of healing is called proliferation. It is the growth and reconstruction phase. In this phase, blood cells help to build new tissues to replace the damaged tissues. During this phase, the body produces a protein called collagen, which acts like a platform, to support the repair process.

(4) *Stage 4.* Remodeling is the last wound healing stage in which inflammation is gradually removed and the collagen is dropped. New tissues called scar tissues take the place of old/damaged tissues. Scar tissues do not have full strength as normal tissues. They may take several months, even a year, to gain full strength [11].

All wound healing phases require oxygen. Even acute hypoxia (deficiency of oxygen in blood) stimulates wound healing. It induces oxygen recovery (tissue oxygenation) as chronic hypoxia will impair the healing [12].

3.2. Role of Temperature and Oxygen in Healing Phases

3.2.1. Temperature. The most significant factor that may affect wound healing is temperature. This factor is considered crucial as it may directly and indirectly influence other wound characteristics. Healing process contains a series of chemical and enzymatic actions which may be disturbed by abnormal temperature range. The wound care education institutes accepted that normal temperature is necessary for all enzyme and cell functions. Any increase and decrease in temperature negatively affect the wound healing process. Different studies showed that temperature of internal environment as well as external environment affects wound healing. Temperature of internal body blood vessels is facilitated by vasoactive molecules that promote vasodilation (blood vessel dilatation to decrease blood pressure) or vasoconstriction (phenomenon of the blood vessel constriction, which increases blood pressure) [3].

Human body's normal functioning depends upon body temperature as normal temperature is necessary for appropriate functioning of every system in the body, with every activity within the body dependent on an appropriate temperature. Therefore, no one can deny the importance of temperature in wounds and wound healing. The human body maintains a constant body temperature of 37°C (±0.5°C) although there are many changes occurring in environmental temperatures. In simple terms, human body temperature could define thermal balance between energy supplied from the core and perfusion and energy lost to the environment through conduction, radiation, evaporation, and convection. Temperature of skin is affected by both internal and external (environmental) factors. Wound healing is affected by temperature as body temperature could affect local blood flow and lymphocyte extravasation; moreover, temperature is an early indicator of infection which determines wound chronicity [13].

3.2.2. Oxygenation. All stages of wound healing require adequate amount of oxygen to ensure normal healing of the wound. In wound healing, the body needs bacterial defense, cell proliferation, collagen synthesis, and angiogenesis. According to the British journal of dermatology, oxygen's major role is its ability to produce energy. Wounded cells need proper energy levels for reproduction. The adequate amount of energy depends upon oxygen. Hypoxia occurs in absence of proper oxygen, which can slow and even stop the healing process.

Power et al. [13] studied the effect of oxygen on wound healing, and they defined oxygen as the key factor in wound healing. All living tissues require oxygen and nutrients to grow well. In case of skin injury, tissues are damaged and they require healthy regeneration during the healing process. So, skin wound demanded suitable amount of oxygen for healthy recovery. Wound healing requires normal levels of oxygen (i.e., normoxia). These different conditions occur in all phases of wound healing.

(1) Increased Cell Metabolism and Energy Production. Oxygen is vital for enzymatic processes like biosynthesis, movement, and transport, which are essential for cell survival. A major enzyme which works by oxygen is adenosine triphosphate (ATP) which is useful for chemical energy. ATP provides fuel for the active cellular processes, and during the wound healing process, the damaged tissues need increased energy. Such energy is provided by the hyper metabolic state. In addition, such energy is generated from oxidative metabolism that increases the oxygen demand of the healing tissue [14].

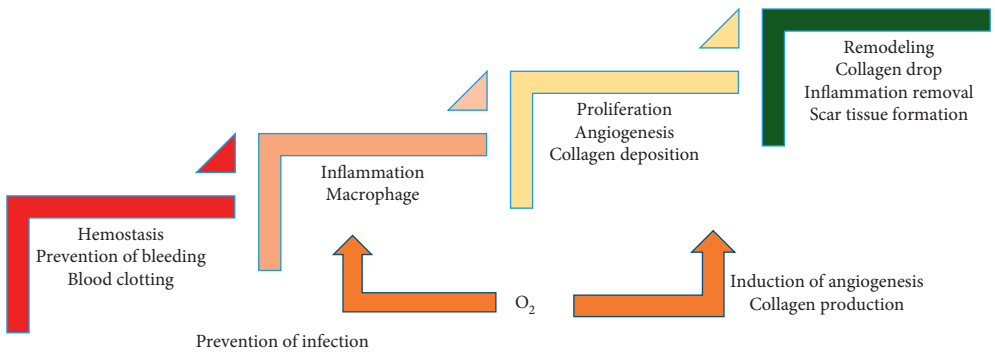

Figure 1: Oxygen's role in wound healing phases.

(2) Collagen Production and Development. Oxygen is essential to make and properly organize collagen, which is the primary component of skin, accounting for 70–80% (dry weight – without water), and acts as the structural scaffold of skin. Organized collagen is bundled into fibers (like strands in rope), which are interwoven and can be stretched in multiple directions without tearing (the collagen fibers are woven similar to fabric)

(3) Infection Prevention. When skin injury occurs, microorganisms cold easily get access to skin's underlying tissues. Replication of these organisms could trigger infection. The condition and severity of the wound infection can be checked by analyzing the status of microorganism in the form of its replication, contamination, colonization, local infection colonization, and/or spreading invasive infection. Contamination means nonreplicating organisms present on a wound, while presence of replicating organisms on wound is termed as colonization. Intermediate stage where the microorganism's replication and the beginning of local tissue's response occurs is called local infection/critical colonization. Presence of replicating organisms within a wound with subsequent host injury is called invasive infection. In surgical wounds, infection can cause serious complication. Oxidative mechanisms of leukocyte can be helpful in destroying bacteria in wounds. Oxygen radicals can be produced by intracellular and molecular oxygen. So, proper oxygen amount is helpful in removing bacteria from the surgical wound site [15]. The second phase of healing process, called inflammation, plays an important role in the removal of contaminating microorganisms. During inflammation, more blood vessels around the wound open to deliver fresh nutrients and oxygen into the wound for healing. This higher level of oxygen level triggers the macrophage, a white blood cell, to enter the wound, fight infection, supervise the healing process, and send messengers, called growth factors, needed to heal the wound. Macrophage is the clear fluid around the wound.

(4) Induction of Angiogenesis. The formation of new blood vessels from existing one is called angiogenesis. The growth and development of body tissues depend upon angiogenesis, which plays a vital role in the wound healing process by growth of damaged tissues. In angiogenesis, higher oxygen level plays a positive role in increasing the rate and quality of new blood vessel growth.

(a) Appropriate level of oxygen in blood is necessary for correct collagen synthesis

(b) Blood vessel growth increases with good oxygen levels

(c) More oxygen in injured tissues can facilitate more angiogenesis, and with higher oxygen, more collagen can be deposited for improved healing [16]

3.3. Connection of Oxygen and Temperature with Wound Hydration. Like other wound characteristics, wound hydration also plays an important role in wound healing. Medical domain researchers believed that the wound hydration status plays a crucial role in wound healing, and such a system is required to detect the hydration status [17].

Hydration is vital for the human body's normal functions as hydration plays a role in body immune system by removing toxins from body with right amount of fluids. Hydration supports fast wound healing due to the following facts:

(a) Fluids are necessary to provide oxygen to wound site

(b) Fluids are essential for nutrient transport to wound cell

(c) Fluids act as solvent for vitamins, minerals, glucose, and amino acids

(d) Fluids also remove waste from the cells

(e) Hydration helps skin fight against toxins

Rapid loss of body weight due to dehydration can affect the level of both body temperature and oxygen in blood. Dehydration effects body temperature as follows:

(a) Body core temperature rises due to lack of sweating

(b) Body heat stays inside which may cause serious complication like heat stroke

(c) Dehydration also affects body oxygen

(d) Dehydration causes decrease in blood volume

(e) Low blood volume in severe dehydration may cause low blood pressure which in turn reduces the amount of oxygen in our body

4. Proposed Approach

In this section, we discuss the structure and working of our proposed system design to monitor wound healing by measurement of wound characteristics and comparing with their standard levels to assure positive flow of wound healing. We proposed a system to measure two major biomarkers of wound to monitor wound healing by analyzing wound hydration level. The proposed methodology is depicted in Figure 2. It consists of two major components:

(1) Biosensor-based sensing system to sense wound biomarker

(2) Fuzzy inference system to predict biomarker effect on wound hydration

The proposed system's overall working is carried out by the following steps:

(1) Measuring wound biomarker by biosensor sensing system

(2) Defining standards for biomarker values

(3) Designing rules for the proposed system

(4) Designing a fuzzy system based on designed rules for identification of wound hydration levels

4.1. Hardware Design of Biosensor Sensing System. In the first phase of the proposed system, we measured wound characteristics by using a Arduino-based biometric sensing system. In wound characteristics, we choose body temperature and blood oxygen level. We designed Arduino UNO-based circuit to measure wound characteristics. For measurement of wound characteristics, we used a biometric sensing system. This system is based on Arduino-based circuit which is composed of the following components:

(1) Arduino UNO microcontroller

(2) MAX30100 heart rate sensor module

(3) LM35 temperature sensor

4.1.1. Arduino UNO Microcontroller. To design the circuit of a BM sensing system, we used the Arduino UNO open source microcontroller board on which we attached biometric sensors for measurement of wound characteristics. This microcontroller has 6 analog pins (see Figure 3) and 14 digital pins for connecting sensors, and these pins can be programmed by using Arduino IDE. The Arduino IDE could be used for programming Arduino board pins on the system after attachment of board with the system. A type B USB cable is available for connecting the Arduino board with the system.

4.1.2. MAX30100 Heart Rate Sensor Module. In our designed circuit, we used MAX30100 for measurement of blood oxygenation level. MAX30100 is a heart rate monitor and pulse oximetry sensor. It could detect pulse oximetry and give output in SpO_2 and heart rate with help of its components, i.e., two LEDs, a photodetector, optimized optics, and a low-noise analog signal processor. It required 1.8 V and 3.3 V power supplies for operation as shown in Figure 4. Some features of MAX30100 are as follows:

(1) Very low power required for its working (operates from 1.8 V to 3.3 V)

(2) It possesses ultra-low shutdown current (0.7 μA, type)

(3) It can output data very fast

4.1.3. LM35 Temperature Sensor. In our designed circuit, we used the LM35 sensor for measurement of body temperature (see Figure 5). LM35 is a temperature sensor, and it output temperature in °C which could be further converted into °F as per requirement. Temperature could be measured more accurately with LM35 compared with thermistors. LM35 is a low self-heating device, and it prevents the rise of temperature in air. It operates in the range of −55°C to 150°C. The output voltage varies by 10 mV in response to every °C rise/fall in ambient temperature, i.e., its scale factor is 0.01 V/°C. Interfacing LM35 and MAX30100 with Arduino Microcontroller Board is simple.

4.2. Fuzzy Inference System Design. In our proposed system, we used fuzzy inference mechanism for identification of wound hydration level based on body temperature and body oxygenation level by using biosensors.

The fuzzy inference system is based on fuzzy logic by which machines could reason like human as these systems can handle all possibilities between digital values YES and NO. Like human beings, fuzzy systems (see Figure 6) can handle all types of output possibilities, e.g., yes, certainly yes, possibly yes, cannot say, and so on. Fuzzy logic can handle input of various sizes and ranges. In simple words, we can say fuzzy logic can handle fuzzy sets [18].

Fuzzy set is a simple set of elements in which each element assigns a grade of membership between 0 and 1. We can say if A is a fuzzy set in universe X, then there exists a membership function $\mu A\ (x)$ of set A $\mu A\ (x)$: $X \longrightarrow [0, 1]$, where $\mu A\ (x) = 1$ if x is totally in A, $\mu A\ (x) = 0$ if x is not in A, and $0 < \mu A\ (x) < 1$ if x is partly in A.

Fuzzy inference system consists of the following components.

Rule base: it contains working rules for FUZZY system in IF-THEN form. Rules can contain more than one condition by using logical connection AND, OR.

Database: fuzzy rules use some functions called membership functions to predict the output. This membership function is placed in a database. (Algorithm 1).

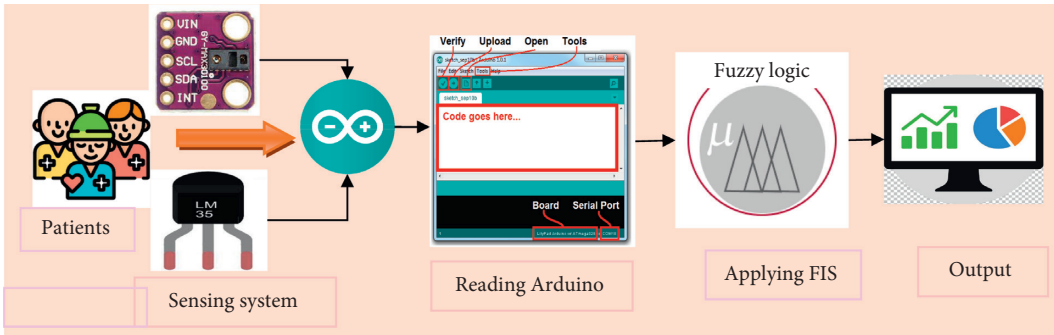

Figure 2: Architecture of the proposed approach.

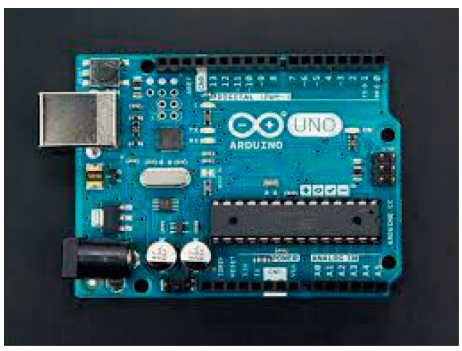

Figure 3: Arduino microcontroller.

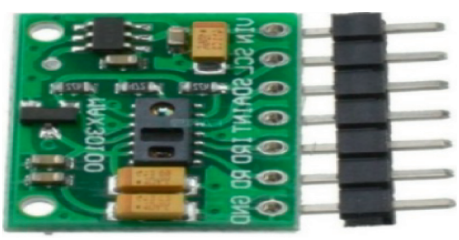

Figure 4: MAX30100 heart rate module.

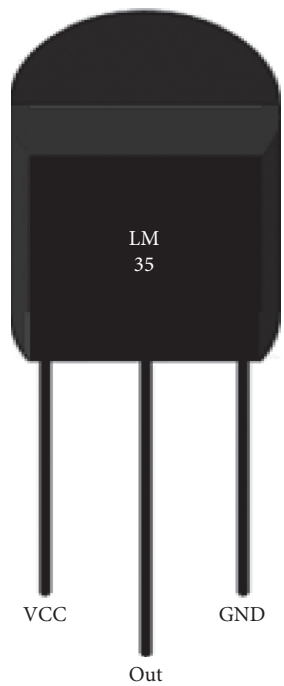

Figure 5: LM35 temperature sensor.

(a) *Decision-Making Unit*. Fuzzy system is applied on rules for mapping inputs to these operations for decision-making

(b) *Fuzzification Interface Unit*. Input values are provided to fuzzy logic in crisp quantities during fuzzification; these crisp quantities are converted into fuzzy quantities

(c) *Defuzzification Interface Unit*. Reverse process of fuzzification, i.e., conversion from fuzzy quantities to crisp quantities.

4.2.1. Linguistic Variable of System. The linguistic variable holds natural language values instead of numerical values. The linguistic variable is divided into a set of linguistic terms [19]. In our proposed system, we read values of temperature and blood oxygenation; both these variables have standard values in natural language defined in Tables 1 and 2. Therefore, we define two linguistic variables for the proposed fuzzy system.

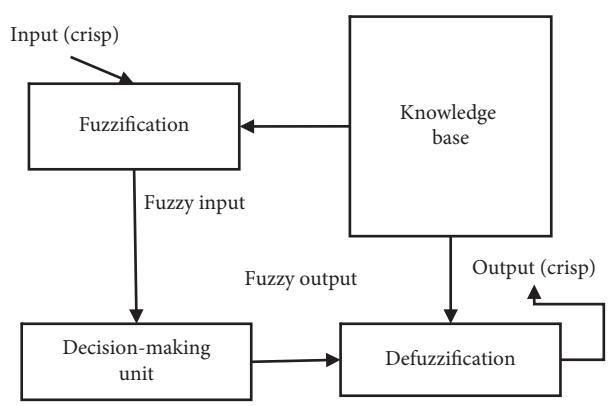

Figure 6: Block diagram of fuzzy system.

(a) Hypothermia: normal body temperature is 98.6°F (37°C). If temperature drops from normal range, then this condition hypothermia occurs when the patient's body balances the heat loss and heat gain

(1) Complete Initialization step by performing given task.
  (a) Define linguistic variables.
  (b) Define membership function.
  (c) Define rule base.
(2) Perform fuzzification of input by membership function.
(3) Evaluate rules by rule base.
(4) Combine each rule result,
(5) Convert fuzzy output to nonfuzzy output (defuzzification).

Algorithm 1: Working algorithm for fuzzy system.

Table 1: Standard body temperature range.

Standard	Celsius (°C)	Fahrenheit (°F)
Hypothermia	<35	95.0
Normal	36.5–37.5	97.7–99.5
Fever/hyperthermia	>37.5 or 38.3	99.5–100.9
Hyperpyrexia	>40.0 or 41.5	104.0–106.7

Table 2: Standard oxygen level range.

Standard	Oxygen (%)
Normal	95–100
Hypoxemia	<95
Hyperoxia	>100

that causes dangerously low body temperature. In hypothermia, body temperature falls below 95°F (35°C).

(b) Hyperthermia: if temperature is high but not as much to cause fever, then this condition is called hyperthermia. This condition could occur due to heatstroke, drug reactions, etc.

(c) Hyperpyrexia: high temperature range of 41.5°C (106.7°F) causes high fever, and this condition is called hyperpyrexia.

Temperature (t) is a linguistic variable which defines body temperature of a person suffering from skin wound.

Linguistic terms for temperature (t) = {Hypothermia, Normal, Hyperthermia, Hyperpyrexia}. Oxygenation (O) is a linguistic variable used to handle blood oxygen saturation level, and linguistic terms for oxygenation (O) = {Normal, Hypoxemia, Higher}.

4.2.2. Membership Function. The membership function quantifies linguistic terms and represents the fuzzy set by plotting a graph. In general, fuzzy set Y membership function on the universe of discourse X is defined as μY: $X \longrightarrow [0, 1]$. Universe of discourse is the range of all possible values for input. Each element of X is mapped to a value between 0 and 1. This mapping is called the membership value or degree of membership. It quantifies the degree of membership of the element in X to the fuzzy set Y.

Many types of membership function are used according to requirement of system:

(a) Singleton
(b) Gaussian
(c) Trapezoidal
(d) Triangular
(e) Piecewise linear

In our proposed FIS system, we use the trapezoidal membership function (see Figure 7). The trapezoidal membership function described in [20] is given in the following equation:

$$\text{Trapezoidal}(x; a, b, c, d) = \begin{cases} 0, & x < a, \\ \dfrac{x-a}{b-a}, & a \le x \le b, \\ 1, & b \le x \le c, \\ \dfrac{d-x}{d-c}, & c \le x \le d, \\ 0, & d \le x, \end{cases} \quad (1)$$

where x represents the real part of the variable within the universe of discourse and a, b, c, and d represent x-coordinates of the trapezoid in the following order: $a < b < c < d$.

4.2.3. Rule Base of Fuzzy System. After choosing the membership function, the next step in designing a fuzzy system is construction of rule base for the fuzzy system. This rule base is responsible for controlling the output variable. Rules are provided in IF-THEN format; IF part is called condition/premise and THEN part is called conclusion. We use rules mentioned in Table 3 for our proposed FIS.

4.2.4. Fuzzification. After defining rule base, fuzzification takes place in two steps.

Fuzzifying of input in which fuzzy rules are evaluated and then using fuzzy operations to combine results of individual rules in order to get final output is known as inference mechanism. There are three basic operations in the fuzzy set and classical set, i.e., union, intersection, and complement.

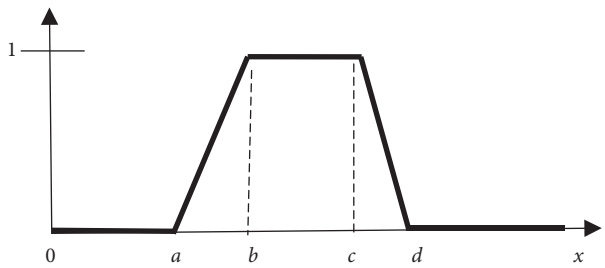

Figure 7: Trapezoidal membership function.

Table 3: Proposed system working rules.

Temperature (°C)	Oxygenation (%)	Hydration level
Normal	Normal	Hydrated
Normal	Hypoxemia	Mildly dehydrated
Normal	Higher	Hydrated
Hyperthermia	Normal	Hydrated
Hyperthermia	Hypoxemia	Mildly dehydrated
Hyperthermia	Higher	Hydrated
Hypothermia	Normal	Hydrated
Hypothermia	Hypoxemia	Mildly dehydrated
Hypothermia	Higher	Hydrated
Hyperpyrexia	Normal	Mild dehydrated
Hyperpyrexia	Hypoxemia	Dehydrated
Hyperpyrexia	Higher	Mildly dehydrated

Fuzzy set A and B are defined by membership functions μA and μB, respectively. Union of set A and set B defines the membership function's universe as given in the following equation: equation (2).

$$\mu A \cup B(x) = \mathrm{MAX}(\mu A(x), \mu B(x)). \tag{2}$$

Intersection: the membership function which defines the intersection of both sets is given in the following equation:

$$\mu A \cap B(x) = \mathrm{MIN}(\mu A(x), \mu B(x)). \tag{3}$$

Complement: compliment is taken if the fuzzy set can be defined by a membership function as given in the following equation:

$$\mu Ac(x) = 1 - \mu A(x). \tag{4}$$

4.2.5. Defuzzification. When fuzzification is done to obtain values that belong to the fuzzy set, it converts it into crisp output. This could be done by using the membership function of the output variable. Most commonly used defuzzification algorithms are listed below:

(a) Center of Gravity

(b) Center of Gravity for Singletons

(c) Left Most Maximum

(d) Right Most Maximum

In our proposed system, we use the centroid defuzzification method developed by Sugeno in 1985. This method is most widely used by researchers for defuzzification of generated fuzzy output. This technique is expressed mathematically as [21]

$$x^* = \frac{\int \mu i(x) x \, \mathrm{d}x}{\int \mu i(x) \mathrm{d}x}, \tag{5}$$

where x^* represents defuzzified output, $\mu i(y)$ represents aggregated membership function, and x is used for representing an output variable in Equation (9).

Defuzzified method COG shown in Figure 8. Here, x-axis represents the output variable x and aggregated membership plot on y-axis is represented by μ.

5. Implementation

We designed a fuzzy inference system for detection of hydration levels by taking biomarkers body temperature and SpO_2 levels read by Arduino UNO circuit as input to system. The proposed FIS design and its working are explained in this section.

5.1. Implementation of Biosensor-Based Sensing System. We implemented a sensing system by using hardware mentioned in Section 4.1. We need to measure two parameters such as temperature and oxygen in blood for which we set some standards (already defined by the WHO). Such standards for sensors calibration are described as given below.

5.1.1. Body Temperature. Human body temperature varies from time to time. There are standard values of temperature by which wound characteristics could be identified as shown in Table 1.

5.1.2. Oxygenation. The oxygen saturation in blood is known as oxygenation. We used predefined standard ranges of oxygenation to measure oxygen levels.

(a) Normal: normal oxygen saturation level is between 80 and 100 millimeters of mercury (mm Hg). Pulse oximeter sensor normal readings for blood oxygen levels typically fall between 95 and 100 percent.

(b) Hypoxemia: if blood oxygen level falls below normal level, then this condition is known as hypoxemia. This condition needs to be resolved. The lower level of oxygen can result in higher hypoxemia. Hypoxemia can create serious health problems by disturbing body tissue and organs. If MAX30100 reading of oxygen saturation is below 95 percent, it will be considered as low as shown in Table 2.

(c) Hyperoxia: if oxygen level is higher than normal level, that is >100%, it will be considered as hyperoxia. This condition occurs in people who take oxygen supplement.

5.1.3. Proposed Biosensor Circuit Description. We designed a biosensor system by designing a circuit based on Arduino UNO in connection with LM35 and MAX30100. LM35 is used to sense body temperature and MAX30100 is used to

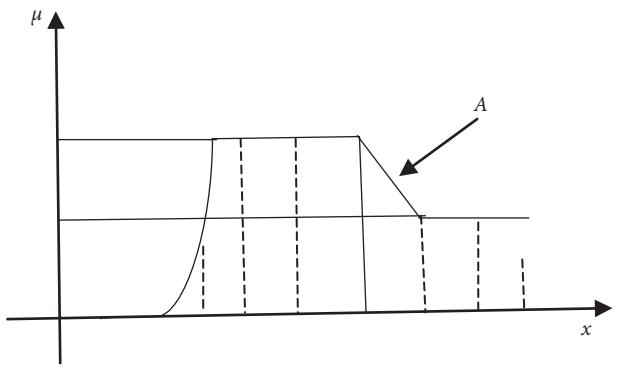

Figure 8: COG defuzzification method.

measure heart rate and blood oxygenation level SPO_2. Complete interfacing details of proposed circuit are given in Table 4.

We recorded values of body temperature with LM35 and heart rate + oxygenation level with MAX30100.

5.2. Sensor Calibration Chart. In our proposed system, after reading biomarkers through biosensors, we have to use some learning techniques to predict wound hydration using biomarker range and recommend suitable actions for faster wound healing. We used the MATLAB fuzzy inference system to accomplish this goal. To design a fuzzy system, we define working rules of the system as given in Table 3.

5.3. Implementation of Fuzzy Inference System Using MATLAB and Simulink. We used MATLAB and Simulink for designing the proposed FIS system. The proposed FIS basic components and their functions as described in previous section were implemented in MATLAB by using fuzzy toolbox. In the proposed system, two input variables are defined temperature and SpO_2. One output variable is defined as hydration-level, and the used inference method is Mamdani. The proposed FIS model is shown in Figure 9. We define the trapezoidal membership function for temperature by using the configuration setting shown in Table 5.

The proposed system membership function of variable temperature after applying settings mentioned in Table 5 is shown in Figure 10.

For second input variable SpO_2, we applied the configuration mentioned in Table 6 to apply the trapezoidal membership function.

The proposed system membership function of variable SpO_2 after applying settings mentioned in Table 6 is shown in Figure 11.

We defined one output variable hydration level. The membership function of output has four plots, namely, Hydrated, Mildly Hydrated, Dehydrated, and Mildly Dehydrated. The defined membership function for hydration level is shown in Figure 12.

After configuration of input and output variable along with their membership functions, we defined the rule for the proposed FIS by using rule editor of MATLAB fuzzy toolbox. The proposed rules are shown in Table 7. Generated

Table 4: Interfacing of biosensor system.

Arduino UNO	Connection link
5 V	LM35 ⟶ VCC MAX30100 ⟶ VIN
GND	LM35 ⟶ GND MAX30100 ⟶ GND
A5	MAX30100 ⟶ SCL
A4	MAX30100 ⟶ SDA
A0	LM35 ⟶ VOUT
D2	MAX30100 ⟶ INT

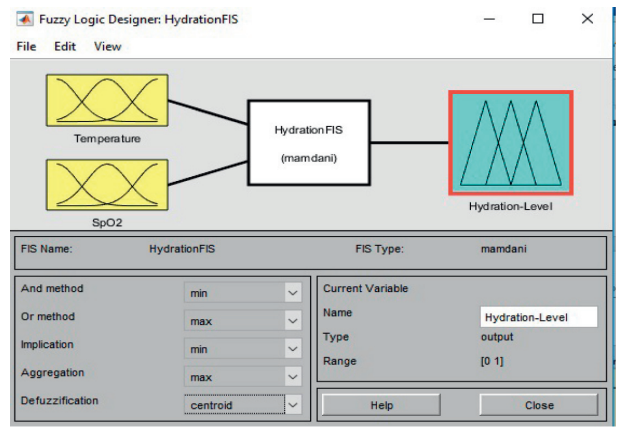

Figure 9: Proposed FIS model.

Table 5: Membership function settings for temperature.

Input variable	MFS plot name	MFS plot range
Temperature	Low	0–35
Range	Normal	35–37
[0–50]	Fever	37.5–38.5
	High	38–50

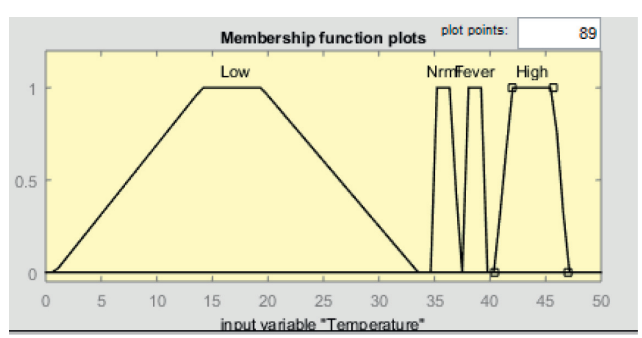

Figure 10: Membership function temperature.

Table 6: Membership function setting for SpO_2.

Input variable	MFS plot name	MFS plot range
SpO_2	Low	0–95
Range	Normal	95–100
[0–110]	High	100–110

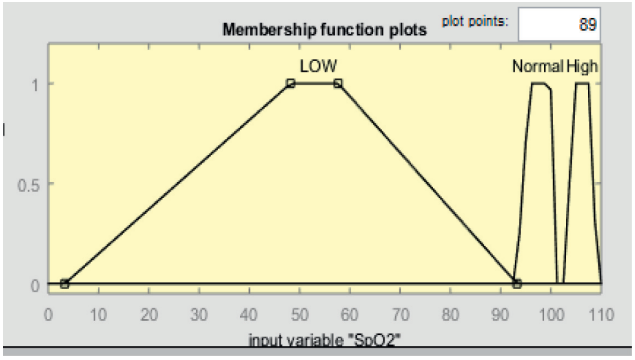

Figure 11: Membership function of SpO_2.

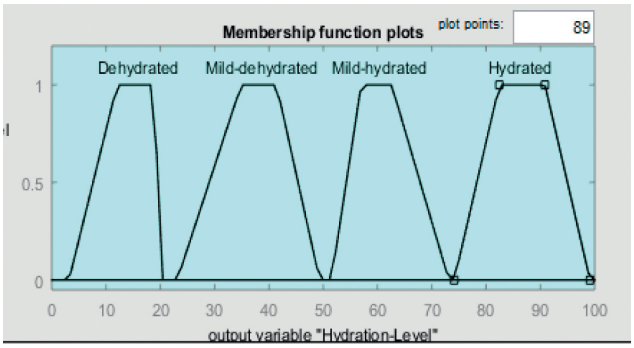

Figure 12: Membership function for output hydration level.

Table 7: Mean values of experiment samples.

Case number	Mean-TMP	Mean-SpO_2
Case 1	36.2	95.24
Case 2	36.6	96.1
Case 3	34.14	93.06
Case 4	37.78	96.1
Case 5	39.18	92.2

rules' performance could be viewed in Rule Viewer of MATLAB fuzzy toolbox. Rule Viewer shown in Figures 13 and 14 showed working of the proposed FIS rule set.

6. Experiments and Results

We provided 500 different input cases to the proposed system in order to check the accuracy rate of the proposed biosensor system and FIS. We collected input data from 5 different patients suffering from skin wounds having different wound hydration levels by using the proposed biosensor-based Arduino UNO circuit and provided these input cases to proposed FIS for prediction of wound hydration levels. In this section, we describe experiment design by choosing 5 instances from each patient data. These selected input data instances are shown in Table 6.

6.1. Data Collection. The working of the proposed system is checked by experimentation on 5 different patients suffering from skin wounds. We collected their data at different time intervals by using the proposed biosensing system. We collected 100 instances from each patient at different time intervals and chose 5 instances of different intervals from each case as shown in Table 8.

6.2. Data Sampling. We performed data sampling to reduce the size of input data; for sampling, we selected the random sampling technique to choose input data cases from datasheets of 5 different patients. Each patient data contains 100 instances; we picked 5 input values from each case on random basis, each input instance having equal chance of selection; each input instance had 1/100 chance to be in selected data [22].

6.3. Computing Mean. We selected 5 random input instances; next, we computed mean of instances to obtain one instance value from randomly selected sample. Mean of the sample is the arithmetic average of the data sample. The formula used for computing mean, which was also used by Sattar et al. [23], is given in the following equation:

$$\sum_{i=1}^{5} \frac{X_i}{N}, \tag{6}$$

where X_i = sum of input instances in the sample and N = total no. of instances in the sample/sample size.

By applying the mean formula, we computed mean of the data sample given in Figure 14. Computed mean is given in Table 7.

6.4. Data Analysis to Compute Hydration Level Using Proposed FIS. After obtaining the mean value from each sample, these mean values of both input variables are given to the to the proposed FIS to get the hydration level.

Mean values of Case 1 = [36.2, 95.24], Case 2 = [36.6, 96.1], Case 3 = [34.14, 93.06], Case 4 = [37.78, 96.1], and Case 5 = [39.18, 92.2]; we provided these instances to the proposed FIS in order to predict hydration levels of given instances. Obtained rule viewer shown in Figure 15 generated hydration level highlighted in given Figure 15, which showed that proposed FIS predicts hydration level 86 for case 1 in which temperature is 36.2 and oxygen saturation is 95.24. Here, both temperature and oxygen are at normal level. The FIS-predicted hydration level is precise enough to support our assumption about hydration levels for normal temperature and oxygen saturation range [24]. Similarly, Case 2 shows normal body temperature and blood oxygen saturation, and the proposed system predicted a hydration level of 86.6 %, indicating normal hydration level, which supports our assumption. Case 3 showed low temperature values and high oxygen saturation values while Case 4 showed inverse values, i.e., high temperature values and low oxygen values; for both cases, the proposed FIS indicated 50 % hydration level which showed mild hydration level matching with our assumptions. In the last case, the temperature values are very high and oxygen saturation levels are very low; therefore, the proposed system showed low hydration level value, i.e., only 36.5 %, indicating mild dehydration level of the body.

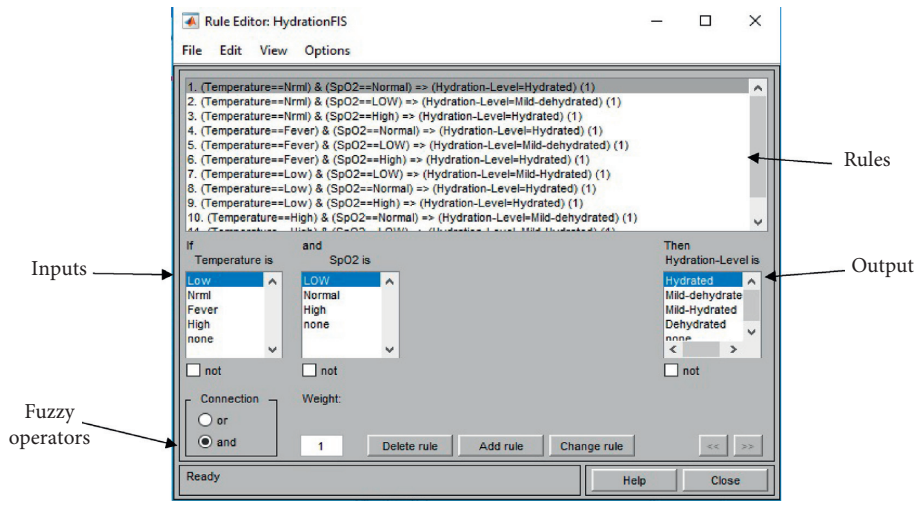

Figure 13: Rule Editor of the proposed FIS.

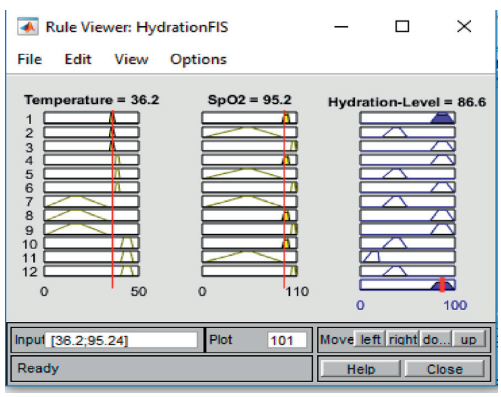

Figure 14: The proposed FIS Rule Viewer.

Table 8: Datasheet of 5 cases at different time intervals.

Case number	Time	Temperature	SpO_2
Case 1	10:57:24	36	95
	11:10:27	36.2	95.9
	11:20:30	36.5	95.3
	12:15:32	36	95
	13:37:33	36.3	95
Case 2	11:01:24	36.5	96.2
	11:10:27	36	96.3
	12:20:30	36	96
	12:50:34	37	96
	11:37:33	37.5	96
Case 3	11:10:48	34.5	93
	11:50:51	34	93
	12:30:53	34	93
	13:30:56	34	93.3
	14:10:59	34.2	93
Case 4	11:14:59	37.8	96
	13:14:02	37.6	96.5
	14:14:05	37.6	96
	15:14:08	37.9	97
	16:14:12	38	95
Case 5	10:30:59	39	93
	11:30:02	39	92
	12:35:05	38.9	94
	13:20:08	39	92
	14:10:08	40	93

Figure 15: Predicted hydration level by the proposed system.

6.5. System Accuracy Rate. In previous section we discussed detailed working of FIS on 5 chosen instances from each patient input instances datasheet each having size 100. To validate the system's overall performance, we discuss FIS-predicted response for all input instances [25]. All obtained results are elaborated in Table 7. In Table 9, HD column stands for Hydrated, MHD stands for Mildly Hydrated, DHD stands for Dehydrated, and MDHD stands for Mildly Dehydrated. To compute the accuracy rate of each case, we use the following formula:

$$\text{accuracy} = \frac{\text{wrongly predicted}}{\text{total instances}} * 100. \tag{7}$$

Table 9 showed that for case 1 input instances proposed FIS produced only one instance that did not support expected result and hence showed 99% accuracy rate, for case 2 only two instances proposed output did not match with expected output.

Here, the system showed overall 97% accuracy rate%. Case 3 had 4 instances which showed different outputs than expected, and the system accuracy rate was 96%, and Case 4 had high error rate as output of 6 input instances did not match with expected output; hence, the system showed 94% accuracy rate. Accuracy graphs for all cases given in Figure 16 showed that the proposed FIS showed only minor wrong prediction. We computed the system overall accuracy rate for all experiments by using the following equation:

$$\text{accuracy} = \frac{\sum_{i=1}^{n} X_i}{N} * 100, \tag{8}$$

where X_i represents the accuracy rate of each experiment and N is the total no. of experiments.

The average accuracy of the system is 97% for all the case studies.

Table 9: FIS accuracy rate for input datasets.

Dataset	Input size	True class	HD	MHD	DHD	MDHD	ACC (%)
Case 1	100	Expected	80	18	00	02	99
		Obtained	80	17	01	02	
Case 2	100	Expected	60	30	02	08	98
		Obtained	58	30	04	08	
Case 3	100	Expected	20	50	05	25	96
		Obtained	20	47	04	29	
Case 4	100	Expected	35	35	00	30	94
		Obtained	35	32	01	32	
Case 5	100	Expected	50	30	00	20	98
		Obtained	50	28	00	22	

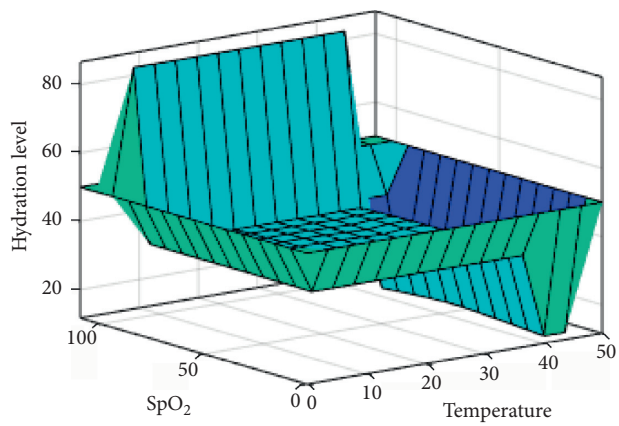

Figure 16: Proposed FIS surface view.

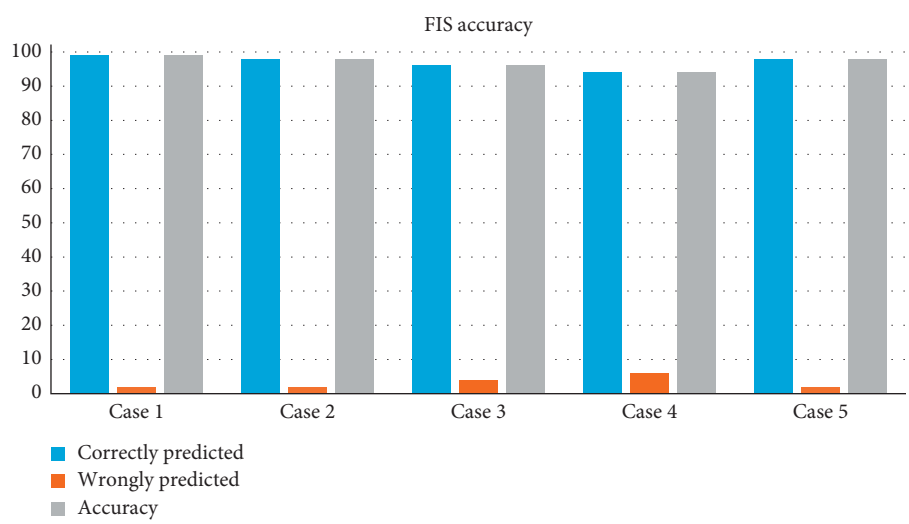

Figure 17: Proposed FIS accuracy graph.

The proposed FIS surface view is given in Figure 16 in which x-axis shows input temperature, y-axis shows second input SpO_2, and z-axis shows the output hydration level. The accuracy is shown in Figure 17.

Our obtained accuracy level, i.e., 97%, is satisfactory with current experiments, but in future, improvements could be made by increasing the number of working rules based on particular wound type and other biomarker effects on wound hydration.

7. Conclusion

Wound characteristics have significant effect on wound healing. There are a few factors involved in wound healing;

most of them are biomarkers, i.e., temperature, body oxygen saturation level, and wound moisture level. These biomarkers can not only influence wound healing but also show correlation with other wound characteristics as well, i.e., temperature and oxygen levels correlated with wound hydration levels and vice versa. For efficient wound monitoring system, it is necessary to focus on these biomarkers. In current research, we proposed a smart wound hydration monitoring technique based on biosensors. Our proposed solution consists of Arduino-based circuit to sense body biomarkers by suing biosensors LM35 and MAX30100 for temperature and oxygenation levels, respectively; after sensing biomarker levels, the system can predict wound hydration level by applying the proposed fuzzy inference system. The designed fuzzy inference system facilitates wound healing by predicting wound hydration levels; in case of low hydration levels, patients should increase their liquid in take for faster wound healing. The proposed system acts as a wound guard as it enables patients to monitor their wound condition. By using it, the patients can avoid harmful wound conditions by taking precautions in time. Therefore, our proposed system plays an active role in health care of patients at their home and acts as an efficient IoT application of healthcare domain like other IoT applications. Here, the proposed system provides an efficient way to boost healing at patient center. In future, smart wound monitoring systems should focus on identification of other wound characteristics in order to facilitate patient-centric efficient wound monitoring.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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