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Snoring detection based on a stretchable strain sensor

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Snoring is caused by the stenosis of the upper respiratory tract, which can lead to the vibration of the palatine uvula. Snoring brings not only harm to the snorer [1] but also sleep deprivation to those around them [2]. Furthermore, studies show that loud snorers have a 67% greater chance of suffering from a stroke and a 34% higher risk of having a heart attack. To identify people at risk from these diseases, snoring recording and analysis become highly important [3].

In literature, polysomnography (PSG) is regarded as the standard method for monitoring sleep quality [4]. However, the cost of this measurement is high and the operation as well as analysis of the measurement result requires medical experts, which makes it infeasible for snorers to use at home. There have been other efforts aiming at snoring detection in recent years. For example, sound can be used to evaluate human health [5]. Qian et al. [6] recorded overnight audio data of one snorer and used a machine learning method to detect snoring. However, audio recordings are prone to be affected by noise in the environment, and machine learning requires a lot of computation resources. Besides the sound-based approach, a piezoelectric vibration sensor was used to detect snoring by Sirohi and Chopra [7], however, the signal strength depends on whether the piezoelectric sensor is tightly attached to the snorer's skin. A nasal cannula has also been used in snoring detection by measuring its vibration in the nares [8]. Unfortunately, this method is affected by nasal blockage, mouth breathing, and the movement of the cannula in the nares. In addition, a nasal cannula can bring discomfort to snorers. A wearable self-powered sensor based on a flexible piezoelectric nanogenerator was used to detect snoring in [9]. This sensor can be used in the respiration and health-care monitoring fields. However, it is still a type of piezoelectric sensor and requires tight attachment to the skin. Therefore, there is a high demand for a natural and comfortable way to detect snoring and to avoid the issues mentioned above.

It can be observed that a slight vibration occurs at the throat during snoring. The vibration data can be analyzed to determine whether snoring is occurring. Following this idea, this article proposes a new method for snoring detection based on a new stretchable strain sensor which detects the deformation of the snorer's throat. This sensor is comfortable to wear and does not require to be tightly attached to the skin. Moreover, this sensor is cheap, light, and portable, which makes it promising for use at home. The design principle and the fabrication process of the strain sensor can be found in the supporting materials.

Snoring detection method. There are several typical actions during sleep that may cause throat deformation, such as light breathing (normal sleep), deep breathing, coughing, swallowing, turning over, and snoring. The throat deformations during these actions can be recorded by the strain sensor. Strain sensor attachment to the volunteer's throat is shown in Figure 1(a). The strain sensor itself and its measurement circuit are shown in Figure 1(b). The volunteer's throat vibration data during snoring are plotted in Figure 1(c-I). Figure 1(c-II) displays the swallowing action. It can be seen that swallowing occurred at 24.5 s, where a large fluctuation in the data profile occurs. Coughing and turning over actions have similar profiles to swallowing. It is evident that the frequencies of these actions are much lower than that of the snoring action, which can be easily distinguished. Deep breathing during sleep is shown in Figure 1(c-III). Note that the frequency of snoring is similar to that of deep breathing; however, it is crucial to distinguish snoring from deep breathing. Fortunately, by careful observation, the following two facts can be observed: (1) the amplitude of the snoring signal is much greater than that of deep breathing; and (2) the snoring signal rises more steeply than the deep breathing signal.

The presented snoring detection principle is based on the signal's amplitude and slope.

Amplitude-based detection principle. (1) Determine the amplitude threshold A_{light} of light breathing from experiments. If the recorded signal's amplitude is below A_{light}, the subject is considered to be in the normal sleep

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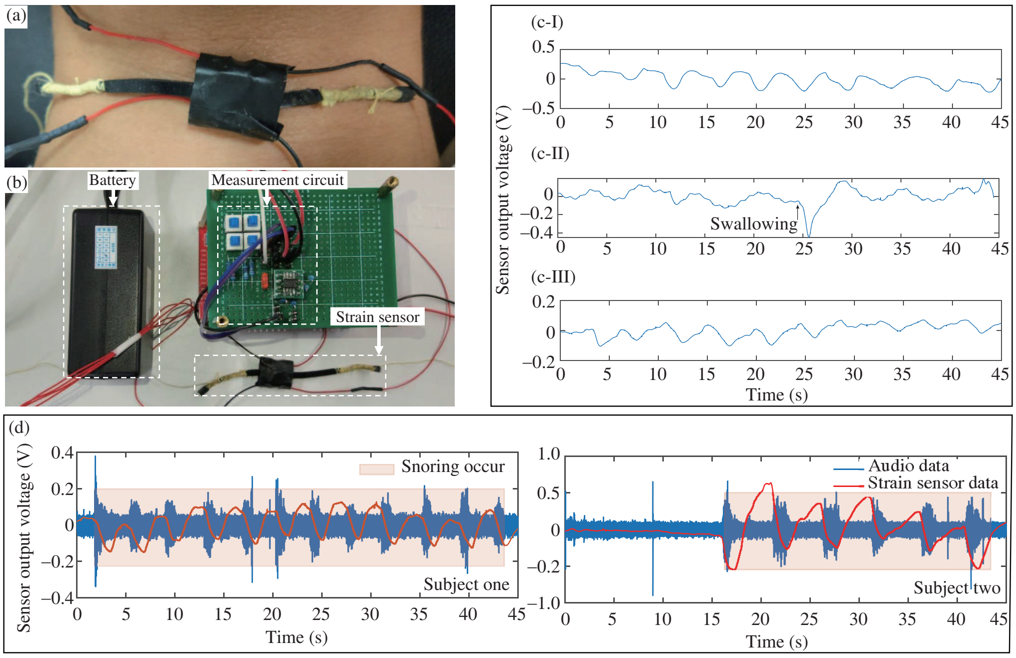

Figure 1 (Color online) The strain sensor and some typical sleep data collected. (a) Attachment of the strain sensor to the subject's throat; (b) the measurement circuit; (c-I) snoring signal during sleep; (c-II) swallowing signal during light breathing; (c-III) deep breathing data; (d) the audio and strain sensor data displayed together during snoring.

stage. (2) If the fluctuation amplitude of the recorded signal is above A_{light} and the total fluctuation time (First, find the longest sequence of local minimum points starting at the current local minimum point, which satisfies that the amplitude difference of any two local minimum points is smaller than the given threshold A_{limit}. Then the total fluctuation time is defined as the time span of this sequence) is longer than a certain threshold T_{last}, then the action is considered to be snoring or deep breathing. (3) Because the amplitude of a snoring signal is higher than that of deep breathing, if the amplitude of a signal goes beyond a certain threshold A_{snore}, the action is considered to be snoring.

Slope-based detection principle. The deformation speed of the subject's throat is different for each sleep action. It can be observed that the deformation speed is relatively high in swallowing and coughing actions and is relatively low in deep and light breathing actions. The deformation speed of snoring lies in the middle of the above two speeds. Because the rising slope of the recorded signal represents the throat's deformation speed, the following algorithm can be obtained. (1) If the rising slope of the recorded signal is steeper than a certain threshold $P_{\max}$, the action is swallowing, coughing, or turning over. (2) If the signal slope is smaller than $P_{\min}$, the action is considered to be light or deep breathing. (3) If the slope is between $P_{\min}$ and $P_{\max}$, the action is recognized as snoring. To prevent false positives, snoring is recognized to occur only when the above two detection conditions hold simultaneously.

Finally, the data pre-processing method is presented. To eliminate the influences of measurement noise and abnormal data points, the recorded signal is first processed using the median mean filtering method. To detect snoring in real time, the recorded data is split into several data segments. Each segment includes ten fluctuation cycles because snoring may occur simultaneously with swallowing and turning-over actions and the total fluctuation times of these actions are usually only one or two cycles. This way, snoring can still

Algorithm 1 Snoring detection algorithm

while (1) **do**
  $T = 0, a = 0, p = 0$, where T denotes the total signal fluctuation time; a denotes the times when the signal's relative amplitude is larger than $A_{\texttt{snore}}$, p denotes the times when the signal's rising slope is between $P_{\min}$ and $P_{\max}$;
  $C = \emptyset$, where C denotes the set of total signal fluctuation times;
  Obtain 10 cycles of fluctuating data D;
  Unbiased processing of the fluctuating data $D - E(D)$;
  Search 10 local maximum amplitudes $D_m(1) \cdots D_m(10)$ and 10 local minimum amplitudes $D_n(1) \cdots D_n(10)$;
  while $i < 10$ **do**
    Calculate the time difference between two adjacent maximum amplitudes $T(i) = S(D_m(i)) - S(D_m(i-1))$, where $S(D_m(i))$ denotes the time when the ith local maximum amplitude occurs;
    Calculate the relative amplitude of each cycle $A(i) = D_m(i) - D_n(i)$;
    Calculate the rising slope of the signal $P(i) = A(i)/T(i)$;
    if $A(i) > A_{\texttt{light}}$ **then**
      if $A(i) > A_{\texttt{snore}}$ **then**
        $a = a + 1$;
      end if
      if $A(i) - A(i-1) < A_{\texttt{limit}}$ **then**
        $T = T + T(i)$;
      else
        $C = \{C, T\}$ and $T = 0$;
      end if
      if $P(i) > P_{\min}$ and $P(i) < P_{\max}$ **then**
        $p = p + 1$;
      end if
    end if
  end while
  if $a > 5$ and $\max\{C\} > T_{\texttt{last}}$ and $p > 5$ **then**
    Snoring is occurring;
  end if
end while

be successfully detected because the majority of the data segment corresponds to the snoring action. Finally, three important features (signal amplitude, rising slope, and the total fluctuation time) are then extracted from the recorded signal for snoring detection. The details of the snoring detection algorithm are given in Algorithm 1.

Experiments. Five subjects are employed to test the proposed snoring detection method. The proposed strain sensor is used to record the data of their throats' deformations. Two typical results are shown in Figure 1(d). To verify whether the subject is in the snoring stage, a microphone is simultaneously used to record the sleep quality. After each experiment, the audio data is divided into the same data segments as the ones of the throat's deformation data. Each time-stamp in the audio data segment can be manually labeled as snoring or no snoring according to the recorded sound. We observe that the snoring detection results by the strain and the audio sensors are consistent, which demonstrates the effectiveness of the proposed detection algorithm.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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