# AN ARTERIAL STIFFNESS MEASURING WRISTWATCH WITH FLEXIBLE TACTILE SENSING DENSE-ARRAY

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## ABSTRACT

This paper reports a wristwatch to measure the arterial stiffness (AS) for the first time. A two-dimensional flexible tactile sensing dense-array is integrated in the watch. The dense-array consists of 29 × 3 ultra-small pressure sensing chips, enabling high-resolution tactile perception. Because the AS is a property about vascular elasticity and compliance, the watch senses the pressure distribution on the radial artery, and records the pressure distribution matrixes (PDM) under different external stresses. Subsequently, a deep learning model is employed to fit the regression relationship between the PDM changes and the AS degree, so that the AS degree would be assessed non-invasively and unobtrusively. Eventually, the root mean squared error (RMSE) and mean absolute error (MAE) of the predicted results reach 0.49 and 0.39, respectively, which are superior to all of the previous works.

## KEYWORDS

Arterial Stiffness (AS), flexible sensing, tactile perception, pressure distribution, ResNet, Pulse Wave Velocity (PWV).

## INTRODUCTION

Cardiovascular diseases (CVD) are currently the leading cause of mortality all over the world. Principally as a result of atherosclerosis, arteriosclerosis, or inflammatory and degenerative conditions of the arterial wall, arterial stiffening affects the hemodynamic states and severely increases CVD risk. Pulse wave velocity (PWV) has been proved to be an independent predictor of CVD, and is thereby regarded as the gold standard for AS diagnosis. Unfortunately, direct measurement of PWV is complex and demanding, for it requires sophisticated clinical equipment as well as skilled technicians [4]. A variety of AS estimating methods were introduced in previous studies: atherosclerosis index (AI) is calculated from serum cholesterol [5]:

$$AI = \frac{TC - HDL}{HDL} \tag{1}$$

, where TC denotes the total blood cholesterol; while HDL the high-density lipoprotein. However, AI is susceptible to drugs, for instance, assorted antihypertensive drugs will reduce its value. Stiffness parameter $\beta$ [6,7]:

$$\beta = \frac{D}{\Delta D} \ln \frac{P_s}{P_d} \tag{2}$$

, where $D$ represents the diameter of the artery, and $\Delta D$ the change in arterial diameter caused by fluctuating blood pressure; $P_s$ and $P_d$ stand for the systolic blood pressure and diastolic blood pressure. But $\beta$ is quite hard to gauge for it involves high-fidelity observation of the diameter changes in a given vessel. Ankle brachial index (ABI) [8]:

$$ABI = \frac{P_s\_ankle}{P_s\_brachium} \tag{3}$$

, where $P_s\_ankle$ and $P_s\_brachium$ are the systolic blood pressures sampled at ankle and brachial arteries, separately. Ambulatory arterial stiffness index (AASI) [9]:

$$AASI = 1 - k \tag{4}$$

, where $k$ indicates the fitting slope of a series of points ($P_s$, $P_d$) over a period of time. Although ABI and AASI are widely adopted in clinical examinations for risk stratification, they are derived from the ratio of blood pressures measured on different arterial sites or at different times, which are infeasible for ambulatory monitoring. Moreover, ABI mainly reflects the degree of arterial stenosis and obstruction in the lower limbs. With reference to AASI, a subject's blood pressure might not change much in a relatively short period of time, which leads to great randomicity and instability in this index. Therefore, both ABI and AASI's abilities to assess CVD risk are rather limited.

As illustrated in Figure 1, there are several methods to directly predict PWV such as digital volume pulse (DVP) [10], arterial stiffness index (ASI) [11] and augmentation index (AIx) [12,13].

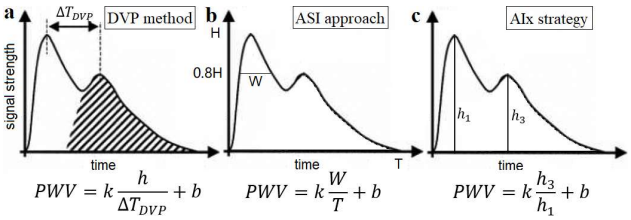


*Figure 1: Previous studies for PWV prediction.* ***a*** *Estimation method of DVP [10]. h denotes the height of a subject. k and b are customized coefficients.* ***b*** *Calculation approach of ASI [11]. W indicates the time the signal remains at a high level.* ***c*** *Assessment strategy of AIx [12,13]. The curves on display are pulse waveforms sourced from sphygmography or photo-plethysmography (PPG).*

Nevertheless, according to our experiments, the precisions of the models listed in Figure 1 are far from satisfying. Equipped with the flexible tactile sensing dense-array, our newly-developed wristwatch aims to reckon PWV and evaluate AS degree with a higher accuracy.

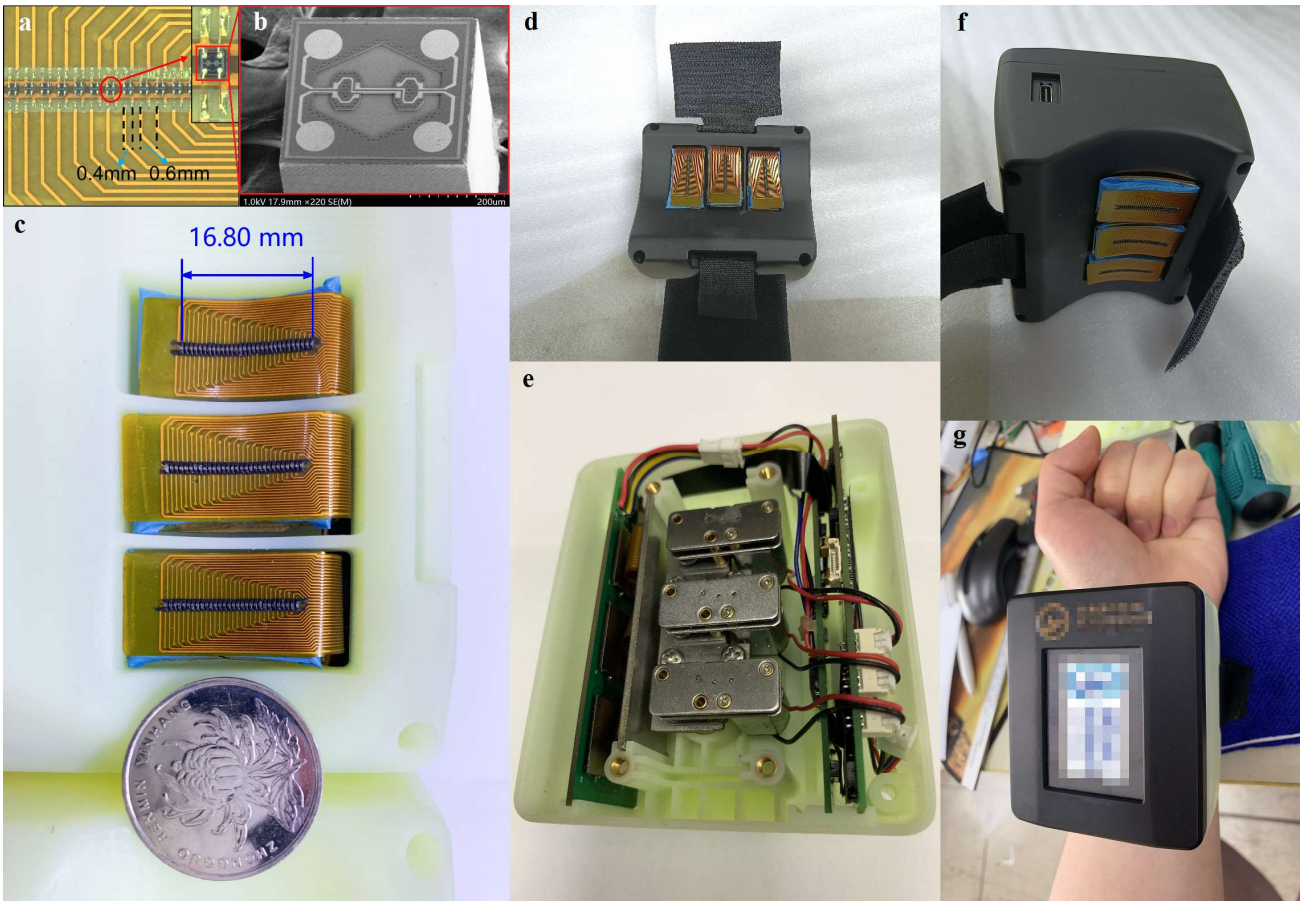


*Figure 2: The wristwatch with flexible tactile sensing dense-array.* ***a*** *The 2-dimensional array involves 29 × 3 ultrasmall pressure sensors (0.4 mm × 0.4 mm each) with a pitch of 0.60 mm, allowing high resolution acquisition of tactile information.* ***b*** *The scanning electron microscope (SEM) image of one MEMS pressure sensing chip.* ***c*** *The array has a sensing width of 16.80 mm.* ***d*** *3 columns of sub-arrays together form the 2-dimensional array.* ***e*** *3 columns are driven by 3 separate motors so that the array may press the artery in different segments with multi-stresses.* ***f*** *3 parallel arrays sense the vascular stiffness on 3 adjacent sites, enhancing system fault tolerance and reliability of measurement results.* ***g*** *Being worn in the wrist, the watch measures AS according to the variation in pressure distribution under varying stress.*

## EXPERIMENTAL METHODS

### Flexible Tactile Sensing Dense-Array

In order to achieve high-resolution tactile perception, a sort of mini-size absolute pressure sensors previously designed by our research group [1,2] are employed in the dense-array. In the size of 0.4 mm × 0.4 mm, the ultra-small MEMS chips are fabricated by a sophisticated microhole inter-etch and sealing (MIS) process and exhibit high full-scale (FS = 150 kPa) output sensitivity of 0.65 mV kPa-1 / 3.3 V, low hysteresis of 0.10% FS, low repeatability error of 0.04% FS, low nonlinearity of about ± 0.10% FS, and low repeatability error of 0.11% FS [3]. Figure 2b shows the scanning electron microscope (SEM) image of a 0.4 mm × 0.4 mm pressure sensing chip, from which the beam-island-reinforced structure is explicitly revealed.

As shown in Figure 2a and 2c, 29 such micro pressure sensors are packaged on a flexible printed circuit (FPC) board in a straight line to form a unidimensional tactile sensing dense-array with a span of 16.80 mm, easily achieving full coverage of the radial artery region in the wrist. The dense-array has a pitch of 0.60 mm, already reaching the human fingertip touch resolution, which allows sensitive perception of subtle changes in pressure distribution.

### Time-Variant Tactile Mapping

User wears the watch and let the tactile array detect the radial artery in the wrist. First, the array is pressed into the skin by the 3 motors and deforms the artery to the most. Then the motors gradually retreat, from the deepest to the shallowest position with 5 depths [16]. While the flattened vessel returns to normal, the array senses the tactile mappings under the diminishing 5 stresses. The sampling rate is set to 16 Hz, the motors stop at each of the 5 depths for 2 sec, so that a time-variant tactile mapping with a size of 160 × 87 is obtained. Detailed delineation is found in Figure 3. The data was collected from 176 volunteers and every volunteer was required to be sampled every day for 20 days, on both left and right arms. As a result, a total of 7040 tactile mappings were accumulated.

### Regression model based on ResNet

We treat these tactile mappings as images and 80% of them are split to train a ResNet-based regression model for PWV prediction [14,15]. As described in Figure 3, the network consists of 2 convolutional layers, 2 batch normalization layers, 3 residual blocks, 1 global average pooling layer, and 1 fully-connected (FC) layer. The 3 sequential residual blocks are utilized to address the

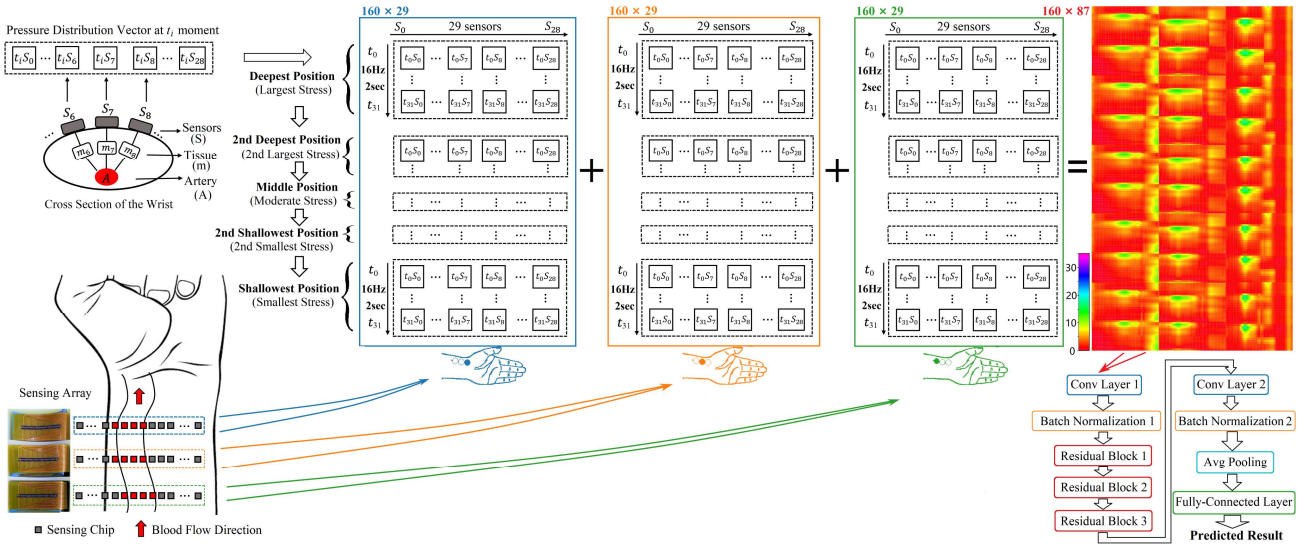


*Figure 3: The array in the watch is pressed on the radial artery to sample the varying pressure distribution matrixes (PDMs) from 3 adjacent sites, and pieces them together. As a result, a comprehensive time-variant tactile mapping is concatenated, from which the features about vascular elasticity and compliance will be extracted by a ResNet afterwards.*

vanishing gradient problem. In the convolutional layers, the stiffness features are extracted from the time-variant tactile mappings [18]. Accordingly, the predicted PWV results are output from the FC layer. Due to the limited sample size (less than 10,000), *K*-fold cross-validation is applied (with $K = 4$) to trace the model performance while training.

### True Value of PWV

The true values of PWV are also measured through our sensing arrays, from the brachial artery in the elbow to the radial artery in the wrist, as the quotient of wave propagation distance (WPD) and pulse transit time (PTT):

$$PWV = \frac{WPD}{PTT} \tag{5}$$

The distance between the 2 array sites is recorded with an accuracy of 1 mm. Here, PTT is calculated as the time lag between the maximum slope points in the brachial and radial artery pulse waveforms during the systolic periods. As demonstrated in Figure 4c, the maximum slope points are labeled by the maxima of the first derivative curves of the pulse waveforms. The PWV is so large of more than 10 m/s that the PTT is on the millisecond level. In order to detect the PTT effectively, the sampling rate is raised to 10 kHz specifically for PWV measurement, enabling the time resolution to reach 0.1 ms.

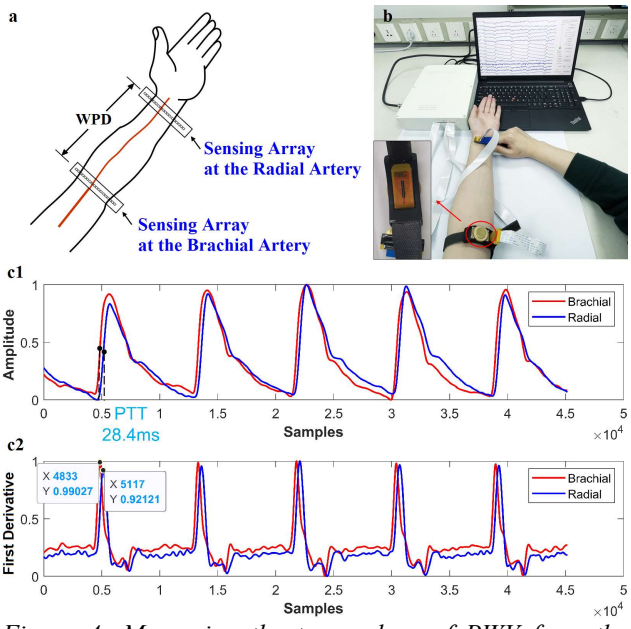


*Figure 4: Measuring the true values of PWV from the brachial artery in the elbow to the radial artery in the wrist. The PTT is calculated as the time between the max slope points in the brachial and radial pulse waveforms during the systolic periods. The sampling rate is set to 10 kHz specifically for this experiment.*

## EXPERIMENTAL RESULTS

The trained ResNet is tested on the remaining 20% samples. The overall root mean squared error (RMSE) and mean absolute error (MAE) of our regression model are 0.49 and 0.39, respectively, very much lower than those of DVP, ASI and AIx. To evaluate the effectiveness and reliability of our model, we analyze the consistency between the predicted PWVs and the true values by the Bland Altman method. As presented in figure 5b, the result shows that the differences and mean values are within 95% confidence intervals. Therefore, our wristwatch proves to be an effective device for ambulatory CVD monitoring.

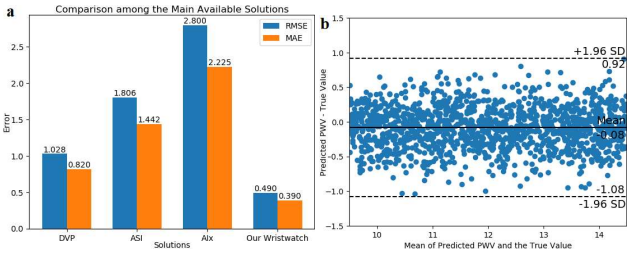


*Figure 5: **a** The RMSE and MAE of the main available solutions. **b** The Bland Altman evaluation for the predicted PWVs.*

## CONCLUSION

A wristwatch combined with a deep learning model to achieve AS assessment is proposed in this paper. Using silicon-based pressure sensors with compact size, high sensitivity and stability, the flexible sensing array is able to acquire reliable tactile information from the radial artery and surrounding region. A ResNet-assisted regression model is built to extract the key features from the time-variant tactile mappings. On the basis of it, PWV are reckoned with a RMSE of 0.49 and a MAE of 0.39.

By means of our flexible tactile sensing dense-array, the wristwatch is capable of evaluating AS degree non-invasively and unobtrusively, highlighting its great potential for intelligent wearable application. Compared with previous solutions, our wristwatch is not only more convenient but more accurate, is expected to serve as a low-cost home-based ambulatory device for cardiovascular health monitoring.

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