Stable Measurement of Blood Flow While Running using a Micro Blood Flowmeter

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Abstract: Skin blood flow during exercise has been studied before, with measurements made using laser Doppler blood flowmeters; however, their use was limited to activities with minimal motion, such as riding bicycle ergometers, because conventional devices are large and their measurements easily altered by movements of the optical fiber, rendering them inappropriate for running. We have previously developed a micro integrated laser Doppler blood flowmeter using microelectromechanical systems (MEMS) technology. The micro blood flowmeter is wearable and can measure signal stably even while the wearer is moving. We monitored skin blood flow during running at velocities of 6 km/h, 8 km/h, and 10 km/h, and were successful in measuring a stable signal under these conditions. We found that at the forehead the skin blood flow increases and, in contrast, at the fingertip it initially decreases during running. We also found that the level of these increases and decreases correlated with the running velocity.

1 INTRODUCTION

Recently, more people have started running. The Sasakawa Sports Foundation reported that the number of people who run more than twice a week has doubled in the last ten years in Japan (2010), and the number of marathon completions is up more than 1.6-fold from ten years ago in the United States (Mathews et al., 2012). Runners, especially those with hypertrophie cardiomyopathy, should be aware of the possibility for harm or even death due to exercise-induced issues such as cardiopulmonary arrest (Maron et al., 1996). Therefore it's necessary to observe health index of those person while running.

Many studies on the physiological effects of exercise have been conducted using laser Doppler blood flowmeters, which can noninvasively measure skin blood flow (Kellogg Jr. et al., 1993, Yasuda et al., 1994. Alonso et al., 1998). Many varieties of these blood flowmeters have been developed (Watkins and Holloway, 1978, Wunderlich et al., 1980), yet they face several challenges: for example, their large size and the high power consumption necessary for monitoring blood flow while subjects run. Furthermore, such instruments are easily affected by movement or vibration of the optical fiber in the devices, which is also used as a strain sensor (Newson et al., 1987). Therefore, laser Doppler blood flowmeters were primarily used in experiments having little subject motion, such as with stationary bicycles, rather than running.

To meet and overcome these challenges, a laser Doppler blood flowmeter that didn't require the use of optical fibers was developed (Mul et al., 1984).

We have also previously applied microelectromechanical systems (MEMS) technology to a blood-flow-measuring instrument, and developed a micro integrated laser Doppler blood flowmeter which is called MEMS blood flow sensor (Higurashi et al., 2003). The MEMS blood flow sensor can measure blood flow while the subject is moving because it doesn't use an optical fiber. We have also developed a probe for the MEMS blood flow sensor that consumes lower

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electric power using a built-in silicon microlens (Kimura et al., 2010), and have used it to evaluate dehydration (Nogami et al., 2011), alcohol consumption (Iwasaki et al., 2012), and systemic sclerosis (Kido et al., 2007). This probe's design enables wafer-level packaging, improving its fabrication efficiency. Our MEMS blood flow sensor with this newly developed probe is the world's smallest, lightest, and least power-consuming blood flow sensor.

In the present study, we attempted to measure blood flow using our developed MEMS blood flow sensor at the tip of the ring finger, the forehead, and the earlobe while participants ran. Blood flow was measured at three different running velocities (6, 8, and 10km/h) for 30 minutes each on a treadmill. We evaluated the blood flow at each measurement site and then compared blood flow with running velocity.

2 MATERIALS AND METHODS

In this section, we describe the subjects, the MEMS blood flow sensor, the experimental apparatus, and the experimental protocol of the study.

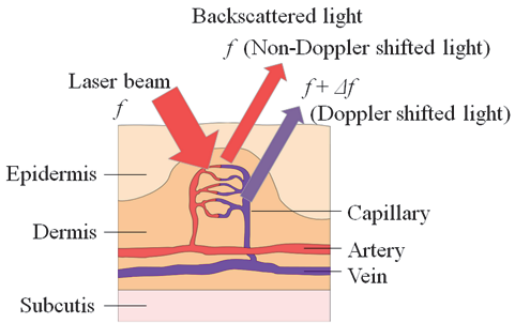

Figure 1: Schematic of laser Doppler flowmetry.

2.1 Subjects

The research complied with the ethical standards of the Human Experimentation Committee of Kyushu University, and with the 2008 revision of the Helsinki Declaration. Seven healthy young men (mean age of 23.4 years old, range 22-26; mean BMI 22.9 kg/m2, range 20.4-29.5) participated in this study. Subjects were fully informed of the experimental details and any potential risks before their participation in the study.

2.2 MEMS Blood Flow Sensor

The MEMS blood flow sensor can measure skin blood flow noninvasively using the principles of laser Doppler flowmetry. We explain these principles in the first subsection, and lay out the structure of the device in the second, and describe the components of the blood flow signal in the third.

2.2.1 Principles

Figure 1 illustrates the principles behind laser Doppler flowmetry. A laser beam with frequency f is emitted from a light source to the skin and penetrates it to a certain depth. Some light scatters from static tissue such as the skin and blood vessels; a small amount of light is scattered from moving tissue such as red blood cells. Because of the Doppler effect, the frequency of the light scattered by the moving tissues changes slightly. The Doppler-shifted and non Doppler-shifted light interfere on the photo diode (PD), which detects the resultant intensity modulations. The first moment of the power spectrum of the beat frequency distribution as obtained using a fast Fourier transform (FFT) is proportional to the product of the average velocity and patient-specific concentration of the red blood cells as they move the body (Bonner and Nossal, 1981).

2.2.2 Structure

The MEMS blood flow sensor contains a probe and a main body, as shown in Figure 2. The probe has an optical MEMS chip and first-stage operational amplifiers, and is attached directly to the subject. The main sensor body has a digital signal processor (DSP), a Bluetooth wireless link, display, and battery. The MEMS blood flow sensor can be run on a 3.7 V square electric battery, as is used in cell phones.

Figure 3 shows a schematic of the optical MEMS chip we developed. We used distributed feedback laser diode (DFB-LD) as a light source of MEMS blood flow sensor. Its wavelength is 1310 nm which easily penetrates human skin. The laser beam emitted from the DFB-LD is reflected vertically by the <111> facet etched mirror, focused by the microlens, and irradiated to the skin. The microlens decreases coupling loss, a serious problem in conventional instruments. The laser power coming from the probe is 2 mW. The laser doesn't harm to human body, because it is not perfectly collimated. Scattered light reenters through the window and is detected by the PD.

2.2.3 Blood Flow Signal

Figure 4 shows the probes of our MEMS blood flow sensor and a conventional, optical fiber-type

instrument attached to adjacent fingertips for comparison, and Figure 5 shows the blood flow signals measured by each. The hand was waved from the 10-second mark. It is apparent that the signal of the fiber-type instrument was greatly affected, while in contrast, the signal of our MEMS blood flow sensor was stable.

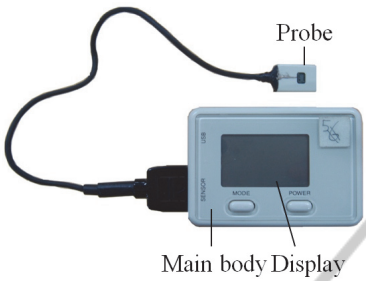

Figure 2: Photograph of MEMS blood flow sensor.

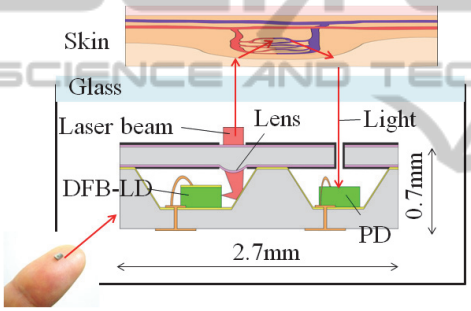

Figure 3: Schematic of cross-sectional view of the optical MEMS chip.

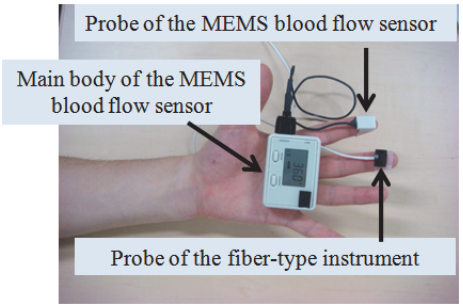

Figure 4: Photograph of MEMS blood flow sensor and fiber-type instrument probes attached to fingertips.

There are three main components of blood flow waves: basic, cardiac, and reflex waves (Kano et al., 1993). Basic waves have periods of about ten seconds, and some researchers have reported that these large oscillations are modulated by the sympathetic nervous system or by sympathetic sympathetic nervous system or by sympathetic vasomotor tone (Sasano et al., 1999); (Mukae et al., 2006). Cardiac waves are much smaller and simply reflect the heartbeat. Reflex waves are a phenomenon in which peripheral blood flow temporarily yet markedly decreases when, for example, the subject takes a deep breath or is engaging in physical activity. We should note that reflex waves only appear in palmoplantar areas.

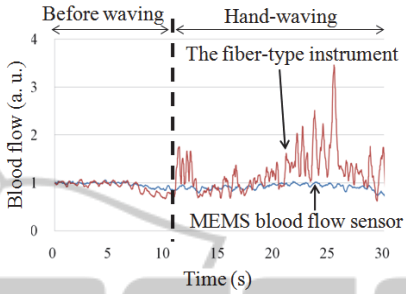

Figure 5: Fingertip blood flow signals measured by the MEMS blood flow sensor and fiber-type instrument during hand-waving.

2.3 Experimental Apparatus

Participants ran on Tempo T931 treadmills (Johnson Health Tech. Co., Ltd., Taiwan). MEMS blood flow sensors were attached with double-side tape and medical tape to the tip of the left ring finger, the left earlobe, and the forehead (using a headband) as shown in Figure 6. In addition to blood flow, we measured body temperature, blood pressure, blood lactate level, and body weight. Body temperature was measured with an MC-510 ear thermometer (OMRON HEALTHCARE Co., Ltd., Japan), which can measure body temperature within one second and can well perform even while running. Blood pressure was measured with an upper-arm type sphygmomanometer.

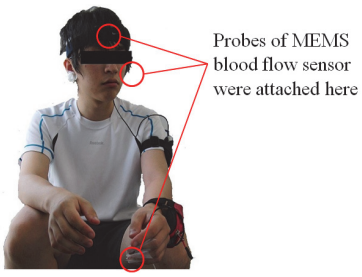

Figure 6: Photograph of subject with attached MEMS blood flow sensor.

Blood lactate level was measured with the Lactate Pro LT-1710 meter (ARKRAY, Inc., Japan), which can measure blood lactate levels from only 5

μl of blood. We obtained blood samples using the Naturalet EZ (ARKRAY, Inc., Japan), a device that can easily obtain small blood samples with minimal pain. We measured blood pressure and lactate levels before and after running, because we couldn't measure them while the subject ran. Body weight was measured before and after the experiment.

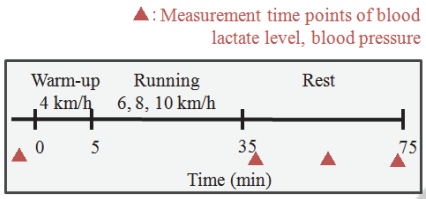

Figure 7: Experimental protocol.

2.4 Experimental Protocol

We measured blood flow at three different running velocities (6, 8, and 10 km/h) for 30 minutes after walking for 5 minutes at 4 km/h as a warm-up. Subjects ran each velocity on different days with intervals of more than three days between sessions, to counteract fatigue from the previous experiment. We observed blood flow when sitting for 40 minutes after running to observe the recovery of blood flow. If subjects complained of exhaustion while running, we stopped the running session but continued to observe blood flow for 40 minutes.

Figure 7 shows the experimental protocol. At the beginning of a session, we measured resting blood flow, body temperature, blood pressure, and blood lactate levels while the subject sat. Then, the subject walked on the treadmill at 4 km/h for 5 minutes. Body temperature was measured 4 minutes after walking onset. The subject ran at a constant velocity for 30 minutes after the warm-up. Body temperature was measured at 5, 10, 15, 20, 25, and 29 minutes of running. We observed blood flow while sitting for 40 minutes. Body temperature, blood pressure, and blood lactate levels were all measured just after, 20 minutes after, and 40 minutes after running concluded.

3 RESULTS

We describe how the stability of blood flow signals differ among measurement sites in the first subsection; how heart rate is isolated from the blood flow signal in the second subsection; and how blood flow changes with velocity in the final subsection.

3.1 Stabilities of Blood Flow Signals in each Measurement Site

Figure 8 shows the experimental data for a representative subject. The blood flow signals corresponding to sensor location are displayed. The data was sampled at 50 Hz, and the values displayed were averaged every 100 points, and plotted at 2-second intervals for clarity. The three signals had different values in the resting states because density of capillary differs across measurement sites and because of individual variability in MEMS blood flow sensor calibration. Blood flow at the earlobe suddenly and greatly increased upon the start of running, indicating that the sensor is very sensitive to subject movement at this location. Blood flow at the forehead gradually increased as the subject began running and gradually decreased after subject had stopped. On the other hand, blood flow at the fingertip decreased at the start of running and gradually increased once it had ended. There were many reflex waves observed in fingertip blood flow during running. We could confirm these changes of blood flow in all subjects.

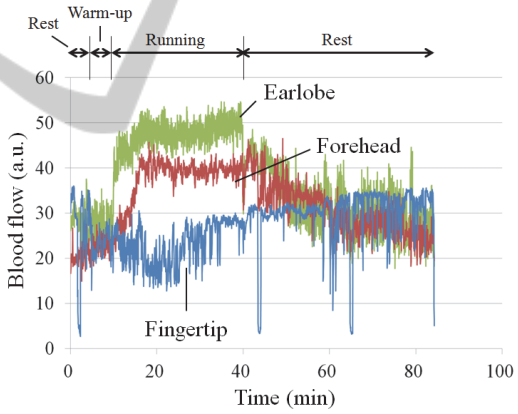

Figure 8: Blood flow signals during running.

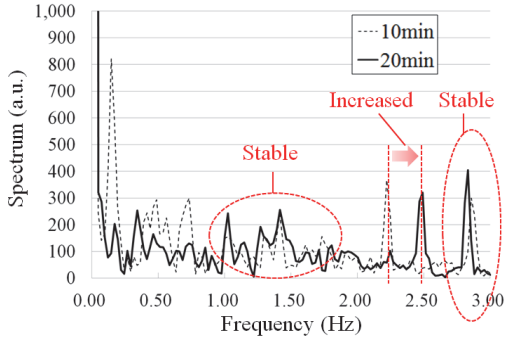

Figure 9: Spectrum of fingertip blood flow at 10 minutes and 20 minutes after start of running.

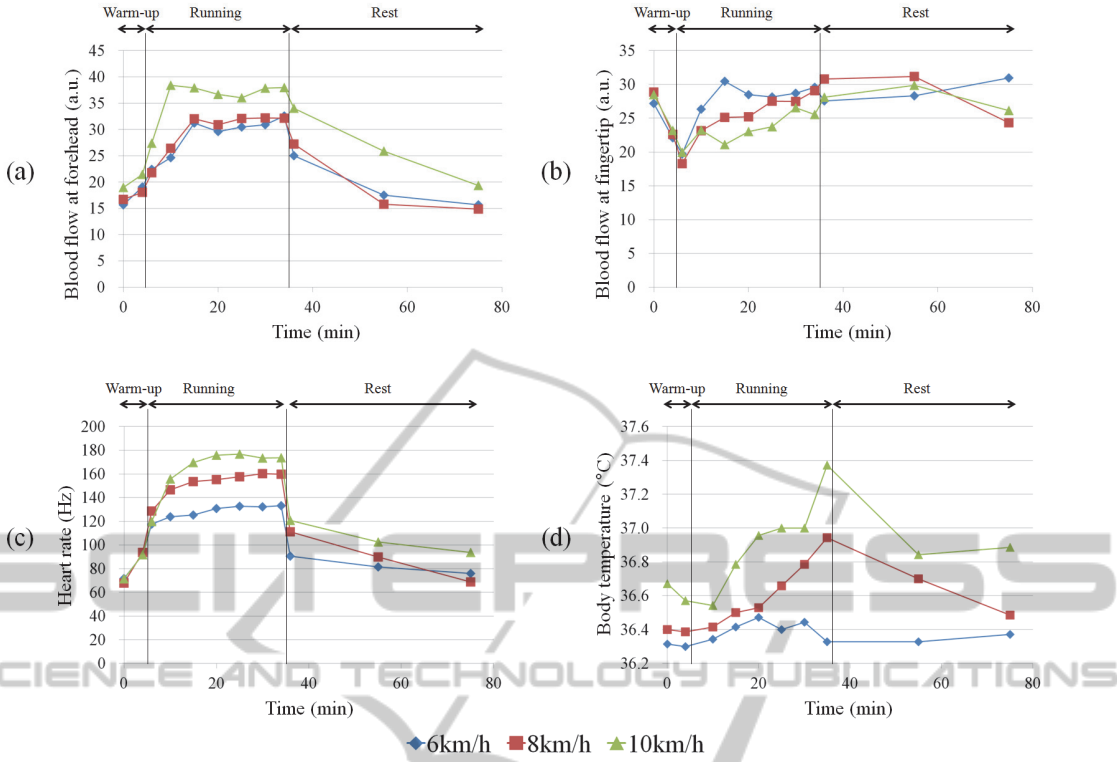

Figure 10: Average changes in blood flow (n=7) at forehead (a) and at fingertip (b), heart rate (c), and body temperature (d) during the running experiment; standard deviations not shown for clarity.

3.2 Separation of Heart Beat from Rhythm of Running

When subjects weren't exercising, we could usually see a single spectral peak around 1 Hz, which was caused by heart rate. However we observed some additional spectrum peaks during running. Figure 9 shows a spectrum distribution of blood flow at the forehead at 10 and 20 minutes after the commencement of running at 8 km/h. These spectra were obtained by performing FFTs on blood flow signal data lasting 40.96 seconds (2048 points). Most spectral peaks remained unchanged between samples, staying at a stable rhythmic frequency due to running at constant velocity. However, one peak did shift, suggesting it was tracking heart rate, increasing during running. We can determine heart rate by performing a FFT on a power spectrum of blood flow data, tracking the rhythmic running peaks as a constant, and observing the incremental increase of the peak corresponding to heart rate: this is possible even while running.

3.3 Changes of Blood Flow with Running Velocity

Mean (n=7) blood flow at the forehead and at the fingertip, heart rate, and body temperature at each running velocity are shown in Figures 10(a), 10(b), 10(c), and 10(d), respectively. All subjects completed the 30 minutes of running in the 6 km/h and 8 km/h sessions. In the 10 km/h session, one subject retired after 15 minutes, and another after 20; all other subjects completed the exercise. Blood flow at the forehead gradually increased during running for each velocity, with the 10 km/h session yielding the highest. On the other hand, blood flow at the fingertip of each velocity suddenly decreased then gradually rose during running for each velocity, with the 10 km/h session yielding the slowest increase. Mean body temperature rose to over 37.0 °C in the later stages of the 10 km/h running session.

Systolic and diastolic blood pressure, blood lactate level, and body weight data are shown in Table 1. The "Baseline" column contains the pre-warm-up data, and the "35 min", "55 min", and "75 min" columns contain values obtained just after, 20 minutes after, and 40 minutes after running, respectively. Differences between the baseline value and the values at each time point were evaluated by paired *t*-test, $p<0.05$ was considered statistically significant. Systolic blood pressure showed a statistically significant increase from baseline just after running for each running velocity. Diastolic

Table 1: Systolic and diastolic blood pressure, blood lactate level, and body weight at each measurement time.

		Baseline	35 min		55 min		75 min	
Systolic blood pressure (mmHg)	6 km/h	114.6 ± 9.9	136.0 ± 11.3	**	113.7 ± 10.4		113.6 ± 14.1	
	8 km/h	118.0 ± 8.6	133.3 ± 12.7	*	115.3 ± 10.5		116.6 ± 7.0	
	10 km/h	116.7 ± 13.9	147.6 ± 14.3	**	119.1 ± 16.5		114.1 ± 13.1	
Diastolic blood pressure (mmHg)	6 km/h	66.4 ± 8.6	74.3 ± 5.6	**	68.4 ± 7.9		71.7 ± 7.7	
	8 km/h	67.0 ± 9.1	67.4 ± 7.3		68.6 ± 9.7		70.7 ± 6.0	
	10 km/h	68.0 ± 8.3	67.7 ± 4.8		66.6 ± 11.2		67.0 ± 8.5	
Blood lactate level (mmol/L)	6 km/h	3.06 ± 2.09	4.97 ± 4.20		4.07 ± 4.51		2.76 ± 2.08	
	8 km/h	1.84 ± 0.44	5.23 ± 6.88		3.10 ± 3.50		2.57 ± 2.35	
	10 km/h	2.09 ± 1.48	7.11 ± 4.46	*	3.60 ± 2.35		2.40 ± 1.23	
Body weight (kg)	6 km/h	67.2 ± 9.1	-		-		66.8 ± 9.1	**
	8 km/h	68.1 ± 9.6	-		-		67.5 ± 9.4	**
	10 km/h	65.2 ± 4.7	-		-		64.6 ± 4.6	**

Baseline= pre-warm-up; 35 min = just after running; 55 min = 20 minutes after running; 75 min = 40 minutes after running.
Differences between the Baseline values and the values at each time point were evaluated by paired *t*-test (*: $p<0.05$, **: $p < 0.01$).

blood pressure significantly increased from baseline just after running only for when running velocity was 6 km/h. Blood lactate level was significantly higher than baseline only when subjects ran at 10 km/h. Body weight significantly decreased after running for all velocities due to sweating, with the dehydration amount reaching almost 1 percent of body weight.

4 DISCUSSION

In this study, we succeeded in stably measuring blood flow in running subjects using our previously developed MEMS blood flow sensor. We found that blood flow at the fingertips decreases just after running commences and then gradually increases during continuous running. Conversely, blood flow at the forehead and earlobe showed a sudden rise just after the start of running, gradually increasing during running. Moreover, we found that blood flow at the forehead increased the most when subjects ran at 10 km/h, the only velocity at which mean lactate level was significantly higher than baseline, and at which some subjects complained of exhaustion and retired. These increases in blood flow most likely function to lower the body temperature, helping with sweating to release heat. When subjects ran at 10 km/h, although compensatory blood flow increases were large, body temperature still increased to over 37 °C; and, perhaps because the release of body heat could not catch up with the exercise-generated hyperthermia, some subjects couldn't complete the full time. In contrast to this, blood flow at the fingertip actually decreased. Blood flow at fingertip was likely decreased by neural vasoconstriction, or because muscle tissue was given priority of blood supply over peripheral perfusion at the beginning of running. Blood flow was subsequently increased in order to lower body temperature.

The MEMS blood flow sensor can measure blood flow during running, but it also captures noise caused by running motion. Some spectral waves with the same frequency as running rhythm were observed in a power spectrum distribution of blood flow signal. This noise is likely due to shearing of the skin caused by the running motion. When such shearing occurs, blood vessels move relative to the MEMS blood flow sensor, which then captures the relative, shifted movement (Figure 11). The blood flow signal at the earlobe, where sensors are difficult to affix and the skin is soft and easily sheared, was strongly affected by motion. In contrast, the blood flow signal at the fingertip and forehead, where a solid hold was made possible by medical tape and headbands, were only slightly affected by the running rhythm. Even then we could eliminate the waves by monitoring the spectral pattern change from moment to moment, and treating the pace as constant. Therefore, we think the fingertip and the forehead are suitable measurement sites for blood

flow during running or other activities with significant motion. We may also even be able to eliminate the shearing noise at the earlobe, by filtering it from blood flow signals using a FFT.

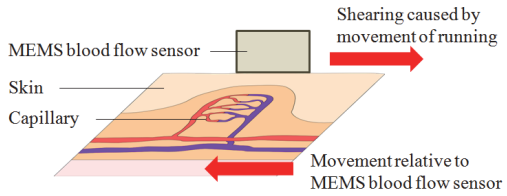

Figure 11: Schematic of blood flow measurement when a shearing occurs.

In conclusion, we have succeeded in stably measuring blood flow during running using the MEMS blood flow sensor. The device also captures the noise caused by running motion; however, we can eliminate this and obtain the heart rate by performing a FFT on blood flow power spectra, cancelling out the steady rhythm of the pace, and observing for an incremental frequency shift in the spectrum peak that corresponds to heart rate. The MEMS blood flow sensor would contribute to researches in areas like sports science or health science. Moreover, we found that the extent of the observed changes to blood flow depend on the intensity of exercise. These results suggest that the MEMS blood flow sensor has potential as a new portable device for detecting the running intensity, and alerting runners to any dangers from excessive exercise by detecting substantially increased or decreased blood flow and heart rate.

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