RespWatch: Measuring Respiratory Rate with a Commercial Smartwatch

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Need for Respiratory Rate Monitoring

- Respiratory Rate (RR) is closely related to health.
  - Detect sleep apnea, assess sleep quality
    - During sleep with little motion
  - Detect stress, opioid overdose, deterioration
    - Daily life with motion

- Traditional RR monitoring techniques are burdensome
  - Respiratory belt
  - Gas mask…

Not suitable for unobtrusive and long-term monitoring!

Respiratory belt
(source: https://sites.psu.edu/resnasdc/2013/06/13/smart-belt-a-low-cost-seizure-detection-device-rice-university/)

Gas mask
Smartwatches

- **Popularity:** more than 20 million sold in US, 2019

- **Embedded sensors**
  - Inertia Measurement Unit (IMU): measure motions
  - Photoplethysmogram (PPG): measure the heart rate

- **Enable long-term and unobtrusive monitoring**

Can we measure respiratory rate with smartwatches?
Limitations of the State of the Art

- Measure RR with smartwatch IMU sensors
  - Measure **micro vibration** of the respiration process
    - Assume limited motion, e.g., sleep, meditation
  - Vulnerable to **sensor noise** and **motion artifacts**
    - Micro vibrations can be the same order of sensor noise
  - Not suitable for RR monitoring in **daily life with motion and noise**


- Can we measure RR with smartwatch **photoplethysmogram (PPG)** in daily life?
Measuring RR with PPG

- PPG: an optical sensor for blood volume changes
  - Transmission mode vs. reflectance mode
  - Commonly used to measure the heart rate

- PPG waveform is modulated by respiration
  - Frequency (RIFV), Amplitude (RIAV), Intensity (RIIV)

![Diagram showing Fingertip PPG and Wrist PPG](image)

**Pulse peaks in the PPG waveform are critical for extracting the modulations.**
Challenges of Measuring RR with Watch PPG

- **Robustness** against noise
  - Significant noise and motion in daily life
  - Lower signal quality than finger PPG

- Trade-off between **accuracy** and **yield**
  - Require both yield and accuracy for real-time and long-term monitoring

- **Constrained** platform
  - Smartwatch has limited resources and battery
RespWatch Approaches

- **Signal processing**: efficient
- **Deep learning**: robust against noise
- **Hybrid**: combining the advantages of signal processing and deep learning

<table>
<thead>
<tr>
<th>Approaches</th>
<th>Accuracy</th>
<th>Efficiency</th>
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<tbody>
<tr>
<td>Signal processing estimator</td>
<td>High under moderate noise</td>
<td>Highly efficient</td>
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<td>Deep learning estimator</td>
<td>Robust to significant noise</td>
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Signal Processing Estimator

- **Preprocessing**
  - 60s window segments
  - Resample and band pass filter

- **Artifact Elimination & Pulse Peak Finding**
  - Fine-grained noise elimination with sliding sub-window
  - PPG pattern detector

- **Respiration Extraction**
  - Extract RR
  - Calculate the Estimation Quality Index
Forward-Backward (FB) Filter

- **Peak positions** of the PPG waveform is the key to respiration extraction

- Challenge: Find the pulse peaks in the presence of noise

- Forward-backward filter allows pulse peaks to be mapped back to unfiltered PPG
Artifact Elimination & Pulse Peak Finding

- Sliding sub-window: size of 10s, step of 2s
- Detect the PPG pattern in each sub-window after the FB filter

- Keep peaks in valid sub-windows
  - Fine-grained noise elimination

- Those peaks are used to
  - construct the respiration signals
  - find peaks to estimate RR

(a) A valid sub-window
(b) An invalid sub-window with artifacts. (The standard deviation of peak-to-valley distances is larger than 0.4.)
**Estimation Quality Index (EQI)**

- Assess the quality of the RR measurement
  - Tradeoff between accuracy and yield

- Existing approach uses motion as a proxy for measurement quality

- Estimation Quality Index (EQI)

\[
EQI_{RIXV,i} = \alpha \cdot \frac{STD(peak\_intervals_{(i)})}{seq\_length_{(i)}}
\]

- Does not rely on an external (e.g., motion) sensor
- Assess the impact of noise in general (not just motion)
- Assumptions: (1) respiration is rhythmic; (2) longer sequence $\rightarrow$ more accurate
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RespWatch: Deep learning Estimator

- **Deep learning**
  - Requires no specialized signal processing
  - Is robust against noise

- **Preprocessing**
  - Resample the data
  - Bandpass filtering
  - Standardization

- **Deep Residual Network (ResNet)**
  - 2-d conv → 1-d conv
  - Classification → regression
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Hybrid Approach

- When to switch between the two basic estimators?
- Based on Estimation Quality Index (EQI)

**Diagram:**

- Raw PPG signals
- Signal processing estimator
- EQI < Thr?
- Yes: Output RespWatch_RIIV
- No: Deep learning estimator
- EQI ≥ Thr?
- No: Output RespWatch_DL

**Combine complementary advantages**
- EQI > threshold → signal processing
- EQI ≤ threshold → deep learning
Experiment

- **Fossil Gen4 Explorist HR** smartwatch (Wear OS)
  - Respiratory belt used to validate respiratory estimation
- **Experiment** in collaboration with the medical school
  - Multiple activities involved

We recruited **32 healthy subjects** (2 subjects’ data discarded)
- In total: \(1.5 \times 30h = 45h\) data collected.
Impacts of Activities

- Series of activities with different motion levels
  - Watch video, do math (working), speech prep., holding cold object, free time

- Speech period is excluded
- Red vertical lines marks intervals when signal processing failed

RespWatch_RIIV: signal processing
RespWatch_DL: deep learning

Deep Learning more accurate
Accuracy vs. Yield

$MAE = \frac{1}{n} \sum_{i=1}^{n} |\hat{y}_i - y_{ref,i}|$

- RespWatch_RIIV
- RespWatch_DL
- Auto_switch_EQI

Switch Point based on EQI
EQI=2.3
Yield=53%

Sort the data windows based on the EQI
Empirical Evaluation on Smartwatches

- Implementation on commercial smartwatches

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<th>Platform</th>
<th>RAM</th>
<th>System</th>
<th>PPG Sensor</th>
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<tr>
<td>Fossil Gen4</td>
<td>Wear 2100¹</td>
<td>512MB</td>
<td>H</td>
<td>PAH8011² (200Hz)</td>
</tr>
<tr>
<td>Fossil Sport</td>
<td>Wear 3100³</td>
<td>512MB</td>
<td>H</td>
<td>PAH8011 (100Hz)</td>
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- Running time on the smartwatch

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<th>Signal processing running time</th>
<th>Deep learning running time</th>
<th>Hybrid expected running time</th>
</tr>
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<tr>
<td>Fossil Gen4 (H)</td>
<td>44.895ms</td>
<td>6592.828ms</td>
<td>2879.811ms</td>
</tr>
<tr>
<td>Fossil sport (H)</td>
<td>38.064ms</td>
<td>7943.434ms</td>
<td>3453.740ms</td>
</tr>
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- Signal processing is much more efficient than deep learning.
- Hybrid approach balances run time and robustness.
Conclusion

- **RespWatch** on commercial smartwatches for robust RR monitoring.

- Exploit the tradeoff between efficiency and robustness against noise.
  - **Signal processing:** efficient
  - **Deep learning:** robustness against noise.
  - **Hybrid:** efficient + robust

- Experiments show the feasibility of running RespWatch on smartwatches.