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Monitoring of the fluid accumulation in lower legs using nanofiber-based mechano-acoustic sensors

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Abstract

Early detection of excessive fluids accumulation in lower limbs usually termed, as peripheral edema is clinically significant for the diagnosis of chronic diseases. Current wearable sensors for edema monitoring comprised of stretch sensor usually suffer from drift over time. Here, we investigated a novel method of monitoring fluid accumulation in body by observing the resonant frequency shift measured by nanofiber based mechanoacoustic sensors. A clear shift in resonance frequency is observed when accumulated fluid volume changed in lower legs. This method can be advantageous over gold standard pitting method or methods employing strain sensors for continuous monitoring of fluid volume change and detection of swelling.

1. Introduction

Peripheral edema usually caused by the retention of fluid in leg tissues is the symptom for various chronic systematic diseases such as heart or kidney failure. Continuous monitoring of such edema helps clinicians and caregivers not only to detect those chronic diseases but also ensure the effectiveness of treatments and therapies, observe any severe changes in patient's condition and intervene if necessary[1–3]. The common methods currently employed includes measuring the body weights everyday, pitting depth and recovery, tape-measurement of leg circumference, foot/ankle volumetry by water displacement. However, these methods suffer from various limitations. For example, body weight can change for factors other than fluid accumulation. Pittting or tape measurement are subjective, accuracy of measuremnet varies from person to person. Therefore, an accurate wearable system for quantifying peripheral edema accurately and continuously is still a challenge[4].

Researchers attempted several wearable sensors for the detection of fluid volume change especially in lower legs. Smartsocks[5], smartcuff[6], swellfit[7] comprising of stretch sensors that measure the circumference of an ankle, are some of the state of the art wearable devices for edema monitoring. However, stretch sensors usually suffer from drift effect. Here, we propose a method of monitoring fluid accumulation in lower legs by measuring the resonnce frequency shift. The method utilizes a recently developed higly sensitive low freqency mechanoacoustic sensors in our group and a mechanical stimulator. The muscle tissue in lower legs usually resonates at low frequency. The stimulator creates a vibration in the leg when stimulated by applying a frequency sweep (30-120 Hz) for 5 s. The corresponding vibration of skin/muscles generates an output voltage which is measured with our mechanoacoustic sensors. When the vibration frequency of stimulator matches the natural frequency of muscle tissue, resonance occurs, resulting in a maximum output in sensor at that specified frequency. The reosnance frequency shifts based on the accumulation of fluids in lower legs. In this way, the increase in fluid volume can be quantified.

2. Experimental Results

The mechanoacoustic sensors were fabricated based on our recent report[8]. The sensor is highly sensitive (acoustic sensitivity, 10.05 V/Pa) in the low frequency region (<500 Hz), ultralight-weight and gas-permeable; making it suitable for continuous monitoring of resonance frequency shift.

The experimental setup for resonance frequency measurement is shown in Fig. 1a. The mechanoacoustic sensor was attached to the lower leg using 3M Tegaderm tape. A vibration stimulator (PET-05-05A, IMV Corporation, Japan) was placed 5 cm away from the sensor site. A frequency sweep (30-120 Hz) for 5 s was applied to stimulator from an external function generator (Agilent 33220A) to produce a vibration on lower leg. The output of the sensor was measured using 16-bit data acquisition device (PowerLab 2/26. ADInstruments) with a sampling rate of 1 kHz. Fig. 1b and 1c shows the voltage output of sensor in response to the stimulation and the corresponding power density, respectively. The resonance at frequency of 78 Hz was clearly observed.

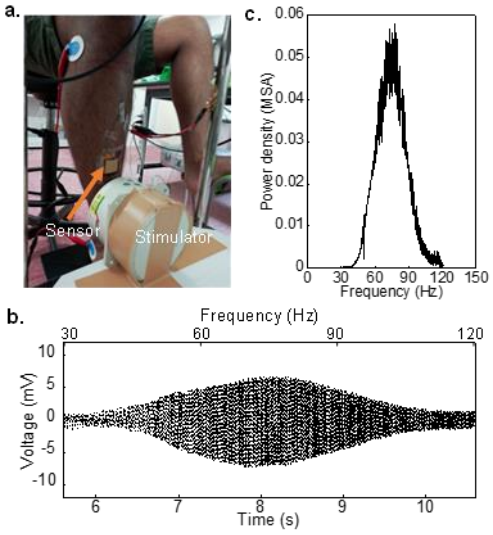

Fig. 1: ***a.*** *Experimental setup for resonance frequency measurement,* ***b.*** *Output voltage of sensor when a sweep of 30-120 Hz is applied for 5 s and* ***c.*** *corresponding power density.*

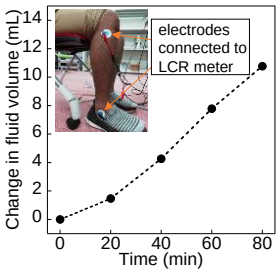

Fig. 2: Fluid volume measurement in lower leg.

To evaluate the compatibility of our proposed method, we also measured the fluid volume in lower leg by bioelectrical impedance measurement system[9]. Two surface electrodes were placed on the skin at the top and bottom of the lower leg (ankle and knee) as shown in Fig. 2 (insets). A small amplitude (400 μA), high frequency (25 kHz) current was injected into the leg and the resistance of tissues was recorded. The subject laid supine for 20 minutes to equalize fluid distribution in lower leg. Then the subject sat for 80 min accordingly as shown in Fig. 2. The resistance and the circumferences at ankle and knee positions were measured with a 20 min interval. Finally, the fluid volume was calculated using the following equation[9]

$$v = \frac{\rho^{2/3}}{3(4\pi)^{1/3}} \left(\frac{L}{C_1 C_2 R} \right)^{2/3} L\left(C_1{}^2 + C_2{}^2 + C_1 C_2\right)$$

where, v is fluid volume; C_1, C_2 are the cirumferences of the top (knee) and bottom (ankle) of the segment respectively; L is the length of segment; R is the resistance of segment; ρ is the resistivity of the blood (98 Ω-cm). As shown in fig. 2, the fluid volume increased gradually over time when subject sat continuously maintaining the same posture.

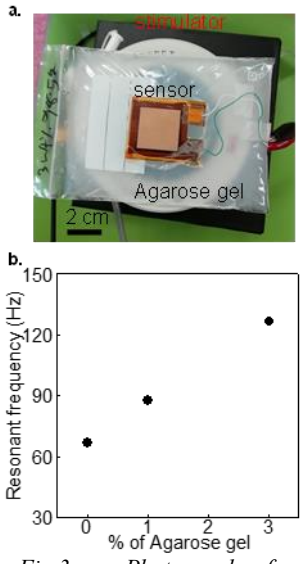

*Fig.3: **a.** Photograph of in-vitro experimental setup **b**. Resonant frequency as a function of agarose concentration.*

In order to investigate accuracy of our proposed method, an *in-vitro* experiment using agarose gel phantoms was performed (Fig. 3a). Three different phantoms (0%, 1% and 3% agar gel) were prepared. The stiffness of agarose gel was varied due to the concentration variation. As expected, the resonance frequency increased with the increase in agar concentration of the phantoms (Fig. 3b). Finally, change in resonance frequency was measured on two healthy male subjects utilizing our proposed method. All the human experiments protocol was thoroughly reviewed and approved by the ethical committee of the University of Tokyo (approval number KE18-14). As shown in Fig 4a and 4b, for both human subjects, the resonance frequency followed the trend of fluid volume change in lower legs. When the fluid volume increased, resonance frequency went down in almost linear fashion and vice-versa. In the previous studies, researchers tried to assess the leg swelling from the diameter change, without quantifying actual change in fluids in leg. Our method can overcome such limitation. In addition, since the performance of mechanoacoustic sensors do not degrade over time, this method can provide a reliable measurement technique for continuous monitoring of change in fluid in the lower legs. In future, the reliability of such measurement will further be confirmed by collecting statistical data for many human subjects.

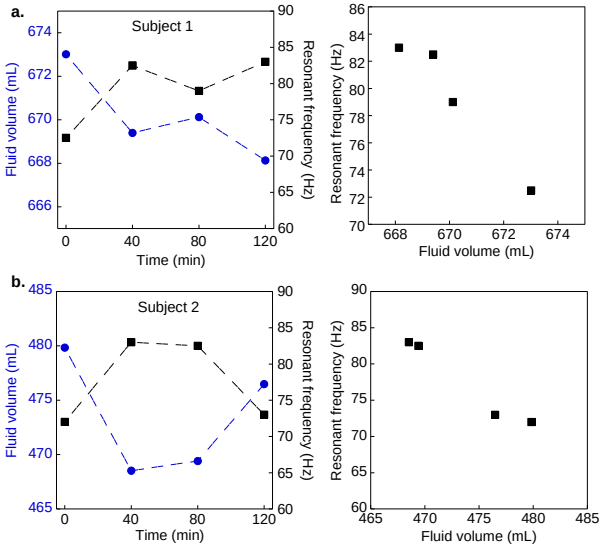

*Fig. 4: Shift in resonance frequency due to fluid volume change in **a.** subject 1 **b.** subject 2.*

3. Conclusions

We demonstrated a simple method of continuous monitoring of fluid volume change in lower legs by observing the resonance frequency shift using a mechanoacoustic sensor. Both the *in-vitro* and *in-vivo* results showed the promise of accurate monitoring of fluid volume change in human legs.

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