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The Correlation Study of Cun, Guan and Chi Position Based on Wrist Pulse Characteristics

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ABSTRACT To analyze the correlation of pulse characteristics at different acquisition positions, the pulse parameters that can identify different pulse and physiological information are given. In this paper, the relevance and difference of wrist pulse characteristics at Cun, Guan and Chi position were studied by pulse diagnosis instrument and time-frequency, frequency-domain and time-frequency domain analysis methods etc. Firstly, the pulse information of Cun, Guan and Chi position is collected from 206 healthy adults. The 66 pulse characteristics of each sampled location are extracted. In addition, the 66 feature indexes of each position are used to calculate the Spearman correlation coefficients among Cun, Guan, Chi position as well as the both hands in detail. Finally, the relevance and difference of wrist pulse at Cun, Guan and Chi position were studied and analyzed by significance test. The pulse characteristics with high correlation at Cun-Guan-Chi position of left and right hands are mainly power spectrum characteristics and time-frequency characteristics, while the features with high correlation between both hands mostly concentrate in the time domain characteristics. This work has studied the relationship between the position of pulse acquisition from quantitative and qualitative aspects, and laid a foundation for the objective diagnosis of pulse condition and the comprehensive disclosure of pulse information.

INDEX TERMS TCM, Cun-Guan-Chi, relevance, difference, pulse characteristics.

I. INTRODUCTION

Pulse feeling, reflecting the rate of the heartbeat, has been widely used in traditional Chinese medicine (TCM) to diagnose various diseases, which can be traced back to 4000 years ago [1]. Modern medical research indicates that the wrist pulse signals are mainly produced by the contraction and relaxation of the heart, and also are affected by the blood movement and the change of the diameter of blood vessels, making them effective for analyzing both cardiac and non-cardiac diseases [2]. The pressure of the radial artery not only plays a role in cardiovascular function assessment [3], but also reflects biological signals that reveal valuable internal physiological information about the entire body [4], [5].

According to TCM method, the terminal region of the radial artery can be divided into three adjacent intervals, namely Cun, Guan and Chi, with the location shown in Figure 1 [6].

A palpation position called Guan is located on the radial artery closest to the styloid process. Cun is about 10mm distal from Guan and Chi about 10 to 15mm proximal from Guan. Each position is divided into three indicators, Superficial, Medium, and Deep in the vertical direction, thereby giving rise to nine indicators. Superficial(Fu), Medium(Zhong), and Deep(Chen) simultaneously are used to observe the physiological or pathological conditions of different organs from different levels and depths at the Cun, Guan and Chi position, which is called ‘‘three positions and nine indicators’’ of TCM [7]. The three positions of the radial artery correspond to the meridians and the visceral organs as illustrated in Table 1. The Cun positions of left and right hands represent the heart and lung, respectively. The Guan positions of left and right hands reflect the health status of liver and stomach, respectively. The Chi positions of the both hands usually reflect the kidney condition. Therefore, the characteristics of

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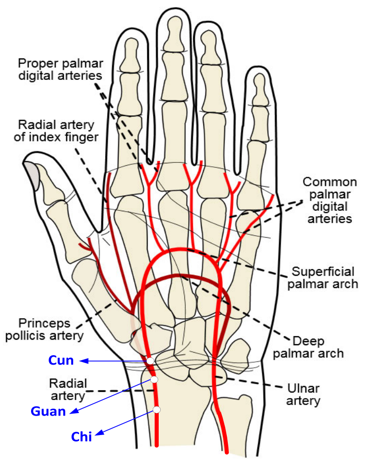

FIGURE 1. The position of Cun, Guan and Chi.

TABLE 1. Mapping the Cun Guan and Chi displacements versus organ of body.

Position	Cun	Guan	Chi
Left arterial wrist	Heart	Liver/Gallbladder	Kidney
Right arterial wrist	Lung/Chest	Stomach	Kidney

Cun, Guan and Chi positions have different meanings and directly reflect the states of different organs of the human body [8]–[10].

On the other hand, the TCM diagnostic of pulse has been widely used in clinical field. The fluctuation frequency, strength, length and width of pulse reflect the real-time situation of human body, respectively. A comprehensive and accurate understanding of the Cun, Guan and Chi position is particularly important for doctors to better grasp the patient's physical information and illness. TCM doctors often use three fingers (index finger, middle finger and ring finger) to diagnose disease in the three radial artery positions, shown in Figure 2. They will perceive the pulse morphology to determine the states of different organs by applying vary pressure simultaneously or sequentially on the three regions and record the change of the required pulse wave. The trained practitioners can gather elaborate physiological and pathological information on the cardiovascular system, organ functions, patients' constitution, behavioral patterns, and previous illness, as well as body's homeostatic balance by diagnosing the condition of pulse [11]–[14].

Despite pulse diagnosis is frequently used in clinics, it has been criticized and doubted by Western practitioners for lack of scientific evidence and characterization of mathematically and physically. Therefore, in order to provide sound scientific evidence and overcome the experiential boundary of pulse diagnosis, it is necessary to define the objective techniques with standardized protocols to obtain pulse signals, and to explain the physical parameters of wrist pulse from the qualitative and quantitative perspectives [15], [16]. Nowadays, with the development of pulse-taking device manufacturing

FIGURE 2. Pulse-taking map at Cun, Guan and Chi position.

technology, the quantification and objectification of pulse diagnosis have made great progress. Several scientific and digital analysis approaches of pulse have been undertaken in recent years. According to the theory of the palpation site and organ, the physiological information expressed at the Cun, Guan and Chi positions has become one of the research focuses [17]. Luo *et al.* designed a dual sense pulse diagnostic instrument that can imitate the pulse diagnosis skills method of ''three positions and nine indicators'' of TCM physicians to obtain the pulse signals of patients. Moreover, his research aimed to examine the pulse appearance sequence in a healthy patient recorded and quantify the pulse diagnosis skills and sensations of TCM physicians at Cun, Guan and Chi positions using the well-known TCM guidelines [18], [19]. Wu *et al.* adopted the optical measurement method to construct the acquisition system of Cun, Guan and Chi position by using three-dimensional digital image, and the displacements of the three acquisition parts were analyzed and recorded according to the pulse amplitude, pressure and other factors [20]. Zhang *et al.* designed a device to detect the pulse image of Cun, Guan and Chi position by 3D image reconstruction and some features were extracted and analyzed including the period, frequency, width, and length etc., [21]. Chu *et al.* studied the difference between pulse-taking depths (Fu, Zhong, and Chen) and pulse-taking positions (Cun, Guan, and Chi). Four parameters, namely peak value, power, ascending slope, and descending slope were elucidated from 3DPM using a two-way analysis of variance [22].

From the point of physics and mathematics, the pulse signal can be regarded as quasi-periodic signal fluctuation. Due to the physical characteristics similarity of pulse signal, acoustic signal and electromagnetic signal, sound and electrical signals, it is a feasible method to study pulse by using physical and mathematical analysis methods to verify the theory of TCM. At present, pulse analysis methods mainly include time domain analysis, frequency domain analysis, time-frequency analysis and nonlinear analysis etc., [23]–[26]. Time domain and frequency domain are often used to investigate the dynamics of radial pulse. The time domain analysis can investigate the amplitude and shape of the arterial waveform. The time domain analysis method mainly explains the waveform by analyzing the main wave parameters, strong pulse wave, amplitude ratio, time value, angle, area value and the internal relationship of pulse change. While the frequency domain method transforms the pulse wave curve from time domain to frequency domain through discrete fast transformation, and obtains the corresponding pulse spectrum curve, from which the information about human physiology is extracted to realize the feature classification. The nonlinear analysis mainly uses the phase space theory, fractal theory and chaos theory to describe and control the dynamic characteristics of the waveform. Clearly, the experimental methodologies used for current research have been widely used in waveform analysis and many useful achievements have been achieved. Lee *et al.* examine the location of Cun, Guan and Chi in the wrist and the relationship between the physical indexes and the anatomical characteristics in healthy Korean adults by time domain feature method [27]. Chang *et al.* used the spectrum analysis method to get the harmonics of $C_0 \sim C_{10}$ at the Cun, Guan and Chi position. His research shows that there are significant differences in harmonics at different positions of Cun, Guan and Chi. The harmonics of the same indicator at different positions and different indicators for the same position are different [7]. Kim *et al.* assess the association of obesity with anatomical and physical indices at Cun, Guan, and Chi positions related to the radial artery by binary logistic regression method [28]. Su *et al.* studied the direct relationship between the hemodynamic state and the position of ''three positions and nine indicators'' by time domain method [14].

However, most of the existing literature works are focused on the previous morphological analysis of pulse, few researches have focused on the characteristics correlation analysis of Cun, Guan and Chi positions. As a matter of fact, there is a strong relationship among the Cun, Guan and Chi three positions in some characteristics. To understand their relationship and difference effectively can help us better understand the working state and external connection of human organs. The pulse parameters that can identify different pulse and physiological information can be given by analyzing the difference and relevance of three pulse acquisition locations. Consequently, it is more interesting to study the relationship of the Cun, Guan and Chi three positions. To the best of author′s knowledge, the research on the Cun, Guan and Chi problem among is still open and remains challenging.

Motivated by the previous works, the relevance and difference of pulse signal characteristics at Cun, Guan and Chi positions were studied. Firstly, the pulse characteristics of Cun, Guan and Chi three acquisition positions were collected from healthy adults, and the features of time domain, frequency domain, time-frequency domain and high-order statistics etc. were extracted, respectively. Secondly, combined with different multi-feature forms, the 66 feature indexes of each acquisition position were used to calculate the Spearman correlation coefficients between Cun, Guan, Chi position as well as the both hands in detail after classifying the volunteers' wrist pulse and giving an initial diagnosis. Finally, the relevance and difference at Cun, Guan and Chi position of wrist pulse were studied and analyzed by significance test. Also, a brief description was given about the physical indexes and physiological properties.

FIGURE 3. ZM-300 intelligent pulse meter.

With all these considerations, the rest of this paper is organized as follows. In Sec. 2, some preliminary work is introduced. In Sec. 3, the analytical principle is described in detail, some computations and concepts of characteristics are briefly recalled, and significance test is outlined. In Sec. 4, the experimental results and analysis are explicitly presented. Finally, some conclusions and suggestions are given in Sec. 5.

II. MATERIALS

A. RECRUITMENT OF TEST PARTICIPANTS

A total of 206 volunteers from Zhengzhou University have been recruited in this study, with a mean age of 24.2 ± 3.5. Among the 206 volunteers, male and female are 104 and 102, respectively. There was no statistical significance ($p > 0.01$) in the ages of volunteers. The study protocol was approved by the Fifth Affiliated Hospital of Zhengzhou University. All volunteers agreed with the exposed terms by signing a written informed consent. In addition, each participant has a questionnaire to ensure the accuracy of the experiment. The basic physiological data of the subjects are summarized Mean ± SD in Table 2. Data were collected by ZM-300 Intelligent Pulse Meter of TCM, which the sampling frequency is 200Hz. The volunteers were asked to sit still or rest for at least 5 minutes before the acquisition. During the collecting process, participants were required to sit or stay supine, relax, not talk and breathe normally. Then, the TCM pulse bracelet was placed over the Cun, Guan and Chi position in the left hand and right hand to capture the pulse signals under six pressures for 10 seconds, respectively. Subjects were excluded from analysis if they lacked complete data for control or outcome variables or had significant disease. Each person collects six groups of data under six different pulse pressures, each group of data consists of 2000 data points. The average displacement of pulse data collected under the optimal pulse pressure is shown in the Table 3.

B. DATA PREPROCESSING

During the pulse acquisition, the pulse signals inevitably be contaminated by subject's respiration and artifact motion,

TABLE 2. Basic physiological data of the participants.

Characteristic	Number or Mean ± SD
Number(n)	206 (male = 104, female = 102)
Age (year)	24.2 ± 3.5
Height (cm)	169.2 ± 8.3
Weight (kg)	66.5 ± 12.3
BMI (kg/m^2)	20.6 ± 4.2
Systolic/diastolic blood pressure (mmHg)	115.5/67.8 ± 16.8/6.4

TABLE 3. Displacement spans for different acquisition position.

Position	Cun	Cuan	Chi
Displacement(mm)	2.6858±0.5054	3.3915±0.7546	3.7519±0.8274

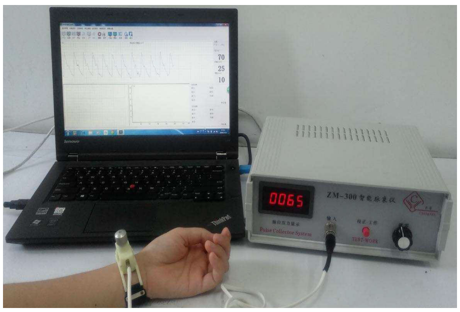

FIGURE 4. Pulse acquisition.

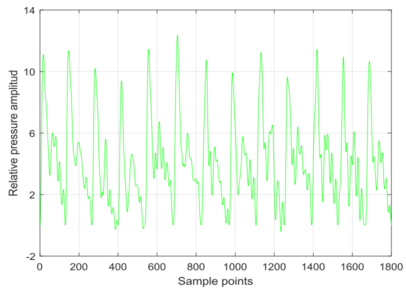

FIGURE 6. Denoised and baseline-removed pulse signal.

etc. Consequently, preprocessing is crucial to attenuate noise and remove the pulse waveform's baseline drift before further analysis. The robust signal preprocessing framework and wavelet-based cascaded adaptive filter are used to denoise and removed baseline wander of pulse wave, respectively. [29], [30]. The original pulse wave and preprocessed pulse wave are shown in Figure 5 and Figure 6, respectively. The abscissa is the number of sampling points, and the ordinate is the relative pressure amplitude in the Figure 5 and Figure 6. Obviously, the characteristics of the original waveform are more clear and easy to extract after de-noising and de-drifting. Thus, pulse features can be extracted more effectively and accurately.

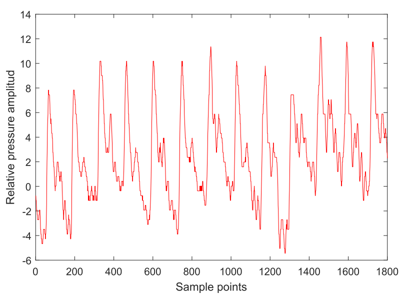

FIGURE 5. Original pulse signal.

III. METHODS

In order to make this work self-contained, some basic concepts of waveform feature are given.

A. TIME DOMAIN FEATURES

Time domain features are used to analyze the dynamic characteristics of signal in time direction. The feature extraction of pulse signal mostly uses time domain analysis method to find out the internal relationship between waveform characteristics and physiological information. The analysis method mainly includes visual morphology method, multi-factor pulse recognition method, pulse rate diagram method, pulse area method and so on. Since pulse wave is the manifestation of various information carried by heart ejection activity and pulse wave propagating along all levels of arteries and vessels. Therefore, the rise, fall, wave and isthmus of pulse wave have corresponding physiological significance. In this study, 23 pulse time domain features were chose for analysis including t_1, t_2, t_3, t_4, t_5, h_1, h_2, h_3, h_4, h_5, A_s, A_d, t, w_1, w_2, A, h_3/h_1, h_4/h_1, h_5/h_1, w_1/t, w_2/t, t_1/t, t_5/t_4.

A typical cycle of measured pulse signal is illustrated including main parameters that are often used to characterize the waveform in Figure 7 and Figure 8.

B. FREQUENCY DOMAIN FEATURES

The frequency domain analysis is to the time domain characteristics are transformed to the frequency domain by the dis-

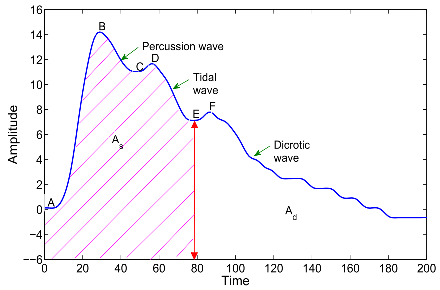

FIGURE 7. The time domain characteristics of pulse.

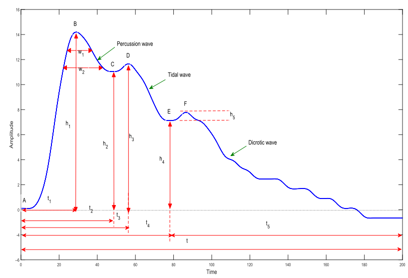

FIGURE 8. The systolic and diastolic area of pulse.

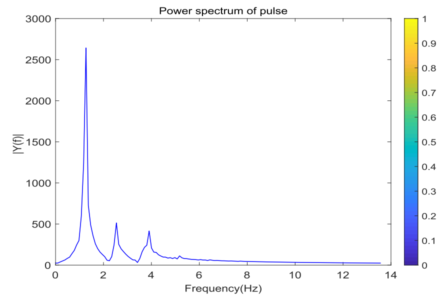

FIGURE 9. The power spectrum of healthy adult.

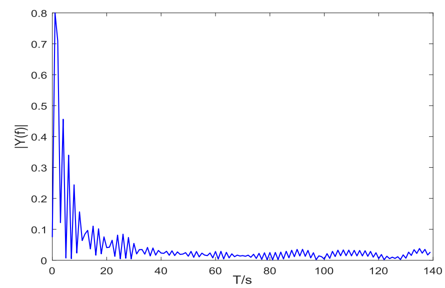

FIGURE 10. The cepstrum spectrum of healthy adult.

crete fast Fourier transform, so as to obtain the corresponding pulse spectrum curve. The frequency domain mainly analysis includes the power spectrum analysis and the cepstrum analysis. For all kinds of pulse at Cun, Guan and Chi three positions, the intensity of pulse signal is different due to the difference of physique, physiology and pathology. Therefore, it is very necessary to discuss the correlation and difference of pulse signals from frequency domain aspects.

Power spectrum, namely power spectral density function (PSD), which is defined as the signal power in unit frequency band. Power spectrum analysis of arterial pulse mainly focuses on the identification of diseases and the relationship among diseases, syndromes and meridians. Cepstrum analysis is mainly taking logarithm of the sample spectrum and then performing Fourier transformation to transform frequency domain information into cepstrum domain information for analysis. The purpose of logarithm is to make the peaks of different sizes in the spectrum by different multiples, and enhance the smaller peaks to reflect the characteristic differences between different signals. Specifically, the power spectrum and cepstrum for pulse signal $x(t)$ are calculated as follows

$$S_x(f) = |F\{x(t)\}|^2 \tag{1}$$
$$C_x(\tau) = F^{-1}\{10logS_x(f)\} \tag{2}$$

For pulse signal $x'(t) = kx(t)$, its power spectrum and cepstrum are

$$S_{x'}(f) = |F\{kx(t)\}|^2 = k^2|F\{x(t)\}|^2 \tag{3}$$
$$\begin{aligned} C_{x'}(\tau) &= F^{-1}\{10logS_{x'}(f)\} \\ &= F^{-1}\{20logk\} + F^{-1}\{10logS_x(f)\} \end{aligned} \tag{4}$$

where, $F\{\}$ and $F^{-1}\{\}$ are Fourier transform and inverse transform, respectively. The amplitude of the three harmonics and corresponding frequencies and the first 30 cepstrum coefficients are taken as the power spectrum characteristics and cepstrum characteristics in this study, respectively.

C. HIGH ORDER STATISTICS

Higher order statistics refer to statistics with order greater than second order, such as higher-order moment, higher-order cumulant, higher-order moment spectrum and higher-order cumulant spectrum. Compared with the traditional second order statistics such as variance, covariance and power spectrum, the high order statistics method not only retains the signal amplitude information, but also reveals the signal phase information. At present, the higher order statistics have mean, median, divergence, kurtosis etc., here, the skewness and kurtosis are used to analysis pulse distribution.

Skewness is a statistic that describes the skew direction and degree of data distribution. The skewness is defined as the third power of the third-order central moment divided by the standard deviation, that is, the third-order standard center distance of the sample. The Skewness is used to describe the symmetry of pulse waveform in this paper.

$$S_k = (\frac{1}{n}\sum_{i=1}^{N}(x_i - \overline{x})^3)/(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2})^3 \tag{5}$$

Kurtosis is a numerical statistic that reflects the distribution characteristics of random variables. It is actually the

TABLE 4. The higher order statistics values.

Position	Left Hand			Right Hand		
	S^2	S_k	K_u	S^2	S_k	K_u
Chi	6.077	0.635	2.299	13.385	0.678	2.657
	5.877	0.837	2.590	9.982	0.874	3.085
	6.459	0.848	3.278	3.505	0.687	2.945
	5.065	1.058	3.384	13.547	0.354	2.086
	16.587	0.195	1.869	14.154	0.457	2.358
	8.630	0.505	2.398	6.857	0.482	2.458
	16.598	0.827	2.859	2.857	0.339	2.433
	6.950	0.445	2.291	8.576	0.657	2.124
	7.2778	0.498	2.381	11.427	0.522	2.227
	22.295	0.790	2.906	18.251	0.658	2.536
Guan	16.547	0.758	2.754	15.547	0.457	2.147
	16.789	0.305	2.105	6.235	0.445	2.547
	6.879	0.245	1.958	5.114	0.614	2.614
	4.295	0.278	1.855	2.257	0.814	2.452
	10.235	0.566	2.385	20.078	0.458	2.167
	15.758	0.785	2.785	13.284	0.333	2.137
	18.048	0.625	2.564	21.845	0.541	2.507
	8.546	0.445	2.255	26.097	0.751	2.455
	9.534	0.657	2.582	27.856	0.596	2.856
	4.857	0.628	2.508	11.604	0.785	2.802
Gun	10.525	0.585	2.257	15.899	0.524	2.358
	11.814	0.845	2.958	2.458	0.778	2.855
	12.258	0.357	3.231	3.582	0.809	2.779
	13.101	0.342	2.054	2.457	0.625	2.566
	7.095	0.740	1.975	6.458	0.224	1.882
	20.201	0.588	2.675	9.851	0.541	3.541
	23.852	0.835	2.584	16.472	0.465	2.637
	6.565	0.245	3.048	11.952	0.585	2.365
	10.289	0.575	1.958	11.982	0.409	2.205
	15.574	0.495	2.058	2.058	0.865	2.909

normalized fourth-order center distance of the signal.

$$K_u = (\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^4)^{\frac{1}{4}} \tag{6}$$

Kurtosis factor is derived from kurtosis, which is defined as

$$K_r = K_u / \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2} \tag{7}$$

where, x_i is the signal to be analyzed, $\overline{x}$ is the mean value of the signal, N is the number of sampling points in the signal. Kurtosis and kurtosis factors are used to describe the amplitude distribution of pulse signals. In addition, the above statistical measure is 0 for Gaussian distribution. Therefore, variance is added as the pulse distribution feature and the following formula is given.

$$S^2 = \frac{1}{N}[(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \cdots + (x_N - \bar{x})^2] \tag{8}$$

Variance can be used to measure the dispersion of variables. Skewness and Kurtosis are compared with normal distribution. Related studies have found that the pulse wave of a complete cardiac cycle is right deviation, so the Skewness is greater than zero. Kurtosis is used to describe the steepness of distribution of all variables. If the shape of pulse graph is steep, the kurtosis is greater than zero, vice versa. The Skewness, Kurtosis and Variance values calculated are shown in Table 4.

D. TIME-FREQUENCY FEATURES

The time-frequency domain can combine the time-domain and frequency-domain information to reflect that the energy of the signal varies with time at different frequencies. The wavelet frequency division is linear and the width is fixed, which does not change with the frequency. The pulse signal is transformed by wavelet, and the result is drawn by time-frequency diagram, which can directly reflect the pulse energy in different states. The calculation formula of wavelet transformation as follows

$$X_\omega(a, b) = \frac{1}{|a|^{\frac{1}{2}}}\int_{-\propto}^{+\propto} x(t)\overline{\psi}(\frac{t-b}{a})dt \tag{9}$$

where, $\overline{\psi}$ is the mother wavelet function, a is the scale coefficient, b is the translation coefficient, $x(t)$ is the time series, $X_\omega(a, b)$ is the wavelet coefficient.

In frequency domain, it can be expressed as follows

$$X_\omega(a, b) = \frac{|a|^{\frac{1}{2}}}{2\pi}\int_{-\propto}^{+\propto} X(\omega)\overline{\psi}(a\omega)e^{j\omega b}d\omega \tag{10}$$

where, X_ω and $\psi(\omega)$ are the Fourier transformation forms of $x(t)$ and $\psi(t)$, respectively.

Because of the strong periodicity of pulse signal, the distribution of time-frequency energy of pulse signal is relatively concentrated in a certain frequency band, and it is basically concentrated in about 0-4Hz. Therefore, the energy of 0-4Hz is divided into four sections, namely

TABLE 5. The energy value of each frequency band.

Frequency/Hz	Left Hand(Mean±Sd)/dB			Right Hand(Mean±Sd)/dB		
	Cun	Guan	Chi	Cun	Guan	Chi
0-1	1.6591±0.9691	1.3633±0.7512	1.9861±0.3768	1.7501±0.9318	1.4932±0.6055	1.4446±0.8341
1-2	2.3268±0.5750	3.4551±0.5955	2.7859±0.3045	1.6789±1.7178	3.0656±0.2463	2.4975±0.9350
2-3	0.6460±0.4916	1.7254±0.5395	0.7587±0.4438	0.3708±0.3248	1.5798±0.3035	0.6435±0.3136
3-4	0.8702±0.4457	0.5957±0.3530	0.5825±0.3652	0.6487 ±0.4079	0.4815±0.2150	0.5416±0.3645

TABLE 6. Pulse characteristics and physiological significance.

Pulse characteristics	Physiological significance
t_1	The time from the beginning of the pulse wave to the peak of the main wave, which corresponds to the rapid ejection period of the left ventricle.
t_2	The time between the starting point of pulse wave diagram and the main wave isthmus.
t_3	The time from the starting point of the pulse wave diagram to the peak of the wave before the heavy pulse corresponds to the arterial tension, resistance state and pulse reflection velocity.
t_4	The time between the starting point of the pulse wave diagram and the descending isthmus, which corresponds to the systolic phase of the left ventricle.
t_5	The time from descending the middle isthmus to the end of a cycle, which corresponds to the diastolic phase of the left ventricle.
t	The time value from the start point to the end point on the pulse graph, which includes left ventricular systolic and diastolic duration.
h_1	Main wave amplitude. It reflects the compliance of the aorta and the cardiac ejection function of the left ventricular. The higher h_1, the stronger the left ventricular contractility.
h_2	Main isthmus wave amplitude. Same physiological significance as h_3.
h_3	Heavy wave front wave amplitude. It reflects the elasticity of arterial vessels and its peripheral resistance.
h_4	Dicrotic notch amplitude. It reflects the peripheral resistance of arterial vessels and the closure of aortic valve.
h_5	Gravity wave amplitude. It reflects the compliance of the aorta and the function of aortic valve.
w_1	The width at $\frac{1}{3}$ of the main wave. The duration of maintaining high intravascular pressure.
w_2	The width at $\frac{1}{5}$ of the main wave. The duration of maintaining high intravascular pressure.
A_s	Systolic area. The area on the pulse graph is related to cardiac output.
A_d	Diastolic area. It is the diastolic area between arterial pressure and venous pressure.
A	The sum of systolic and diastolic areas of pulse wave.
$\frac{w_1}{t}$	The ratio of the width of the main wave at its $\frac{1}{3}$ height to the entire pulse cycle. It reflects the proportion of the duration time of continuous high pressure in the aorta in the entire pulse cycle.
$\frac{w_2}{t}$	The ratio of the width of the main wave at its $\frac{1}{5}$ height to the entire pulse cycle.The proportion of the duration time of continuous high pressure in the aorta in the entire pulse cycle.
$\frac{h_3}{h_1}$	Tension coefficient, which corresponds to the compliance and peripheral resistance of the vessel wall.
$\frac{h_4}{h_1}$	Resistance coefficient, which corresponds to the peripheral resistance. The coefficient increase reflects the increase of peripheral resistance.
$\frac{h_5}{h_1}$	This coefficient refers to aortic compliance and aortic valve function, which less than or equal to 0 reflects poor arterial compliance or aortic valve insufficiency.
$\frac{t_1}{t}$	This coefficient corresponds to cardiac ejection function. High coefficient reflects the decrease of left ventricular systolic function and ejection rate.
$\frac{t_5}{t_4}$	Heart rate, reflecting the acceleration of heart rate.
S_x	Frequency spectrum characteristics of pulse signal.
C_x	Power spectrum characteristics of pulse signal.
S_k	Skew direction and degree of pulse signal distribution.
K_u	Random distribution characteristics of pulse signal.
S^2	Central variance of random distribution of pulse signal
dB	The average energy value of each frequency band in 0-4Hz.

0-1Hz, 1-2HZ, 2-3Hz, 3-4Hz, then the average energy of each segment is taken as time-frequency feature. The energy values of each frequency band are shown in the Table 5.

In general, multi-domain features extraction are implemented in time domain, frequency domain, time-frequency domain and high order statistics. The higher-order statistics and variance are used as supplementary features in time domain, then 26 time domain features are obtained in total. The 36 frequency-domain characteristics are extracted including the 3 harmonic amplitudes and corresponding frequency values and 30 cepstrum coefficients of wrist pulse. The 4 time-frequency energy values obtained by wavelet transformation are used as time-frequency characteristics. Therefore, 66 physiological wrist characteristics can be obtained from each position of the Cun, Guan and Chi, respectively. The pulse characteristics and physiological significance are shown in Table 6.

E. STATISTICAL ANALYSIS

All statistical analyses of clinical data were conducted using SPSS for Windows and t test is used to test the normality assumption before statistical analysis. The statistical tests were performed after logarithmic transformation of the variables that did not satisfy the normality assumption were skewed. Spearman correlation coefficient is a nonparametric index to measure the dependence of two variables, which is evaluated by monotone equation. Moreover, the Spearman correlation coefficient is not affected by outliers and sample size and has a wide range of applications. Therefore, the Spearman correlation coefficients are used to judge the correlation among multi-domain features of pulse. For the sample size N, N original data are converted into hierarchical data, and the correlation coefficient ρ is defined as follows

$$\rho = \frac{\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2(y_i - \overline{y})^2}} \tag{11}$$

The relevance and difference were analysed using two-sample t-tests and analysis of covariance at Cun, Guan, and Chi positions.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, a series of comparative experiments were conducted. All subjects completed the experimental trials and measurements. The relationship analysis of multi-features between Cun, Guan, and Chi position of the left and right hands are presented. Furthermore, the statistical difference analysis is adopted to evaluate the difference of Cun, Guan, and Chi position.

A. THE CORRELATION ANALYSIS OF PULSE FEATURES AT CUN, GUAN AND CHI POSITION

In this section, the 66 pulse characteristics data of each acquisition position were used to study the correlation among the three pulse acquisition positions. The Spearman correlation coefficient graphs of pulse features at Cun, Guan and Chi position of both hands are shown in the Figure 11, Figure 12 and Figure 13, respectively.

The curves of three different color represent the correlation among the three position of Cun, Guan and Chi, respectively, as shown in the Figure 11 - 13. Every turning point represents a pulse feature point. Each figure is divided into five parts, which represents time domain features, time domain supplementary features, cepstrum features, power spectrum features and time-frequency energy characteristics. Part 1 is 23 time domain pulse parameter features, Part 2 is time domain supplementary features such as variance and high-order statistics, Part 3 and Part 4 represent cepstrum features and power spectrum features, respectively, Part 5 is

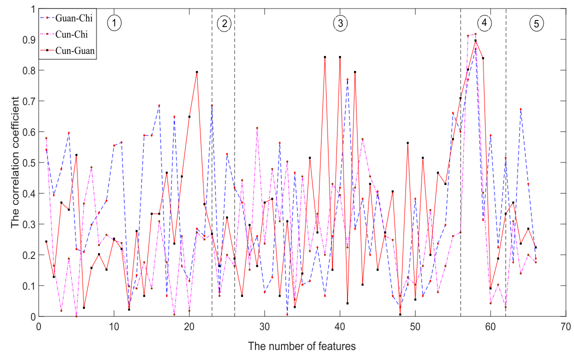

FIGURE 11. The correlation of pulse features at Cun-Guan-Chi position of left hand.

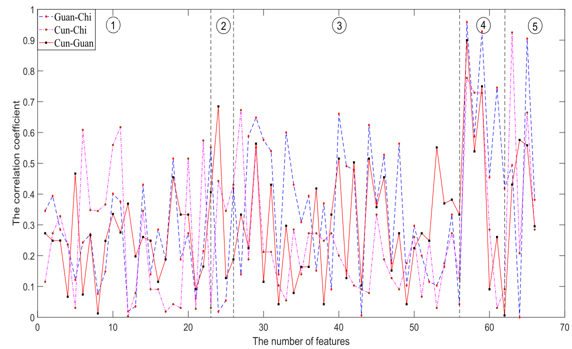

FIGURE 12. The correlation of pulse features at Cun-Guan-Chi position of right hand.

time-frequency energy features. In order to make it easier to observe the Figure 11-13 for readers and better explain the correlation of different acquisition positions, the correlation coefficient values between each feature point are listed in Table 7.

The main conclusions can be drawn from the analysis of Figure 11.

(1) Among the correlation coefficients of the left hand, only the correlation coefficient of the power spectrum characteristic in Part 4 is greater than 0.9, indicating that there is a strong correlation between the collection positions of the Cuan-Chi.

(2) The first two harmonic frequencies of the power spectrum show strong correlation at Cun-Chi position of left hand, while most of the other features do not show strong correlation.

(3) The cepstrum and power spectrum features at Cun-Guan position of left hand show strong correlation, which the correlation was close to 0.9, as shown by the red curve.

The following conclusions can be drawn by observing Figure 12.

(1) The power spectrum and time-frequency energy features at Guan-Chi position of right hand show strong correlation as shown by blue curve, including the first and third harmonic frequencies, and time-frequency energy of 2-3Hz.

(2) The time-frequency energy correlation coefficient of 0-1Hz at Cun-Chi position is greater than 0.9, which indicates that they have strong correlation.

TABLE 7. The correlation coefficient of pulse characteristics.

	Left Hand			Right Hand			Left Hand-Right Hand		
Feature number	Cuan-Chi	Gun-Chi	Cun-Guan	Cuan-Chi	Gun-Chi	Cun-Guan	Cun-Cun	Guan-Guan	Chi-Chi
1	0.541	0.580	0.243	0.345	0.115	0.273	0.353	0.406	0.547
2	0.394	0.165	0.128	0.394	0.273	0.248	0.287	0.273	0.588
3	0.478	0.020	0.369	0.285	0.328	0.249	0.601	0.200	0.503
4	0.560	0.188	0.347	0.237	0.236	0.067	**0.806**	0.316	0.588
5	0.218	0.001	0.524	0.121	0.030	0.467	**0.829**	0.661	0.646
6	0.210	0.367	0.028	0.245	0.608	0.074	0.482	0.632	0.454
7	0.297	0.484	0.158	0.270	0.348	0.267	0.261	0.020	0.053
8	0.336	0.231	0.202	0.076	0.345	0.013	0.010	0.156	0.123
9	0.376	0.265	0.152	0.149	0.366	0.249	**0.769**	**0.747**	**0.899**
10	0.565	0.250	0.252	0.401	0.559	0.335	**0.808**	**0.912**	**0.774**
11	0.565	0.238	0.220	0.375	0.617	0.275	**0.865**	**0.899**	**0.705**
12	0.031	0.098	0.022	0.020	0.003	0.378	**0.847**	**0.799**	0.220
13	0.133	0.091	0.277	0.035	0.078	0.198	**0.731**	**0.814**	0.037
14	0.588	0.176	0.067	0.430	0.350	0.264	0.272	0.345	0.612
15	0.588	0.091	0.333	0.140	0.091	0.248	**0.806**	0.588	0.661
16	0.685	0.310	0.333	0.285	0.091	0.115	0.382	0.382	**0.709**
17	0.066	0.176	0.467	0.188	0.018	0.188	0.552	0.442	0.491
18	0.658	0.006	0.236	0.515	0.042	0.455	**0.855**	0.612	0.624
19	0.164	0.261	0.454	0.188	0.030	0.333	**0.709**	**0.745**	**0.855**
20	0.116	0.018	0.649	0.273	0.515	0.333	0.310	**0.757**	0.078
21	0.285	0.272	**0.798**	0.061	0.027	0.091	0.377	**0.806**	0.109
22	0.264	0.250	0.365	0.215	0.574	0.165	**0.779**	0.600	0.074
23	0.685	0.268	0.268	0.552	0.030	0.401	**0.738**	**0.915**	**0.927**
24	0.079	0.067	0.164	0.018	0.442	0.685	0.249	0.576	0.151
25	0.527	0.200	0.321	0.055	0.345	0.127	0.503	0.454	0.115
26	0.418	0.164	0.188	0.418	0.430	0.188	0.430	0.455	0.055
27	0.369	0.442	0.066	0.140	0.673	0.333	0.091	**0.745**	0.307
28	0.200	0.151	0.297	0.588	0.188	0.224	0.140	0.212	0.588
29	0.261	0.612	0.164	0.649	0.552	0.564	0.261	0.442	0.176
30	0.079	0.236	0.370	0.576	0.215	0.115	0.189	0.188	0.624
31	0.127	0.478	0.384	0.540	0.212	0.430	0.127	0.261	0.648
32	0.564	0.309	0.067	0.140	0.103	0.044	0.151	0.055	**0.709**
33	0.004	0.503	0.310	0.600	0.055	0.297	0.164	0.345	0.685
34	0.467	0.056	0.030	0.434	0.285	0.078	0.430	0.115	0.721
35	0.103	0.455	0.140	0.310	0.139	0.164	0.042	0.055	**0.755**
36	0.115	0.212	0.515	0.394	0.273	0.418	0.418	0.516	0.370
37	0.224	0.333	0.272	0.151	0.273	0.042	0.685	0.018	**0.709**
38	0.067	0.200	**0.842**	0.370	0.249	0.333	0.430	0.018	0.200
39	0.264	0.430	0.152	0.091	0.273	0.333	0.685	0.321	0.430
40	0.418	0.393	**0.842**	0.661	0.200	0.515	0.430	0.406	0.297
41	**0.769**	0.224	0.042	0.491	0.151	0.127	0.624	0.115	0.164
42	0.285	0.418	**0.794**	0.479	0.103	0.501	0.321	0.612	0.491
43	0.382	0.579	0.103	0.006	0.091	0.103	**0.855**	0.345	0.369
44	0.200	0.454	0.430	0.624	0.078	0.515	0.042	0.164	0.733
45	0.406	0.394	0.151	0.369	0.333	0.358	0.554	0.067	0.261
46	0.261	0.261	0.272	0.527	0.188	0.454	0.555	0.164	0.755
47	0.067	0.248	0.406	0.176	0.127	0.151	0.006	0.212	0.399
48	0.030	0.066	0.006	0.564	0.091	0.272	0.273	0.078	0.551
49	0.103	0.128	0.565	0.103	0.176	0.042	0.103	0.224	0.091
50	0.381	0.103	0.055	0.297	0.261	0.224	0.066	0.321	0.648
51	0.067	0.164	0.515	0.200	0.067	0.272	0.127	0.078	**0.733**
52	0.115	0.345	0.200	0.115	0.258	0.248	0.127	0.054	0.600
53	0.236	0.078	0.467	0.103	0.030	0.552	0.370	0.588	0.648
54	0.297	0.164	0.430	0.164	0.176	0.369	0.355	0.358	0.273
55	0.661	0.261	0.576	0.333	0.273	0.382	0.637	**0.755**	0.321
56	0.600	0.273	0.710	0.042	0.127	0.333	0.200	0.455	0.261
57	**0.770**	**0.912**	**0.802**	**0.960**	**0.777**	**0.900**	0.439	0.461	0.246
58	**0.870**	**0.917**	**0.896**	0.587	**0.729**	0.538	0.067	0.457	0.323
59	0.313	0.401	**0.839**	**0.928**	**0.728**	**0.750**	0.152	0.443	0.376
60	0.580	0.042	0.091	0.455	0.284	0.091	0.285	0.091	0.321
61	0.224	0.103	0.190	**0.755**	0.030	0.261	0.540	0.273	0.406
62	0.515	0.030	0.333	0.418	0.091	0.006	0.273	0.394	0.358
63	0.176	0.309	0.369	0.494	**0.925**	0.431	0.418	0.685	0.128
64	0.673	0.139	0.236	0.004	0.210	0.576	0.200	0.030	0.030
65	0.430	0.200	0.285	**0.904**	0.665	0.559	0.249	0.152	0.661
66	0.188	0.176	0.224	0.382	0.285	0.296	0.491	0.527	0.285

TABLE 8. ***T*-test analysis of five parameters at Cun-Chi position.**

Position	$\frac{\omega_2}{t}$	CC_{12}	First harmonic	Second harmonic	Third harmonic
Cun-Chi	0.0053	0.0026	0.0047	0.0072	0.0029

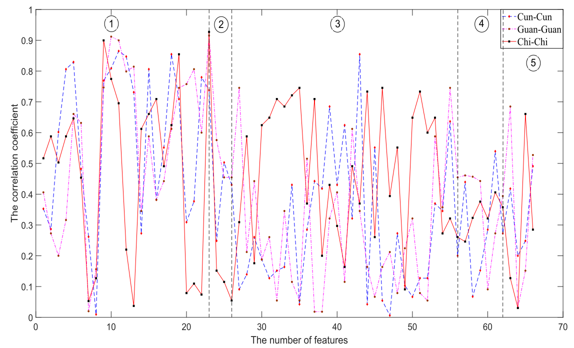

FIGURE 13. **The correlation of the same acquisition position of both hands.**

(3) The correlation coefficient of the first harmonics at the Guan-Cun position of the right hand was up to 0.9, which means that the position is closely relate to the physiological state of human body.

Figure 13 shows the correlation at the same acquisition location of the left and right hand radial arteries. The analysis of the graph shows that most of the significant correlation features of the left and right hands are time domain features. Notice that, the correlation coefficient values of the pulse characteristics at the same position of both hands are mostly less than 0.7. The features with correlation coefficient greater than 0.8 at the same acquisition position of both hands are mainly time domain features, even the correlation coefficients of Guan-Guan and Chi-Chi position can reach more than 0.9. From the perspective of TCM, the three position of Cun-Guan-Chi correspond to different organs of human body, thus the frequencies and amplitudes of pulse wave are significantly different. The analysis of Cun, Guan and Chi can provide the basis for the objectification and quantification of TCM, and truly reflect the relevant characteristics of each position.

To better illustrate Figure 11 - Figure 13, the correlation coefficients of each feature at the Cun-Guan-Chi position are shown in the Table 7. The correlation coefficients of bold type are 0.7∼1, which means that the correlation degree between different features is relatively high. Obviously, it can be find that the pulse characteristics at Cun-Guan-Chi position of left hand and right hand are mostly power spectrum characteristics and time-frequency characteristics with higher correlation coefficients by observing Table 7. Compared with the left hand and the right hand, the features with higher correlation coefficients are mainly the time domain features.

B. THE DIFFERENCES OF PULSE CHARACTERISTICS OF CUN, GUAN AND CHI

In this part, the pulse wave characteristics of Cun, Guan and Chi are analyzed by using the significant difference analysis. Different participants might affect the test results in examining whether the time domain parameters are similar for different indicators at the same position and different positions using the same indicators, a randomized block design was implemented to facilitate significance analysis. The data concerning the normal distribution of variance are implemented t test after square root transformation. Paired comparison between positions for three parameters of harmonic mostly shows significance at Cun-Chi position in Table 8.

For the sake of generality, $p < 0.01$ was used as a significant difference level to analyze the features extracted and the conclusion can be obtained.

(1) The time domain characteristics ω_2/t at Cun-Chi position of the right hand has significant difference.

(2) The 12th cepstrum coefficient (CC_{12}) at Cun-Chi position of right hand is significantly different from other characteristics.

(3) The power spectrum characteristics of the first, second and third harmonics at Cun-Chi position of right hand have significant differences, which indicate that the frequency features and indicators of the different positions truly reflect the physiological conditions of human body.

The 66 features collected of each acquisition position were implemented significant difference analysis, it was not found that there were significant differences among the other features at Cun, Guan and Chi positions except the above features mentioned. Further analysis indicated that the difference of pulse characteristics of the right hand is obvious, which may be relate to the blood flow and human body structure. From the perspective of biological characteristics, the pulse position of left hand is close to the heart, which is greatly affected by the fluctuation of the heart. Thus, the difference is not obvious. In addition, it can be found from the analysis of pulse characters that the pulse amplitude of Chi position is smaller than that of Cun and Guan positions, the pulse amplitude of Guan position is the largest. Those are consistent with the description of TCPD theory and the results have important reference values for the pathologic study.

Undoubtedly, pulse wave is caused by cardiovascular kinetics and is also a response to the dynamics of viscera. In the theory of TCM, viscera is a kind of functional tissue, which is not only related to the real organs, but also related to the Qi circulation of meridians. The differences among the features of Cun, Guan and Chi position reflect different physiological and pathological information of human body. The relevant studies have found some characteristic factors closely related to human body. These closely related characteristic factors can be used as effective indicators to judge the human condition. For instance, w_2 corresponds to the duration of aortic pressure rise, which is related to the time

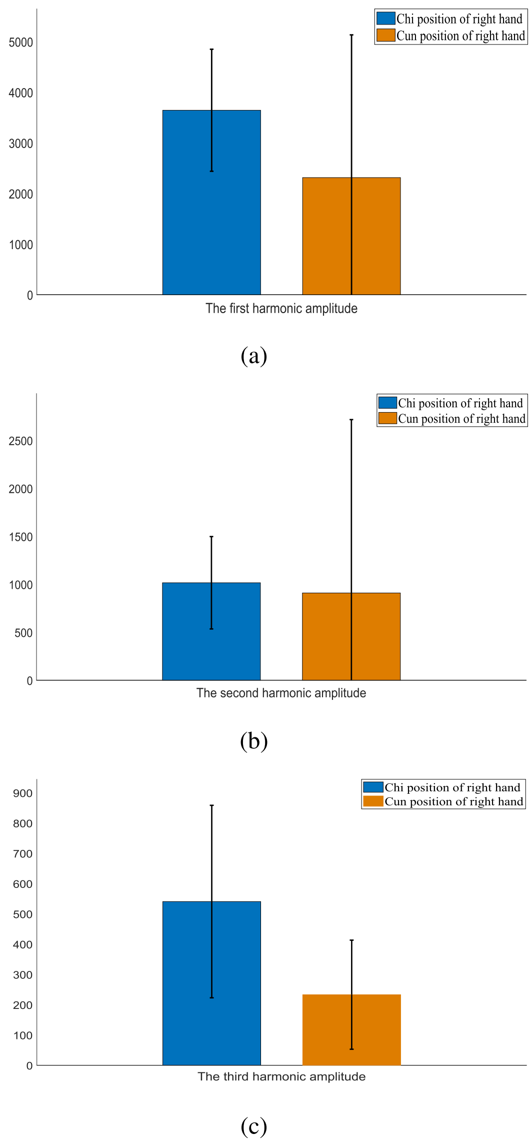

FIGURE 14. **The significant difference chart of power spectrum characteristics at Chi-Cun position of right hand.**

of h_3 appearance and peripheral resistance of blood vessels. The CC_{12} and harmonics are closely related to the resonance state of viscera. Although the neurovascular structure of each organ is different, the resonance effect is mainly based on heartbeat harmonic. Therefore, different harmonic characteristics often reflect the stable state of human circulatory system, which need to be analyzed in combination with the harmonic characteristics of different acquisition position. The pulse characteristics were highly correlated with radial artery depth at the Guan and Chi positions and arterial blood flow velocity at the Chi position. Additionally, the findings also have an implication on the study of pulse diagnosis characteristics and the selection of location, which need to be more cautious when analyzing and using the pulse waves measured at different positions to explain the state of a particular organ. In brief, these analyses are consistent with the theoretical description of TCM, which proves the validity and practicability of the pulse characteristics collected, and have important reference value for pathological research.

V. CONCLUSION

The standardization and quantification of the measurements of wrist pulse waves and pulse acquisition position are important research topics in TCM. The characteristics of pulse wave obtained from wrist radial artery include time-domain, frequency-domain and time-frequency and high order statics, which can better explain the relationship between the three acquisition positions. Although previous studies have shown that the pulse characteristics of the three acquisition points are different, little attention has been paid to the pulse characteristics correlate between the same position of different hands or different positions of the same hand.

In this work, the pulse information at Cun, Guan and Chi position of healthy adults is collected, and the characteristics of time domain, frequency domain, time-frequency domain and high-order statistics are extracted, respectively. The correlation coefficients and t test were used to analyze the pulse characteristics of volunteers, and the relevance and difference at Cun, Guan and Chi position of both hands were explained in detail. Our study revealed pulse correlation among Cun, Guan and Chi position as well as the difference. Meanwhile, the relevant research provides the basis for the quantification and objectification of TCM diagnosis and treatment indicators. The future works should carry out the research of pulse characteristic attribute and physical property, and explain the clinical significance and anatomical properties of each pulse parameter in clinical practice. The findings will contribute to our knowledge of the wrist arterial pulse diagnosis and pulse characteristics at Cun, Guan, and Chi positions for the development of a better pulse diagnosis system.

COMPETING INTERESTS

The authors declare no competing interests.

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