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Measurement of Post-Exercise Response of Local Arterial Parameters Using an Adjustable Microfluidic Tactile Sensor *

Md Mahfuzur Rahman, Hannah Twiddy, Leryn Reynolds, and Zhili Hao, *Member, IEEE*

***Abstract*— In this work, we demonstrate an adjustable microfluidic tactile sensor for measurement of post-exercise response of local arterial parameters. The sensor entailed a polydimethylsiloxane (PDMS) microstructure embedded with a 5×1 resistive transducer array. The pulse signal in an artery deflected the microstructure and registered as a resistance change by the transducer aligned at the artery. PDMS layers of different thicknesses were added to adjust the microstructure thickness for achieving good sensor-artery conformity at the radial artery (RA) and the carotid artery (CA). Pulse signals of nine (n=9) young healthy male subjects were measured at-rest and at different times post-exercise, and a medical instrument was used to simultaneously measure their blood pressure and heart rate. Vibration-model-based analysis was conducted on a measured pulse signal to estimate local arterial parameters: elasticity, viscosity, and radius. The arterial elasticity and viscosity increased, and the arterial radius decreased at the two arteries 1min post-exercise, relative to at-rest. The changes in pulse pressure (PP) and mean blood pressure (MAP) between at-rest and 1min post-exercise were not correlated with that of heart rate and arterial parameters. After the large 1min post-exercise response, the arterial parameters and PP all went back to their at-rest values over time post-exercise.**

***Clinical Relevance*— The study results show the potential application of an affordable, user-friendly device for a more comprehensive arterial health assessment.**

I. Introduction

Pathological changes in the arterial wall alter arterial parameters: physical properties and geometries of the arterial wall, and consequently undermine blood circulation in the arterial tree. To date, numerous clinical studies have established arterial parameters as clinical indices for detection and diagnosis of arterial abnormalities (e.g., atherosclerosis). Among them, Pulse Wave Velocity (PWV) is indicative of arterial elasticity E [1]:

$$PWV = \sqrt{\frac{Eh}{2r_0\rho_b}} \tag{1}$$

where h and r_0 denote the arterial wall thickness and radius at diastolic blood pressure (DBP), respectively; and ρ_b denotes blood density. Peripheral vascular resistance (PVR) is dictated by arterial radius r_0 [1]:

$$PVR = \frac{8\eta_b}{\pi r_0^4} \tag{2}$$

where η_b denotes blood viscosity. Together with E and r_0, arterial viscosity η is expected to be altered by pathological changes. Although the clinical value of η was identified in some clinical studies, technical complexity involved in its measurement has prevented it being studied as extensively as E and r_0 and being widely used in clinical studies [2].

Arterial pulse waveform reflects changes in arterial parameters and has been analyzed for estimation of arterial parameters. Then, acquiring a pulse signal with minimum distortion from the true pulse signal in an artery holds the key for accuracy in estimated arterial parameters. This demands achieving good sensor-artery conformity so that the pulse signal in the artery is maximally transmitted into the sensor and in the meantime minimum suppression occurs to the true pulse signal in the artery [3]. As such, a device needs to be adjusted for fitting different artery sites and subject-specificity (i.e., overlying tissue at an artery). Yet, the device used and subject-specificity affects the measured pulse signal and consequently estimated arterial parameters [1, 3].

Estimation of local E, η, and r_0 currently requires simultaneous measurements of two pulse signals using an imaging instrument and a tonometer and calibration of the pulse signal from the tonometer [2]. To alleviate technical complexity involved in the current methods, we previously developed a microfluidic tactile sensor for pulse signal measurements and proposed vibration-model-based analysis for estimation of E, η, and r_0 from a single measured pulse signal with no need of calibration [1]. We validated the vibration-model-based analysis with the post-exercise response of local arterial parameters of five subjects, which was estimated from pulse signals measured using two identical sensors at the radial artery (RA) and the carotid artery (CA) [1]. Later on, we added a PDMS layer to the sensor for improving sensor-artery conformity [3].

This work aimed to further validate the sensor and the vibration-model-based analysis for estimation of three arterial parameters by adding PDMS layers of different thicknesses to two identical sensors at the RA and the CA, measuring nine (n=9) young healthy male subjects different from those in the previous study [1], and conducting the measurements with two new operators. Moreover, their blood pressure and heart rate was simultaneously measured using a medical instrument for comparison. Post-exercise response of arterial parameters was utilized to remove the influence of different PDMS layers and subject-specificity on estimated arterial parameters [1].

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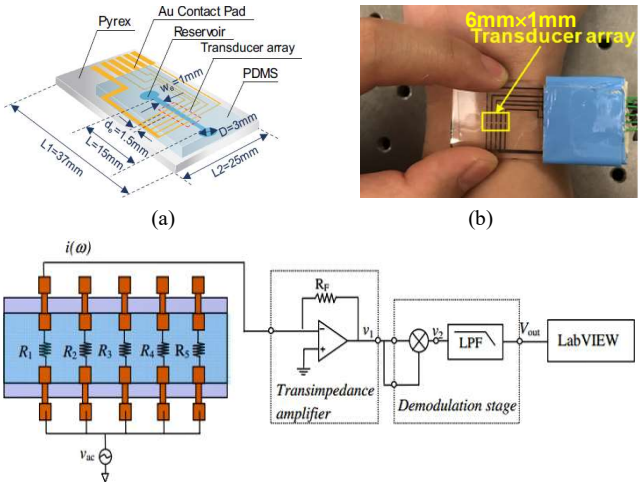
M. Rahman and Z. Hao are with the Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, VA 23529 USA (corresponding author, Z. Hao, phone: 757-683-6734; fax: 757-683-5354; e-mail: zlhao@odu.edu).

H. Twiddy and L. Reynolds are with the Department of Human Movement Sciences, Old Dominion University, Norfolk, VA 23529 USA.

II. METHODS

A. The Microfluidic Tactile Sensor

As shown in Fig. 1, the microfluidic tactile sensor entails a PDMS microstructure embedded with an electrolyte-filled microchannel. Five pairs of metal electrodes are uniformly aligned along the microchannel length. Electrolyte and the five electrode pairs form a 5×1 resistive transducer array. In a pulse measurement, the pulse signal at an artery deflects the microstructure and registers as a resistance change by the transducer aligned at the artery. To monitor the resistance change, a 100kHz ac voltage v_{ac} is applied to the electrodes on one side of the sensor, each electrode on the other side of the sensor is connected to their associated circuit for converting the ac current from the sensor to a DC voltage output V_{out}. The details about the sensor design, fabrication, and operation can be found in the literature [3].



(a) (b) (c)

Figure 1: The microfluidic tactile sensor (a) schematic (b) picture (c) operation of the sensor and its associated circuit for each transducer

B. Vibration-Model-Based Analysis of a Pulse Signal

Due to its time-harmonic nature, the measured pulse signal is treated as a vibration signal of the arterial wall. As shown in Fig. 2(a), the arterial wall is then modeled as a unit-mass dynamic system [1]:

$$M\frac{d^2u_r}{dt^2}+D\cdot\frac{du_r}{dt}+K\cdot u_r=\frac{\Delta p(t)}{\rho_w h} \qquad (3)$$

with $$\text{M=1},\ K=\frac{E}{\rho_w r_0^2},\ D=\frac{\eta}{\rho_w r_0^2} \qquad (4)$$

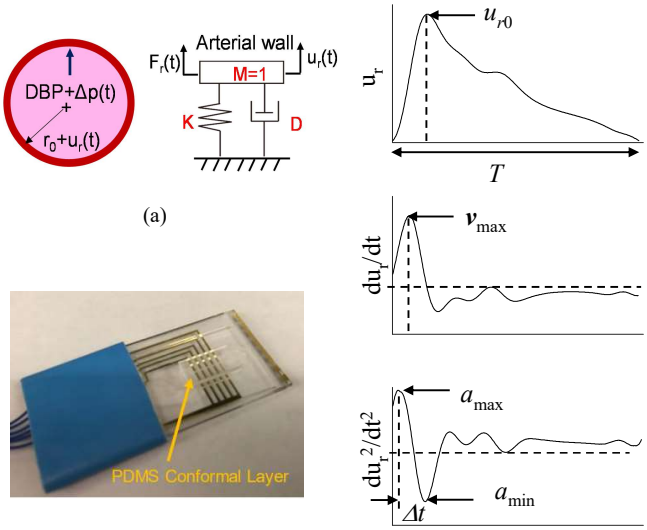
where ρ_w denotes arterial wall density. Here, K and D denote the spring stiffness and damping coefficient, respectively, of the arterial wall. K and D are related to the three arterial parameters in (4). As shown in Fig. 2(b), by treating the measured pulse signal as the radial displacement $u_r(t)$ of the arterial wall, K and D can be estimated from the six features in the measured pulse waveform and its 1st-order and 2nd-order derivatives [1]:

$$D=\frac{(a_{\max}-a_{\min})}{v_{\max}}\cdot\frac{\Delta t}{T},\quad K=\frac{(a_{\max}-a_{\min})}{u_{r0}}\cdot\frac{\Delta t}{T} \qquad (5)$$

Consequently, the arterial parameters and PWV are further estimated from K and D [1]:

$$E\propto K\cdot D^{-2/3},\ \eta\propto D^{1/3},\ r_0\propto D^{-1/3},\ PWV\propto\sqrt{K\cdot D^{-1/3}} \qquad (6)$$

Note that the estimation of arterial parameters and PWV in (6) results from a scaling analysis. Thus, they are relative evaluations and have no unit.



(a) (c) (b)

Figure 2: (a) The unit-mass dynamic model of the arterial wall (b) Six features of the measured pulse waveform (wall displacement u_r) and its 1st-order derivation (velocity du_r/dt) and 2nd-order derivative (acceleration d^2u_r/dt^2) for estimation of K and D (c) A PDMS layer on top of the sensor for achieving good sensor-artery interaction

C. Measurement Protocols

This study was conducted under approval by the Institutional Review Board (IRB) of Old Dominion University (ODU). Table I summarizes the characteristics of the nine (n=9) young healthy male subjects in the study. Two identical sensors were utilized for measurements at the RA and the CA. As shown in Fig. 2(c), PDMS layers of different thicknesses were added between the sensor and the measured artery of a subject and the PDMS layer that allowed achieving the maximum pulse amplitude was chosen as the best-fit layer for good sensor-artery conformity. For the first two subjects, 1mm-thick and 2mm-thick PDMS layers were used at the RA and the CA, respectively. For the rest seven subjects, 2mm-thick and 3mm-thick PDMS layers were used at the RA and the CA, respectively.

TABLE I. CHARACTERISTICS, BLOOD PRESSURE, AND HEART RATE OF THE SUBJECTS AT-REST (n=9)

Variable	mean ± std
Age (years)	29.8 ± 4.8
Weight (kg)	68.7 ± 2.1
Height (cm)	176.1 ± 24.9
BMI (kgm^{-2})	26.2 ± 3.5
SBP (mmHg)	126.8 ± 11.6
DBP (mmHg)	80.9 ± 9.0
MAP (mmHg)	96.2 ± 9.5
PP (mmHg)	45.9 ± 6.4
HR (beats per min)	79.6 ± 10.8

In a pulse measurement, a subject stayed in a sitting position and remained still. The pulse signals at the two arteries on the right side of the body were simultaneously measured using the two sensors and the best-fit PDMS layers by two operators. Afterwards, the subject conducted

moderate-intensity exercise (e.g., either jump up/down or squat) for 5min. The pulse signals at the two arteries were simultaneously measured 1min, 5min, 10min, 20min, and 30min post-exercise using the same PDMS layers. Eight consecutive pulse cycles from each measured pulse signal were processed to estimate the values of arterial parameters. A medical instrument (a PARAMED monitor) was used to measure the systolic/diastolic blood pressure (SBP/DBP) and heart rate (HRm) at the left brachial artery of the body simultaneously with the sensors. While pulse pressure (PP) was calculated as PP=SBP-DBP, mean blood pressure (MAP) was calculated as MAP=1/3(SBP-DBP)+DBP. All the statistical analysis was conducted in IBM SPSS.

III. Results and Discussion

A. 1min Post-exercise Response

Table II summarizes the mean and standard deviation (std) of the estimated arterial parameters and the measured blood pressure and HRm at-rest and 1min post-exercise. The estimated arterial parameters at both arteries and the measured PP between at-rest and 1min post-exercise reveal statistically significant difference. The 1min post-exercise response was defined as the change of a parameter at 1min post-exercise, relative to at-rest. As shown in Table III, while the estimated ΔHRs and Δr_0 at the two arteries were correlated with statistical significance, no correlations of ΔE, $\Delta\eta$, and ΔPWV between the two arteries were obtained.

TABLE III. THE 1MIN POST-EXERCISE RESPONSE OF (A) ARTERIAL PARAMETERS AND PWV AT THE RA AND THE CA AND THEIR CORRELATIONS BETWEEN THE RA AND THE CA

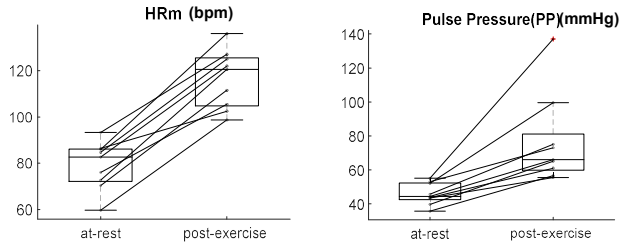
	RA	CA	Pearson correlation coefficient	p-value
ΔHRs	36.1 ± 10.1	35.8 ± 9.7	0.985***	0.000
ΔE	19.5 ± 6.2	27.3 ± 15.5	0.085	0.829
Δη	0.3 ± 0.1	0.2 ± 0.1	0.644	0.061
Δr_0	-0.06 ± 0.02	-0.04 ± 0.03	0.710**	0.032
ΔPWV	2.4 ± 0.7	2.8 ± 1.2	0.431	0.247

The measured PP, SBP, DBP, and MAP were not correlated with HRm, arterial parameters, and PWV at the two arteries both at-rest and 1min post-exercise. The 1min post-exercise response of PP and MAP are denoted by ΔPP and ΔMAP, respectively. No correlations of ΔPP and ΔMAP were observed with ΔHRm, ΔE, $\Delta\eta$, Δr_0, and ΔPWV at the two arteries either. As illustrated in Table IV, ΔHRm was correlated with ΔHRs at the RA and the CA. Interestingly, although ΔHRm was not correlated with ΔPP and ΔMAP, ΔHRm was correlated with $\Delta\eta$, Δr_0, and ΔPWV at the RA.

TABLE IV. CORRELATIONS OF ΔHRM WITH THE 1MIN POST-EXERCISE RESPONSE OF ARTERIAL PARAMETERS AND PWV AT THE RA AND THE CA, ΔPP AND ΔMAP

ΔHRm with	RA		CA	
	Pearson correlation coefficient	p-value	Pearson correlation coefficient	p-value
ΔHRs	0.922***	0.000	0.912**	0.001
ΔE	0.553	0.123	0.227	0.557
Δη	0.825**	0.006	0.646	0.060
Δr_0	-0.787*	0.012	-0.603	0.086
ΔPWV	0.674*	0.046	0.469	0.202
	Pearson correlation coefficient		p-value	
ΔPP	0.172		0.658	
ΔMAP	0.271		0.481	

As shown in Fig. 3, the heart rate (HRm) and PP of all the subjects measured by the medical instrument increased 1min post-exercise, as compared with at-rest. Yet, there is no correlation between the heart rate change and the PP change. There was an outlier in the measured PP 1min post-exercise. As shown in Fig. 4, at both arteries, arterial elasticity and viscosity and PWV all went up 1min post-exercise, while arterial radius dropped 1min post-exercise. All the arterial parameters and PWV at the RA contained no outliers, the arterial viscosity and radius at the CA included outliers.



(a) (b)

Figure 3: Boxplots of (a) HRm and (b) PP at-rest and 1min post-exercise

B. Post-exercise Response Over Time

As shown in Fig. 5, the PP and HRm went down to their at-rest level over time post-exercise. The estimated arterial parameters and PWV at the RA and the CA also went back to their at-rest level. Note that HRm almost coincided with the estimated HRs at the two arteries over time post-exercise.

TABLE II. COMPARISON OF THE MEASURED RESULTS BETWEEN AT-REST AND 1MIN POST-EXERCISE OF THE NINE SUBJECTS USING PAIRED STUDENT'S T-TEST (MEAN ± STANDARD DEVIATION, * P<0.05, ** P<0.01, *** P<0.001; HRS: HEART RATE FROM THE SENSOR; HRM: HEART RATE FROM THE MEDICAL INSTRUMENT.)

	RA		CA	
	At-rest	**1min post-exercise**	**At-rest**	**1min post-exercise**
K	250.04 ± 44.51	416.04 ± 58.67***	243.8 ± 56.9	418.1 ± 78.4***
D	8.4 ± 1.2	11.9 ± 1.2***	8.1 ± 1.4	10.5 ± 2.5**
E	60.5 ± 8.7	80.0 ± 9.8***	60.9 ± 12.8	88.2 ± 17.5**
η	2.02 ± 0.1	2.3 ± 0.1***	2.0 ± 0.13	2.2 ± 0.16**
r_0	0.49 ± 0.02	0.44 ± 0.02***	0.50 ± 0.04	0.46 ± 0.03**
PWV	11.04 ± 0.8	13.5 ± 0.9***	11.0 ± 1.2	13.8 ± 1.3***
HRs	79.2 ± 11.9	115.3 ± 1 1.9***	79.0 ± 11.2	114.8 ± 11.9***
	At-rest		**Post-exercise**	
PP (SBP-DBP)	45.81 ± 6.4		76.5 ± 26.3**	
MAP	96.2 ± 9.5		110.8 ± 15.5***	
SBP	126.7 ± 11.6		161.8 ± 32.4**	
DBP	80.9 ± 9.0		85.3 ± 8.1**	
HRm	79.1 ± 10.3		116.5 ± 12.6***	

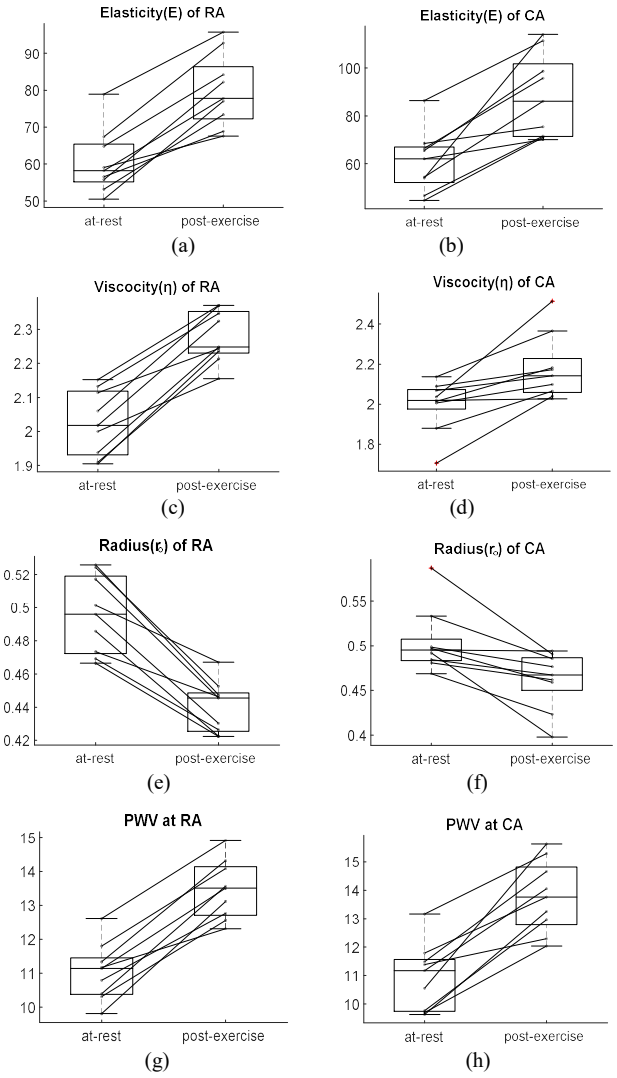


Figure 4: Boxplots of (a) E (b) η (c) r_0 (d) PWV at the RA and the CA at-rest and 1min post-exercise

C. Discussion

Studies were conducted on post-exercise response of the CV system to a bout of exercise, revealing that *E* and *PWV* go up immediately post-exercise and decrease to a level at or below at-rest values [4]. r_0 at the CA was found to decrease immediately post-exercise and then recover to its at-rest value over time post-exercise [5]. As such, our results on the post-response of *E*, r_0, *PWV* at the CA were consistent with the related findings in the literature. To date, no studies have reported on the post-exercise response at the RA and the post-exercise response of arterial viscosity. Our results suggest that the post-exercise response at the RA followed the changing trend at the CA.

In our study, no correlation of ΔHRm was found with ΔPP and ΔMAP, which was consistent with the finding in the literature [6]. No correlation of ΔPP with ΔE, $\Delta\eta$, Δr_0, and ΔPWV might indicate that blood pressure, arterial parameters, and *PWV* reflect different aspects of the CV system and need to be measured for a comprehensive assessment of arterial health. There are two major study limitations. First, the sample size is relatively small. Second, medical instruments were not used to measured r_0 and *PWV* for comparison.

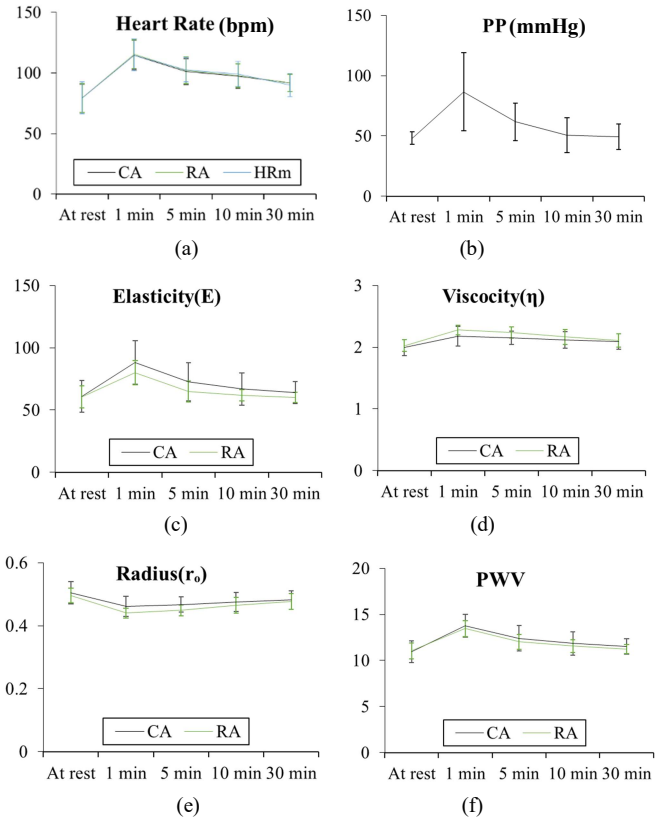


Figure 6: at-rest and 1min, 5min, 10min and 30min post-exercise response (mean ± std) from nine (n=9) subjects (a) HRm and HRs (bpm) (b) a) PP (mmHg) (c) E (d) η (e) r_0 (f) PWV

IV. Conclusion

This work proposes using an adjustable microfluidic tactile sensor for acquiring a pulse signal with minimum distortion and post-exercise response to alleviate the influence of the device used and subject-specificity on the measured pulse signals and consequently estimated arterial parameters. The proposed method is validated by the measured results, showing the potential application for a more comprehensive arterial health assessment with great simplicity and affordability.

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