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Original Article

Design and Implementation of a Fuzzy Intelligent System to Estimate the Photoplethysmogram Systolic Features by Persian Medicine Pulsology

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Abstract

Introduction: In Persian medicine (PM), pulsology is one of the most important ways of knowing the internal states of the body and diagnosing diseases. On the other hand, the photoplethysmogram (PPG) signal provides significant information about the heart function for specialists. In this design, fuzzy systems have been used to correlate features from both PPG signal and PM pulsology. Such a system may help pave the path towards a worldwide accepted paradigm of integrative medicine.

Methods: Using the information of 64 individuals, a fuzzy system was designed by MATLAB software. First, the information related to age and pulse parameters including frequency, strength, speed, length, and width were acquired by a PM specialist via traditional pulse examination and considered as input variables. Subsequently, their PPG curve was also recorded by a PO80 beurer pulse oximeter. Afterwards, variables of slope, height, and time of systolic upstroke curve at points of 25%, 50%, 75%, and 100% amplitude of PPG curve were calculated and considered as output variables.

Results: A system with 236 rules was designed and the error of this system was less than 0.05, which is considered an acceptable estimate.

Conclusion: This designed pilot system estimated the PPG systolic features using PM pulsology with an error of less than 0.05, which can be used to help improve the clinical skills of PM students and practitioners and can establish the relationship between PM and common medicine.

Keywords: Pulse, Persian medicine, Fuzzy system, Photoplethysmogram, Pulsology

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Introduction

The latest global medical approach and also reputable medical centers are towards integrative medicine, which is the combination and integration of approved diagnostic and treatment methods of traditional and complementary medicine with conventional medicine (1). One of the most rooted schools of traditional medicine is Persian medicine (PM) which is currently faced with academic criticism and revival in many countries, including its motherland,Iran. Pulse diagnosis is one of the most important methods of clinical diagnosis in PM, which has been used for many centuries by traditional medicine specialists to assess the health status and disease of clients (2, 3). As pulsology includes more than a quarter of the pages written about semiology in major PM textbooks, the use of its capacities seems fruitful and usable for identifying and diagnosing diseases aside from conventional methods of diagnosis (4, 5). On the other hand, there are concerns and considerations regarding the experience and analysis of pulse results by practitioners and the training of students in this field because pulse examination in PM is done with the fingers of a specialist, which can be associated with errors, and inferring from the rules of the pulse is complicated due to the high number of these rules. In recent years, broader and newer dimensions of artificial intelligence applications, such as fuzzy systems, have been shown to help develop a standard PM Pulse diagnosis and its integration with conventional methods of diagnosis because fuzzy logic is a soft computing method that studies reasoning systems in which graded true and false concepts are considered (3, 5, 6). Fuzzy logic is very suitable for the development of knowledge-based systems in medicine, as well as disease diagnosis and real-time monitoring of patient's data (6-8).

This research aimed to evaluate the usability of Persian medicine pulsology to estimate the slope, height, and time of the systolic curve of PPG signal with the help of a fuzzy system design. Thus, a fuzzy system was designed to estimate the different characteristics of the systolic upstroke of photoplethysmogram (PPG) signal using selected pulse parameters of PM. The significant and innovative aspect of such a study is to validate and evaluate the talents of PM practitioners and their diagnostic claims in analyzing the pulse, by using the capabilities of Artificial Intelligence, especially fuzzy systems. This will help integrate the approved statements of centuries of traditional knowledge and clinical experience of PM physicians into conventional medicine benefiting human health. Below, the concepts related to the pulse of PM and the PPG signal, as well as fuzzy inference systems, are reviewed and then the method of design and analysis of the results of the fuzzy system is stated.

Pulse

In PM literature, – li ke modern physiology,the regular periodic expansion of an artery due to the ejection of blood into the arteries by heart contractions is known as pulse. Each pulse is considered to include two movement periods of expansion and contraction, and two pauses, lying in between every two movements. The pulse of each individual is analyzed by different parameters to determine the health and disease status. These parameters include pulse expansion in three spatial dimensions, strength, speed, frequency, vessel fullness and consistency, quality of the overlying skin and tissue, pulse uniformity or diversity, and pulse weight or music. However, in this study, we have minimized the acquired pulse parameters to the parameters of frequency, strength, speed, length, and width as they theoretically seemed to be most related to the systolic phase curve of the PPG signal (1, 9-11).

Fuzzy systems

Fuzzy logic is currently used in various branches of science. In artificial intelligence, which is designed based on non-deterministic data, fuzzy logic and rules of this logic are widely used. The fuzzy set A in the global space U is defined by a function $\mu_A(x)$ that takes values in the interval [0,1] and is defined as Equation (1):

$$A = \{(x, \mu_A(x)) \mid x \in U\} \quad , \mu_A(x) \in [0,1] \qquad (1)$$

Therefore, a fuzzy set is a generalization of a classical set; in other words, a classical set could only have two values 0 and 1, while the membership function of a fuzzy set is a continuous function in the range [0,1]. The structure of a fuzzy expert system consists of four parts: fuzzification of inputs, rules, inference engine, and defuzzification of outputs. Suppose in the if-then fuzzy rules with the given centers is a normal set, and the rules base with the product inference engine are given by Equation (2) and singleton fuzzifier and center average defuzzifier are given by Equations (3) and (4):

$$\mu_B(y) = max_{l=1}^{M}\left[sup_{x\in U}\left(\mu_A(x)\prod_{i=1}^{n}\mu_{A_i^l}(x)\mu_{B^l}(y)\right)\right] \qquad (2)$$

$$\mu_A(x) = \begin{cases} 1 & if \quad X = X^* \\ 0 & if \quad X \neq X^* \end{cases} \qquad (3)$$

$$y^* = \frac{\sum_{l=1}^{M}\bar{y}^l w^l}{\sum_{l=1}^{M} w^l} \qquad (4)$$

Then, the fuzzy system will be in the form of Equation (5):

$$f(x) = \frac{\sum_{l=1}^{M}\bar{y}^l\left(\prod_{i=1}^{n}\mu_i^l(x)\right)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_i^l(x)\right)} \qquad (5)$$

where y and x are the input and output variables of the system and A and B are the fuzzy sets related to the input and output of the system, n is the number of input variables, and M is the number of rules of the fuzzy system; also, $x^* \in U$ has a membership value 1 at x^* and 0 at all other points in U, $\bar{y}^l$ is the center of the lth fuzzy set, and w^l is its height. It is noted that the fuzzy system in the form of Equation (5) can approximate all continuous functions with the desired accuracy (12). Therefore, with these fuzzy systems, all continuous functions can be estimated with the desired accuracy.

Photoplethysmogram

Photoplethysmogram (PPG) is a non-invasive optical technique used to measure blood volume changes per pulse (13). PPG has a wide application in healthcare where it is used to predict vital health-related parameters. Also, PPG has been used for determining the heart rate, atrial stiffness, blood oxygen saturation, and blood glucose levels (14). The PPG sensor consists of two components: a Light-Emitting Diode to illuminate the skin surface and a photo-detector for measuring the changes in light absorption over a period of time. The high-frequency part of the PPG signal contains information regarding heart pulsation. This part is superimposed onto a large non-pulsating lower frequency part affected by various factors which are respiration, absorption from non-vascular tissue, and sympathetic nervous system activity (13, 14).

The pulse wave analysis refers to signal processing and extraction of certain characteristic features from the PPG waveform. This method requires only one measurement sensor, PPG. Developments in computing and data analysis tools have simplified the pre- and post-processing of physiological signals such as PPG (13).

Systolic time intervals (STI) provide a temporal description of successive phases of the cardiac cycle and are physiologically influenced by the same variables that influence the left ventricular function (15). STI is one of the first non-invasive heart function tests that is simple and reliable to perform. It has shown significant diagnostic and prognostic value in evaluating the overall functions of the heart. By using systolic time intervals, successive stages of the cardiac cycle can be detected. STI is a promising tool used to follow up on the long-term condition of patients with chronic cardiovascular diseases (14, 16, 17). Figure 1 shows a PPG signal diagram indicating the points of 25% (a), 50% (b), 75% (c), and 100% (d) amplitude of the systolic peak on the systolic upstroke curve.

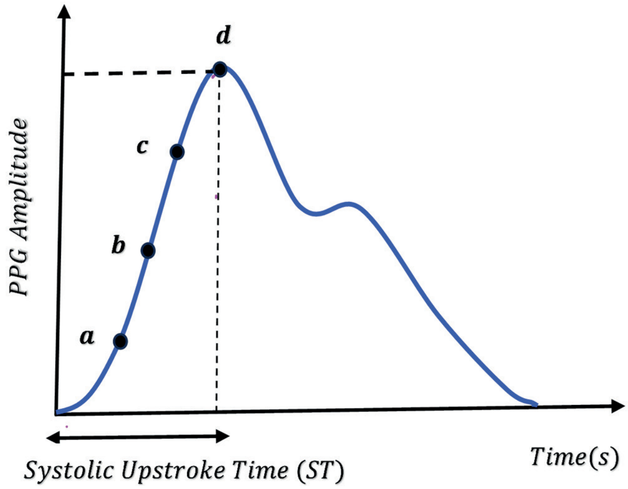

Figure 1: A PPG signal curve indicating the points of 25% (a), 50% (b), 75% (c), and 100% (d) amplitude of the systolic peak

In recent years, the use of fuzzy systems to diagnose, predict, and control diseases is increasing. Even in the detection of the Covid-19 virus, much research has been done with the help of fuzzy systems, including the works done by Painuli et al. (18), Abeer Fatima et al. (19), as well as Dehghander et al. (20, 21). Among the few cases where fuzzy systems have been used in PM, some of them are discussed. In 2015, Dehghander and his colleagues used fuzzy theory to rank the temperature of feverish diseases in Persian medicine, also known as Iranian traditional medicine. In this research, considering eleven input variables, and five output variables, and compiling 32 rules, they presented their proposed model (3). Also, in another study, Dehghander and his colleagues in 2016 used fuzzy theory to determine the retentive causes of the pulse by the pulse parameters of PM. They presented their proposed model assuming ten input variables, three output variables, and 25 rules (6). Also, Dehghandar et al., in another study in 2022 estimated the gradient of brachial blood pressure in men with 11 input variables and one output variable, and 36 rules, and explained how to estimate the gradient of brachial blood pressure in men using pulse parameters of PM (8).

Considering that PPG is a technique for measuring blood volume changes per pulse and PM pulse parameters show the quality and changes of blood in each pulse, which are very closely related, in this research with the help of a fuzzy intelligent system the PPG systolic features are estimated by PM pulse parameters.

Materials and Methods

In this study, the slope, height, and time of several selective points of the systolic upstroke curve of the PPG signal were estimated by selective pulse parameters of Persian Medicine with the help of fuzzy system design. Given the absence of similar studies, this is a pilot study with a sample population of 64 individuals. These individuals were examined at the Ahmadieh PM Clinic of Tehran University of Medical Sciences. In this research, the individuals were between 7 and 69 years old and all were healthy; heart patients were excluded from this data. First, the pulse was examined according to traditional PM pulse examination by a PM specialist physician, and the information related to the pulse parameters, including pulse frequency, strength, speed, length, and width were evaluated and recorded with very low, low, medium, high and very high values with numbers 1 to 5. Subsequently, their PPG diagrams were also recorded in 5 seconds by a PO80 beurer pulse oximeter.

The system design process is shown in Figure 2.

According to the definition of relations (2) and (4) related to the structure of the fuzzy system and their compatibility with the fuzzy systems of this research and the high accuracy of the defuzzifier of relation (3), the design of the fuzzy system based on the singletone fuzzifier, product inference engine and center average defuzzifier was performed similarly to previous studies (8, 20). To calculate the slope, height, and time of selected points of the systolic upstroke curve of the recorded PPG diagrams, first, the coordinates of the graphs were obtained for each person in a 5-second period, and the average of the systolic PPG signal was plotted using the polynomial interpolation method. Then, the slope, height, and time values at points of 25% (a), 50% (b), 75% (c), and 100% (d) amplitude of systolic peak on the systolic upstroke curve were obtained.

Next, the data were normalized, by Equation (6), to simplify and decrease the error of data comparison and after normalization; all the data were between 0 and 1.

$$x_{new} = \frac{x_{old} - x_{min}}{x_{max} - x_{min}} \qquad (6)$$

where x_{new} is the new normalized data, x_{old} is the current data, x_{min} is the smallest data, and x_{max} is the largest data.

The input data and the output data of the slope, height, and time of the systolic upstroke curve at 25% of PPG curve peak amplitude are shown in Table 1.

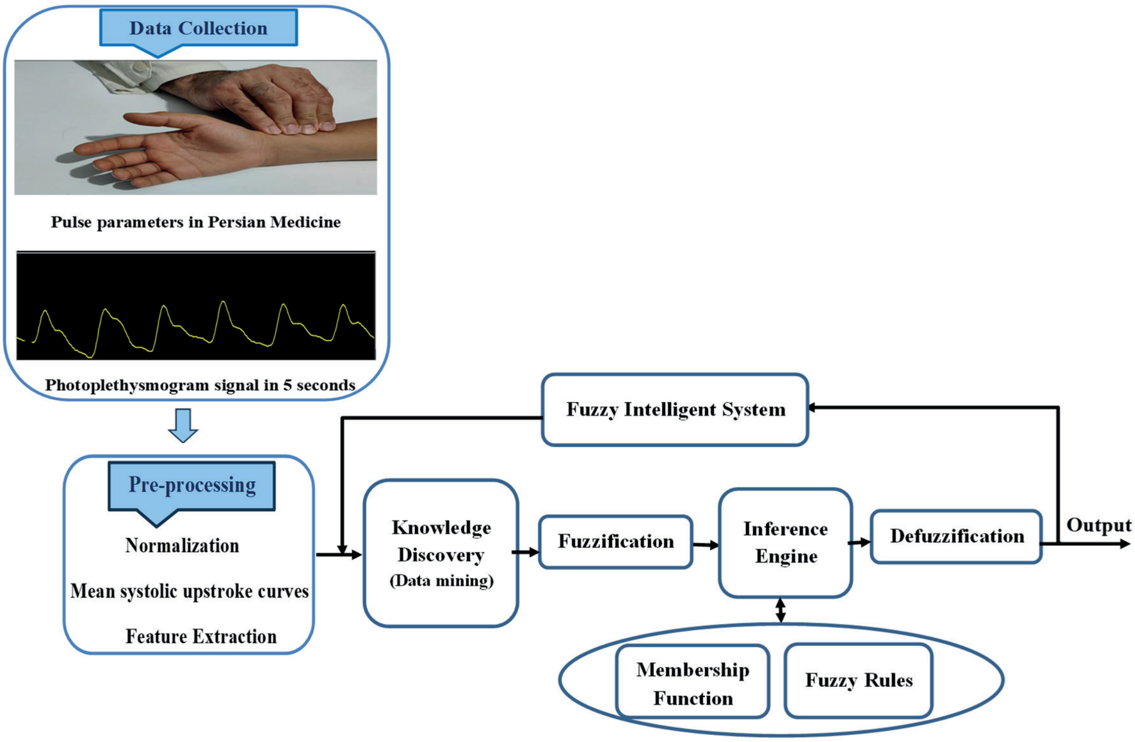

Figure 2: The flowchart of Designing a fuzzy intelligent system to estimate the PPG systolic features PM pulsology

Table 1: Values of input and output data at 25% of PPG curve peak amplitude

I/O	Variables	Max	Min	Mean
I_1	Age	69	7	35
I_2	Pulse Frequency	5	1	2.53
I_3	Pulse Strength	5	1	3.79
I_4	Pulse Speed	3	1	2
I_5	Pulse Length	3	1	2
I_6	Pulse Width	5	1	3
O_1	PPG Slope	14.5	3.2	8.85
O_2	PPG Height	51.62	16.82	34.22
O_3	PPG Time	0.0742	0.0339	0.0541

Then, all the data except speed, length, and width were normalized; therefore, taking into account the intervals obtained after data normalization, we determined the input variables of age, frequency, and strength with Gaussian Membership functions, as shown in Figure 3.

For the input variables of pulse speed, length, and width, the triangular membership function was used. In addition, the division of the output variables of slope, height, and time has been done with the Gaussian membership function, as shown in Figure 4.

The definition of fuzzy sets in the membership functions was done in such a way that the input and output spaces were covered and, therefore, complete fuzzy sets were used. Also, as can be seen, the fuzzy sets are designed in such a way that the condition of Equation (7) is satisfied in them and they are normal.

$$\forall A_i^l : \exists x_i \mid \mu_{A_i^l}(x_i) = 1 \quad (7)$$

In other words, in every fuzzy set A_i^l , there is a member x_i whose height is equal to 1. Then, 5 variables of pulse frequency, strength, speed, length, and width plus the variable of age were considered as 6 input variables, and 3 variables of slope, height, and time of the systolic upstroke curve at each point of 25%, 50%, 75%, and 100% amplitude of systolic peak of PPG curve were considered as the output variables.

Finally, as to the accuracy of the system, it is necessary to mention that the membership functions are designed to have an error of less than 0.05. In other words, if an input can activate or fire any of the designed rules, each of the fuzzy

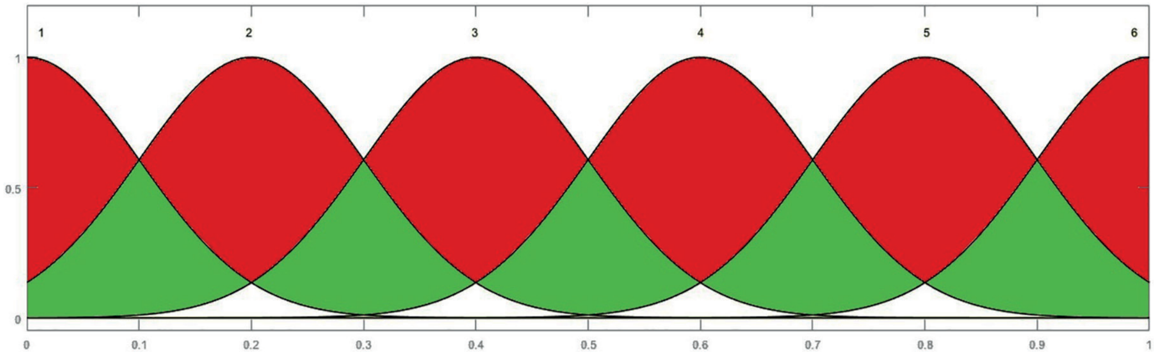

Figure 3: Membership function of input variables of age, frequency, and strength

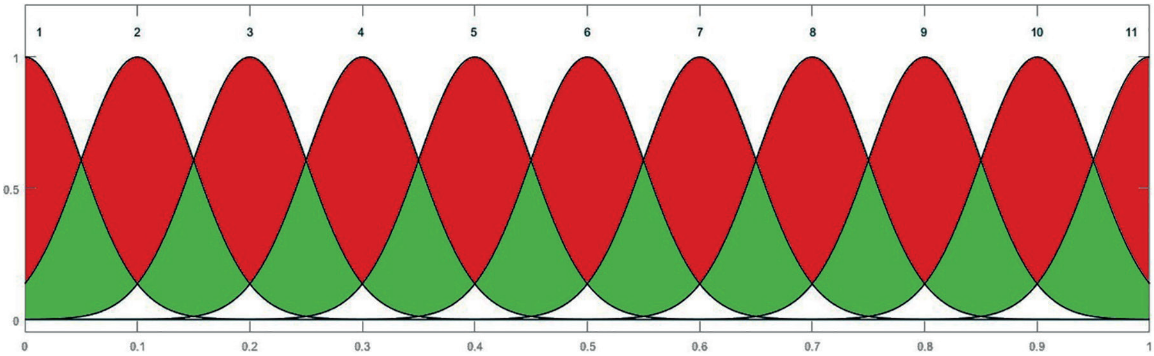

Figure 4: Membership function of the output variables of slope, height, and time

sets $A_1 \ldots A_{11}$ shown in Figure 4, will have an error of less than 0.05, according to Equation (8):

$$\forall\, y \in A_i :\ |y - Y_i| \le 0.05 \quad (8)$$

Where Y_i is center of A_i.

For example, as shown in Figure 5, if the output of fuzzy set A_6 with 0.5 as its center is used, then its estimated output will be between 0.45 and 0.55.

Results

After removing similar and conflicting rules, which were 16 in number, this system was designed with 236 rules, each of which with 59 rules at 25%, 50%, 75%, and 100% of the PPG signal, and based on the defined membership functions, the maximum error created was 0.05. In the following section, the process is shown by an example for person number 1 at point 25% of the PPG signal as follows:

For person number 1, first, in a time interval of 5 seconds, the image of PPG systolic curve was taken, which included 7 pulses; then, using the image processing tool in MATLAB software and determining their coordinates, we calculated the average PPG systolic curve using the interpolation method. A polynomial was drawn which can be seen in Figure 6.

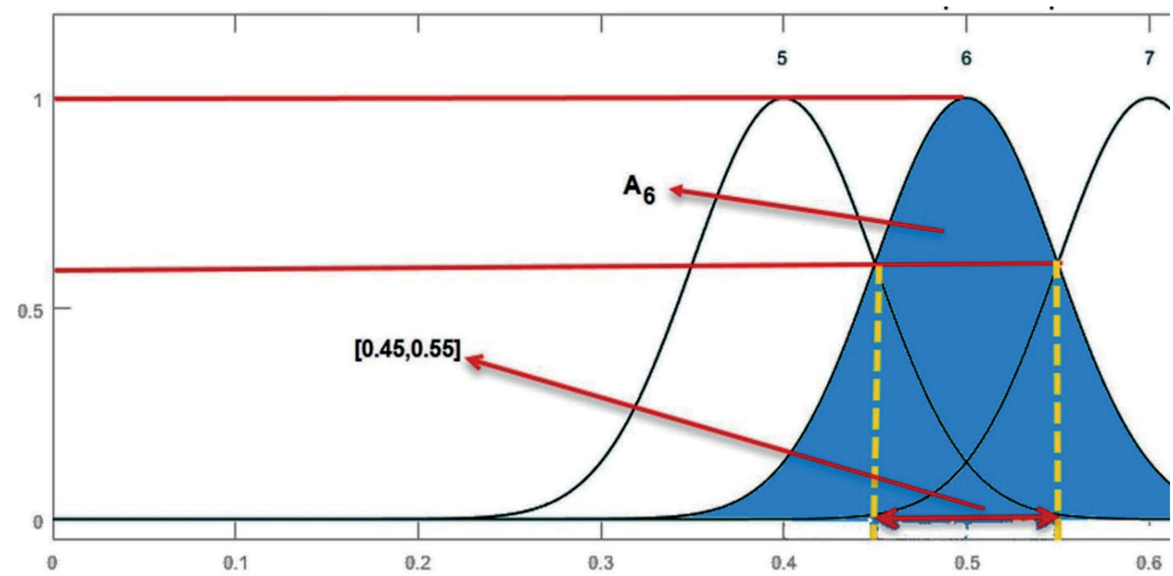

Figure 5: Interval [0.45,0.55] for each output estimate converging with the fuzzy set A_6 output membership functions

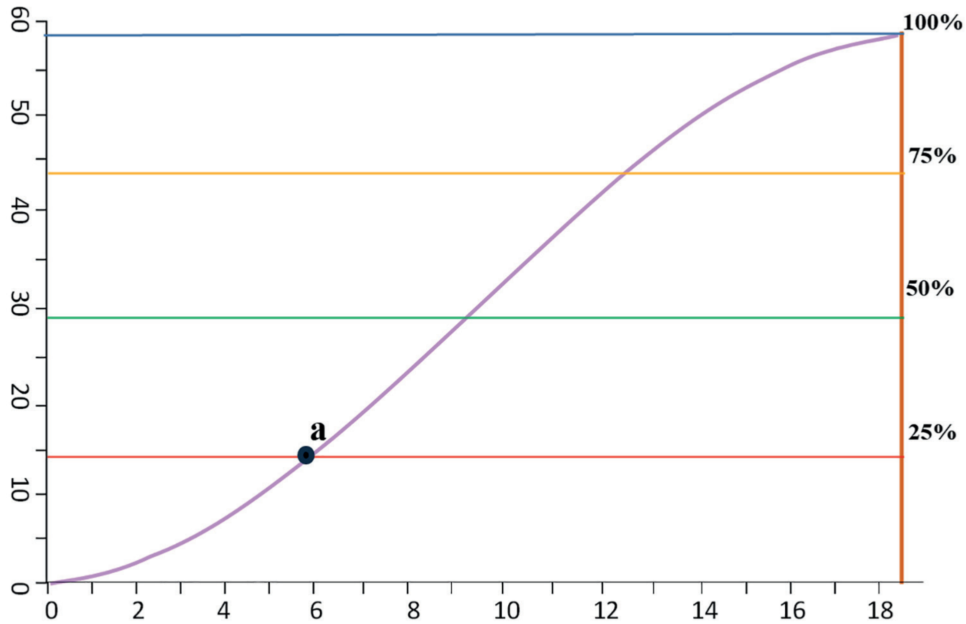

Figure 6: Systolic PPG signal plotted by interpolation, point "a" is the point of 25% of systolic peak amplitude

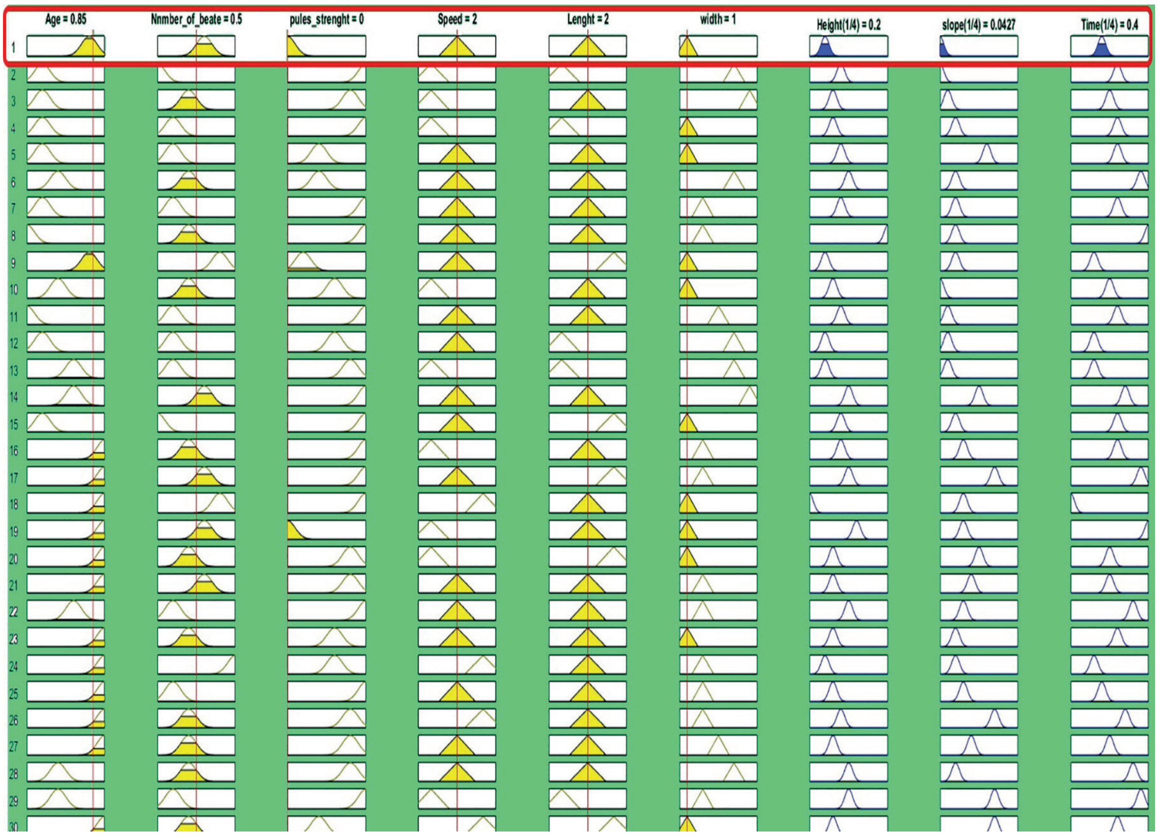

Figure 7: The 3 result outputs (right columns) of the fuzzy system by applying the 6 (left columns) input variable (0.85, 0.5, 0, 2, 2, 1)

The value of the slope, height, and time at point 25% of the PPG curve of Figure 6 was recorded as 3.63, 24.32, 0.048 for this person, which became 0.216, 0.038, 0.356 after normalization of all data. The input data comprising age and pulse parameters, including frequency, strength, speed, length, and width were also applied to the system after normalization (0.85, 0.5, 0, 2, 2, 1), as shown in Figure 7.

In Figure 7, it can be seen that by applying the input (0.85, 0.5, 0, 2, 2, 1), rule 1 is activated and the output of the system for slope, height, and time at point "a" has been estimated 0.2, 0.0427, and 0.4. Considering that the actual values of this output are 0.216, 0.038, 0.356, it can be seen that the error is 0.016 in the slope, 0.0047 in the height, and 0.044 in the time value, which means a maximum error of 0.044 in this example. It is noteworthy that all the error values were less than the specified error limit of 0.05.

Discussion and Conclusion

As mentioned, the aim of this research was to evaluate the usability of Persian medicine pulsology to estimate the slope, height, and time of the systolic curve of the PPG signal with the help of a fuzzy system design. A fuzzy system was designed based on product inference engine and center average defuzzifier. In this system, by compiling 236 rules, acceptable estimates of the slope, height, and time of the systolic upstroke curve at the points of 25%, 50%, 75%, and 100% amplitude of the PPG curve were obtained by PM pulse parameters including frequency, strength, speed, length, and width. According to the definition of membership functions, the maximum error produced was 0.05.

Eventually, according to the set acceptable error value of 0.05 which was based upon the design method of the membership functions for the input and output values of the system and also the results showing errors less than 0.05, the estimation is considered to be acceptable.

With only 64 individuals, reaching an acceptable precision of less than 0.05 error may be considered innovative. On the other hand, due to the lack of similar previous studies to be used as a reference for comparison or verification, it seems that at the pilot study level, the designed system is useful and applicable as it estimates PPG systolic features by using PM pulsology with an error of less than 0.05. However, with more data and variables, its efficiency may be improved.

In previous studies such as (3, 6-8) that were conducted using artificial intelligence and fuzzy systems in PM, the connection and bridge between conventional medicine and PM were not seriously discussed, but in this research, such a connection was made with the correlation of the PPG signal with PM pulsology.

Also, there are concerns and considerations regarding the analysis of pulse results by specialist physician and the training of students in PM because the pulse examination in PM is performed with the fingers of an expert, which can be associated with errors and inferences. The pulse rules are complicated due to the large number of these rules, but by using the PPG signal, this error will be greatly reduced and the analysis results will be much more reliable. Given that PM pulse parameters show the quality and changes of blood in each pulse and PPG is a technique for measuring blood volume changes per pulse, which are very closely related, with the help of a fuzzy intelligent system the PPG systolic features are estimated by PM pulse parameters which can have significant applications and ease the work for similar studies and research in this field.

Subsequently, considering the significant diagnostic and prognostic value of systolic PPG intervals as one of the first-line non-invasive indicators of heart function and also considering the importance of pulse diagnosis in PM, the use of artificial intelligence may not only help increase both clinical skills of PM students/practitioners and accuracy of disease diagnosis and prediction, but also may be promising to bridge the gap between PM and mainstream medicine and help advance the global movement toward integrative medicine.

Ethical Approval

In this study, after obtaining informed consent for admission at Ahmadieh PM Clinic of Tehran University of Medical Sciences as a research and training clinic, we considered only routine pulse examination and plethysmography data obtained for health benefits in the analysis; in addition, no confidential personal information or interventions were involved and thus no additional ethical approval was necessary for this work.

Data Availability

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

Conflict of Interest

There are no conflicts of interest

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