Full-field wrist pulse signal acquisition and analysis by 3D Digital Image Correlation

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A B S T R A C T

Pulse diagnosis is an essential part in four basic diagnostic methods (inspection, listening, inquiring and palpation) in traditional Chinese medicine, which depends on longtime training and rich experience, so computerized pulse acquisition has been proposed and studied to ensure the objectivity. To imitate the process that doctors using three fingertips with different pressures to feel fluctuations in certain areas containing three acupoints, we established a five dimensional pulse signal acquisition system adopting a non-contacting optical metrology method, 3D digital image correlation, to record the full-field displacements of skin fluctuations under different pressures. The system realizes real-time full-field vibration mode observation with 10 FPS. The maximum sample frequency is 472 Hz for detailed post-processing. After acquisition, the signals are analyzed according to the amplitude, pressure, and pulse wave velocity. The proposed system provides a novel optical approach for digitalizing pulse diagnosis and massive pulse signal data acquisition for various types of patients.

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1. Introduction

In Traditional Chinese Medicine (TCM), inspection, listening, inquiring and palpation (望闻问切) constitute the basic diagnostic methods. Palpation, that is pulse diagnosis, is an essential part. In pulse diagnosis, a doctor usually press fingers on three specific acupoints on the wrist to feel the feature of fluctuations caused by radial artery. These acupoints are called “Cun, Guan, Chi (寸关尺)” respectively (see Fig. 2(a)). Pulse condition is analyzed according to the depth, speed, rhythm, strength and so on [1,2]. Combined with the other health information yielded from the four diagnostic methods, a doctor can determine the disease.

Pulse diagnosis has been practiced in thousands of years in Chinese history. But this skill requires long time training and rich experience, and the results usually depends on the doctor’s subjectivity, which restrict the development and application of TCM. To solve this problem, computerized pulse acquisition has been proposed and studied to ensure the objectivity [3–5], and connections between certain diseases and computerized pulse parameters have been found by researchers [6–9].

In most system for pulse signals acquisition, pressure sensor is used to convert pressure signals to digital signals. For example, Lu et al. reported a device using three sensors pressed at the three acupoints to remote monitor the pulse condition under a fixed pressure [10]. Luo et al. used pressure sensor array to get more sampling points on the wrist [11]. However, to our knowledge, traditional devices and systems suffer from similar limitations. First, the acquisition lack full-field comprehensive information for pulse analysis, for example, the range and the full-field distribution of the fluctuations. Second, it is an essential step in traditional pulse diagnosis that doctor applies different pressures on the acupoints “Cun, Guan, Chi” by three fingertips, to feel fluctuations of the pressed area, while most traditional system can only obtain one or several points’ pulse signal under a fixed pressure. To overcome these drawbacks, 3D digital image correlation (3D-DIC) is considered to be a better solution.

DIC is a non-interferometric and non-contacting optical metrology technology for full-field displacement and deformation measurements [12–14]. With development of more than 30 years, it has been widely used in experimental mechanics and other scientific fields [15–20]. In recent decades, 3D-DIC method is developed and improved by using two or more cameras to obtain 3D reconstruction based on binocular vision principle. Artificial or natural speckle on curve surface of an object is utilized as feature to perform points matching. Shao et al. [21] has proposed that using 3D-DIC to monitor the pulse when studying DIC algorithm. In his work, due to being shuttered, only pulse signals around the acupoint being pressed is acquired without pressure changes, while pulse diagnosis requires pulse signals just at the acupoint being pressed. Based on our previous work that DIC algorithm efficiency was promoted for real-time points tracking [22], with the help of PMLAB’s 3D-DIC soft-
ware (Nanjing PMLAB Sensor Tech Co., LTD, Nanjing, China), we established a five dimensional optical pulse acquisition system to record full-field displacements of skin fluctuations under different global pressures or different independent pressures for three acupoints.

The structure of the paper is organized as follows. In Section 2, pulse signal acquisition system was established base on 3D-DIC method. In Section 3, full-field pulse signals are analyzed. In the last section, conclusions of this work are drawn.

2. System establishment

2.1. The principle of 3D-DIC

The goal of DIC calculation is to match points accurately in images on the time sequence. With two or more cameras, 3D reconstruction and more analysis can be realized by principle of binocular vision. Fig. 1(a) shows the universal 3D-DIC device. In DIC method, speckle pattern is an essential part, which must have enough, distinct, isotropic texture. In practice, quality assessment of speckle pattern is significant to obtain accurate results [23,24]. In DIC algorithm, a subset is defined as a certain point with its neighborhoods to distinguish the point on the measured surface.

Current calculation process usually consists two steps: integral pixel search and sub-pixel iteration [25–27]. Integral pixel search can reach integral pixel accuracy. As Fig. 1(b) shows, point of interest (POI) P(x, y), subset and search area are set on the reference image. After the object moves or deforms, the deformed image is obtained. The shift of POI in deformed image can be calculated out by cross-correlation in search area. This value is regarded as the initial value for next sub-pixel iteration. In this work, L-M (Levenberg–Marquardt) iteration method was used. To get more accurate results, linear shape function is induced to describe the deformation of the subset, which is enough for most situations [28]. The shape function parameters is the final matching results.

As shown in Fig. 1(c), usually the first left camera image is chosen as reference image and other images on the time sequence are matched with reference image [26]. After the matching results are obtained, 3D reconstruction of the surface can be performed easily according to the calibration result of the cameras. Thus shape analysis and strain analysis are conducted on the computer.

2.2. Pulse signal acquisition system establishment

In Chinese traditional pulse diagnosis, the doctor presses three fingers on three acupoints to feel the fluctuations caused by radial artery on the wrist. The acupoints are called “Cun, Guan, Chi” respectively as shown in Fig. 2(a). The acupoint Guan is just at the inner side of the radial styloid and can be found conveniently. On the either side of Guan are the acupoints “Cun” and “Chi”. The total length from “Cun” to “Chi” is 3–8 cm according to different ages and body sizes. During this process, the doctor presses “Cun, Guan, Chi” with different pressures to get different feedback. Meanwhile the patient should keep positions of the wrist and the heart at the same height from the ground with seated position or prone position. About one minute is required to take pulse signals in a relaxed manner.

Based on the above principles, requirements for a pulse acquisition system are explicit. First, when collecting pulse signals, the device should be able to adjust the global pressures or independent pressures for three acupoints. Second, signals of three acupoints “Cun, Guan, Chi” should be acquired synchronously. Third, the whole process should be convenient for massive data acquisition for various types of patients. To meet these requirements, a pulse signal acquisition system based on 3D-DIC was established. Coordinate system was built as shown in Fig. 2(a). XOY plane was the fitted plane of the measurement area on the skin after 3D reconstruction. Z-direction displacements were measured and recorded as pulse signals. We adopted the water transferred printing speckle [29] to print proper pattern on the wrist. Before printing, skin protection cream was painted on the wrist to make the speckle easy to wash after acquisition. Fig. 2(b) shows the speckle pattern and a 29×29 pixel subset in the captured image.

Fig. 3(a) is a sketch map of components of the system, and (b) shows the real pulse acquisition device. To imitate fingers pressing on the skin and obtain a full-field displacement map, an inflated transparent bag, which was adhered to the upper plate of the acrylic box, was used to provide global pressure. The bag was connected with an air pump and a mercury difference pressure gauge, therefore the pressure can be adjusted and recorded. Device for independent pressure for each acupoint is presented at the last of Section 3 as an extension of current device. The thickness of the transparent membrane of the air bag was about 0.03 mm to reduce the negative effects of clear imaging. The transparent acrylic box was fixed on the table by screws, to restrict the air bag and keep tight contact between the skin and the air bag. A soft wrist cushion was also important to provide comfortable support against pressure. The pa-
Fig. 2. Illustration for pulse diagnosis and speckle pattern for pulse signals acquisition. (a) positions of “Cun, Guan,Chi” and establishment of coordinate system; (b) water transfer printing speckle pattern.

Fig. 3. Pulse signal acquisition device and noise floor measurement experiment. (a) a sketch map of components of the system; (b) the real pulse acquisition device. Transparent air bag was used to provide pressure while ensuring clear imaging. Acrylic box was used to restrict the air bag and keep tight contact between skin and the air bag; (c) results of the noise floor measurement. The captured image without shelter (right in the figure) has a higher contrast, thus leading to a smaller noise compared to the other group. We think it is tolerable for pulse signals acquisition, because the noise standard deviation is less than 3% of the amplitudes of the fluctuations in the following analysis.

tient should hold a relaxed posture to keep pulse signals stable. A pair of high speed cameras (model: MVC1281SAM-CL500-S02 developed by Micrview Company, China) was placed about 40 cm away over the wrist. The main specifications of the camera are resolution: 1024 × 1024; max sampling frequency: 472 FPS. The calculation efficiency of 3D-DIC is about 20,000 points per second with a pair of Intel CPU E5-2630. The system can realize real-time full-field vibration mode observation with 10 FPS.

During the acquiring process, first, patients should put the wrist on the cushion in seated position and stay relaxed. Second, the air bag was inflated to the desired global pressure with air pump. Third, acquisition, calculation, were performed on the computer.

After the acquisition system was established, a noise floor measurement experiment was carried out. A plate printed with speckle was used to measure noise floor at rest. The experiment were divided into two groups to test the influence of the transparent air bag and the acrylic box. In one group the images were captured without shelter. And in the other group the images were captured when the transparent air bag and the acrylic box were placed between the cameras and the plate. 100 images were captured in one minute, and Z-displacements of all the sample points were counted. Fig. 3(c) displays that the image without shelter has a higher contrast, thus leading to a smaller noise standard deviation: 0.6 μm. And in the other group, the noise standard deviation was 0.79 μm, which was a litter bigger due to the influence of the transparent air bag and the acrylic box. We think it is tolerable for pulse signals acquisition, because the noise is less than 3% of the amplitudes of the fluctuations in the following analysis. More detailed noise source analysis and methods to reduce noise can refer to references [18,23,24].

3. Analysis of pulse signals

3.1. Full-field 3D reconstruction of pulse signals

After the optical pulse acquisition system was established, pulse signals of a volunteer were captured with 472 FPS for 2.5 s. Then full-field reconstruction of pulse signals was obtained through 3D-DIC process. The spatial resolution was 0.1 mm per pixel. The data was acquired when the global pressure equals to 60 mmHg. The subset size and grid size in DIC calculation was 29 pixel and 7 pixel respectively. As shown in Fig. 4(a), the acupoints “Cun, Guan and Chi” are marked as circles, whose radius was about 0.5 cm, corresponding to the regions pressed by fingertips in traditional pulse diagnosis. The average Z-displacement in circles on time sequence represented the pulse signals, as shown in Fig. 4(b). It is worth noting that the image denoting wave trough in the waveform was set as the reference image in DIC calculation, thus the pulse signals of different positions had the same wave trough for convenient comparison. Fig. 4(c)–(f) indicates the Z-displacement distribution maps at different moments marked with dashed line in Fig. 4(b), which demonstrate the pulse fluctuation in one cycle. The length and the width of the pulse region can also be obtained intuitively on the 3D reconstruction image. An animation is attached to show the pulse fluctuation under global pressure 60 mmHg in one cycle.

3.2. Pulse signals analysis under different pressures

In traditional pulse diagnosis, a TCM doctor presses at three acupoints to get fluctuations of the pulse. If the pressure is too weak, the
fluctuations on the skin may not be felt, conversely if the pressure is too large, the pulse may be block so there is no fluctuations. The TCM doctor needs adjust the pressure to get maximum fluctuations to analyze the pulse condition. When the maximum fluctuations are obtained, the doctor compares magnitude of the pressure with health person in his experience. If the pressure is relatively weak, the pulse condition is called “Pu (浮)”, which means superficial and easy to detect. And if the pressure is relatively strong, the pulse condition is called “Chen (沉)”, which means deep and the doctor should press with larger pressure [30,31].

In TCM, this is an important indicator which is thought to be related with multiple aspects such as seasons and diseases. A certain easy-to-understand factor that affects the indicator is the depth of the radial artery under the skin. In this paper, pulse signals under different pressure are acquired and analyzed. Amplitude of the pulse signal is chosen to evaluate whether the fluctuations reach the maximum.

As shown in Fig. 5(a), the pressure scale is 10–120 mmHg, and the sampling interval of pressure is 5 mmHg. The amplitude of pulse fluctuations changes with the different global pressures. At the beginning, with the increase of the pressure, the amplitude increases to maximum, then declines rapidly to zero. However, the global pressures are different when the amplitudes of “Cun, Guan, Chi” reach their maximum, and are 60 mmHg, 75 mmHg and 90 mmHg respectively. For acupoint “Cun”, the pressure is lower than that of acupoint “Chi”. Fig. 5(b)–(d) illustrates the displacement maps of wave crest (upper) and signal waveforms (lower) of three acupoints when the global pressure equals to 30 mmHg, 75 mmHg and 90 mmHg (Fig. 4(d) indicates the displacement map of global pressure 60 mmHg). These four displacement maps demonstrate that as the pressure increases, the maximum amplitude acupoint in the wrist region moves from acupoint “Cun” to acupoint “Chi”. This phenomenon is also agreed with the viewpoint in TCM that the pulse signal at acupoint “Cun” is usually “Fu”, while the pulse signal at acupoint “Chi” is usually “Chen”, which means larger pressure is usually applied at “Chi” acupoint than that of the “Cun” acupoint to obtain maximum amplitude. Animations are also attached when the global pressure equals to 75 mmHg, 90 mmHg (the animation for global pressure 30 mmHg is similar to that of 60 mmHg).

Furthermore, in traditional TCM, different pressures is usually applied at different acupoints. So the device was improved to apply independent pressure on different acupoints. As shown in Fig. 6(a), the air bag was divided into three parts, just like three fingers of a TCM doctor, and connected with three mercury difference pressure gauges to monitor the pressure on three acupoints. Fig. 6(b) shows the speckle image acquired by camera. With different pressures 45 mmHg, 60 mmHg, 75 mmHg applied to “Cun, Guan, Chi” respectively, pulse signals were obtained as shown in Fig. 6(c).

3.3. Pulse wave velocity and heart rate analysis

Pulse wave velocity (PWV) is the pulse propagation velocity through the human circulatory system. It is worth noting that PWV is different from the blood flow velocity. PWV refers to the propagation velocity of systolic pressure in artery caused by the cardiac contraction and is related to vessel parameters and blood pressure, while the blood flow velocity is much slower. In modern medicine, PWV has been widely studied by researchers and used clinically as an important indicator of arterial stiffness [32,33]. The softer, the more elastic the aortic wall, the

![Image](image-url)
Fig. 5. Amplitude analysis of pulse signals under different global pressures. Larger pressure is usually applied at “Chi” acupoint than that of the “Cun” acupoint to obtain maximum amplitude, which is agreed with the viewpoint in TCM. (a) curve of amplitude related with pressure, the global pressures are different when the amplitudes of “Cun, Guan, Chi” reaches their maximum, and are 60 mmHg, 75 mmHg and 90 mmHg respectively; (b) the displacement map and signal waveforms under pressure 30 mmHg; (c) the displacement map and signal waveforms under pressure 75 mmHg (see Video 2); (d) the displacement map and signal waveforms under pressure 90 mmHg (see Video 3).

Fig. 6. Improved device and signal waveforms for independent pressure applied to each acupoints. (a) improved device with three cylindrical air bag to imitate three fingers pressing using different pressures; (b) captured image for improved device. (c) waveforms of “Cun, Guan, Chi” under different pressures.

lower the PWV is. Except for arterial stiffness, high PWV is also reported to be associated with other diseases such as hypertension and poor lung function [34,35].

In TCM, PWV is also an important parameter for estimating physical condition. In pulse diagnosis, the doctor uses three fingers to feel the process of pulse propagation while the pulse wave travels. There are several typical pulse conditions related to PWV. For example, the term “Xianmai (弦脉)” in pulse diagnosis is to describe the pulse condition that the PWV is relatively high and with steep rise and fall, and literally means that the fluctuations are just as the tight string being plucked [36,37]. The term “Huamai (滑脉)” is to describe the pulse waveform is smooth with slower PWV, and literally means the bead rolls in the artery constantly in Chinese [38,39].

PWV can be measured in our system by signal delay between acupoint “Chi” and acupoint “Cun”. The pulse wave travels through “Chi”, then reaches “Cun”. With high speed cameras, 1180 images were captured within 2.5 s with 472 FPS, so signal delay of the two signals can be calculated out by cross correlation function. PWV was the distance between “Chi” and “Cun” (about 5 cm) divided by the delayed time. However, signal delay had large differences under different global pressures, which led to inconsistent calculation results of PWV. For high global pressure more than 55 mmHg, PWV stabilized at a smaller value, while for less global pressure lower than 35 mmHg, PWV stabilized at a larger value. PWV obtained under medium global pressure between 35 mmHg and 55 was not stable. Two typical pressures were chose to elaborate this phenomenon. Fig. 7(a) and (c) show signals of “Cun” and “Chi” under global pressure 30 mmHg and 60 mmHg. Fig. 7(b) and (d) are the cross correlation curves of the signals in (a) and (c) respectively. The signal delay and PWV under 30 mmHg pressure were 0.0064 s (time of 3 frames) and 7.87 m/s, while those under 60 mmHg pressure were 0.0318 s (time of 14 frames) and 1.57 m/s. However, the minimum PWV is greater than 3 m/s according to the reference [40], which is also a consensus in medical field. Thus, results under higher pressure should be abandoned, and results under lower pressure were considered to be authentic. The reason of this problem is probably that compared to acupoint “Chi”, the acupoint “Cun” is usually “Fu” (the concept is explained in Section 3.2). For higher pressure, the fluctuations is suppressed to a greater extent, especially at the very beginning of the rise stage in the waveform, when the pioneer of systolic pressure just reaches the acupoint “Cun” and is not larger enough against the applied pressure. An
Fig. 7. PWV analysis under different pressures. (a) signal waveforms of “Chi” and “Cun” under global pressure 60 mmHg. Obvious signal delay can be observed at the beginning of the rise stage in the waveform, fluctuations are suppressed by high pressure; (b) cross correlation curve of signals in (a) and calculation of PWV. The results is inconsistent with medical consensus that the minimum PWV is greater than 3 m/s. The reason is probably that at the beginning of the rise stage in the waveform, fluctuations are suppressed by high pressure; (c) signal waveforms under global pressure 30 mmHg; (d) cross correlation curve of signals in (a) and calculation of PWV. The results under lower pressure is considered to be authentic.

Fig. 8. Different heart rates in normal state and after exercise are calculated out by FFT method.

evidence for the reasoning is that as shown in the black circle in Fig. 7(a), for higher pressure, the signal delay at the beginning of the rise stage in the waveform is more obvious than that of other positions in the waveform, while this trait is not embodied in Fig. 7(c) for pulse signals under lower pressure. The obvious signal delay can also be observed through the attached slow video under 60 mmHg pressure.

Besides, heart rate can also be easily measured through Fast Fourier Transform Algorithm (FFT) of the pulse signals (20 s). Fig. 8 shows different waveforms and heart rates in normal state and after exercise.

4. Conclusion

In summary, to imitate doctors using three fingertips with different pressure to feel fluctuations of the pulse in certain areas containing three acupoints, a novel optical pulse signal acquisition and analysis system based on 3D-DIC was established. The major conclusion can be summarized as follows:

First, full-field displacements of skin fluctuations caused by pulse were obtained under different global pressures and independent pressures for three acupoints, which constituted a five dimensional optical measurement system. The system can realize real-time full-field vibration mode observation with 10 FPS and maximum sample frequency is 472 Hz for detailed post-processing.

Second, pulse signals under different pressures were demonstrated and analyzed. Different pressures are required to get maximum amplitudes of fluctuations for different acupoints. Larger pressure is usually applied at acupoint “Chi” than that of the acupoint “Cun” to obtain maximum amplitude, which is agreed with the viewpoint in TCM that the acupoint Cun is usually “Fu (μ®)”, while the acupoint “Chi” is usually “Chen (ǚ®)”. 
Third, PWV under different global pressure is calculated out and discussed. High pressure is likely to suppress fluctuations at the beginning of the rise stage in the waveform, leading to an incorrect result. PWV estimation under lower pressure is considered to be authentic.

Fourth, the proposed method provides a novel optical approach for digitalizing pulse diagnosis and massive pulse signal data acquisition for various types of patients.

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Supplementary materials

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