CPSL
Cyber-Physical Systems Laboratory

RespWatch: Measuring Respiratory Rate with a Commercial Smartwatch

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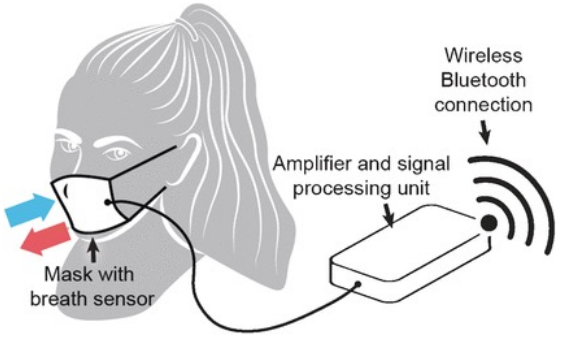
Need for Respiratory Rate Monitoring

- 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…



Gas mask

(source: https://phys.org/news/2016-04-paper-based-electrical-sensor-respiration.html)

Not suitable for unobtrusive and long-term monitoring!

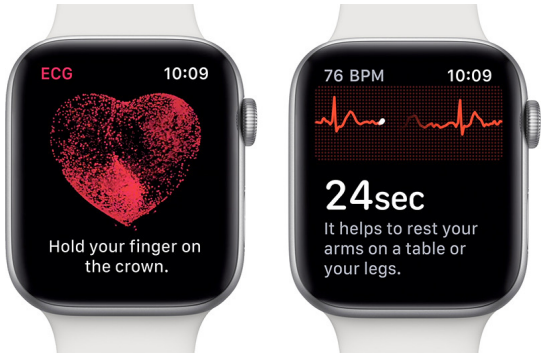


Respiratory belt

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

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**



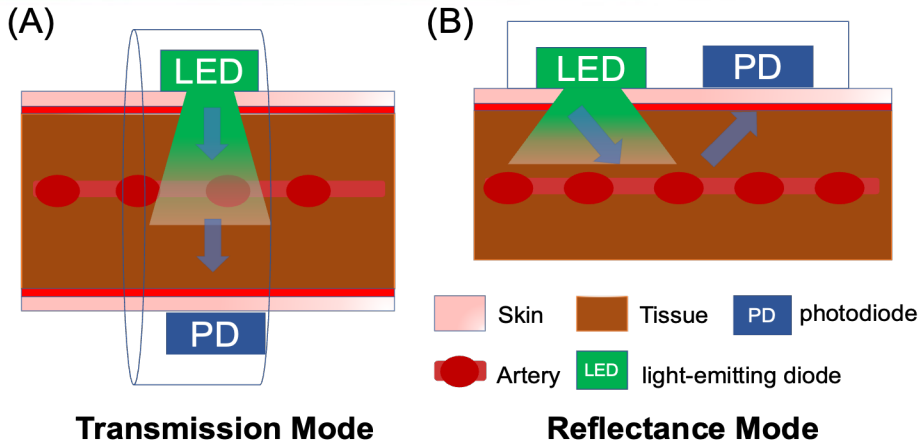
Hernandez, J., et al., Biowatch: estimation of heart and breathing rates from wrist motions. *International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth)*. IEEE, 2015.

Hao, T., et al., MindfulWatch: A smartwatch-based system for real-time respiration monitoring during meditation. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1.3, 2017.

- 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)

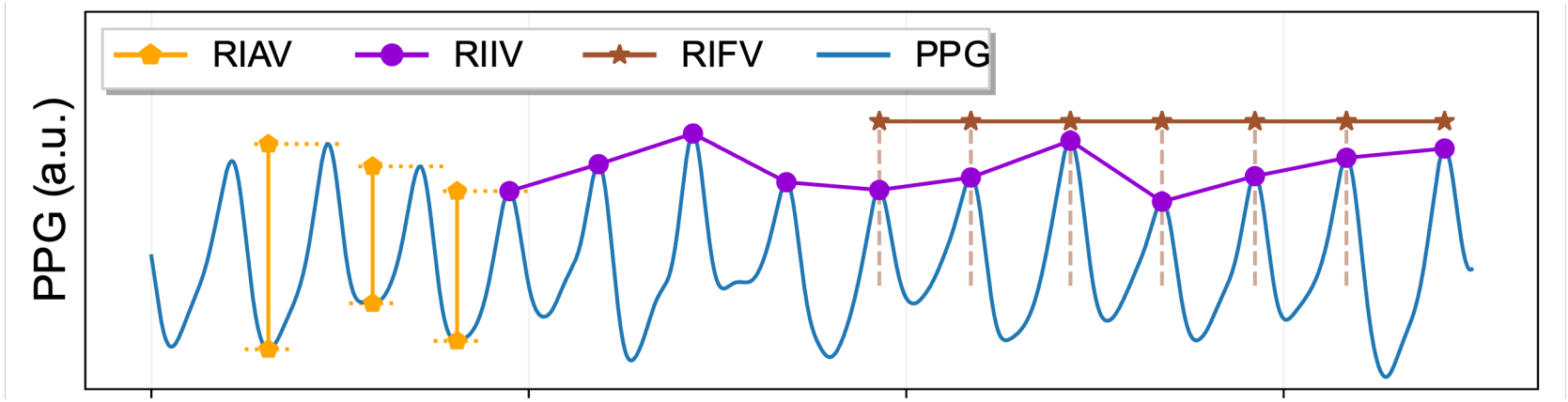


Transmission Mode

Fingertip PPG

Reflectance Mode

Wrist PPG



***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

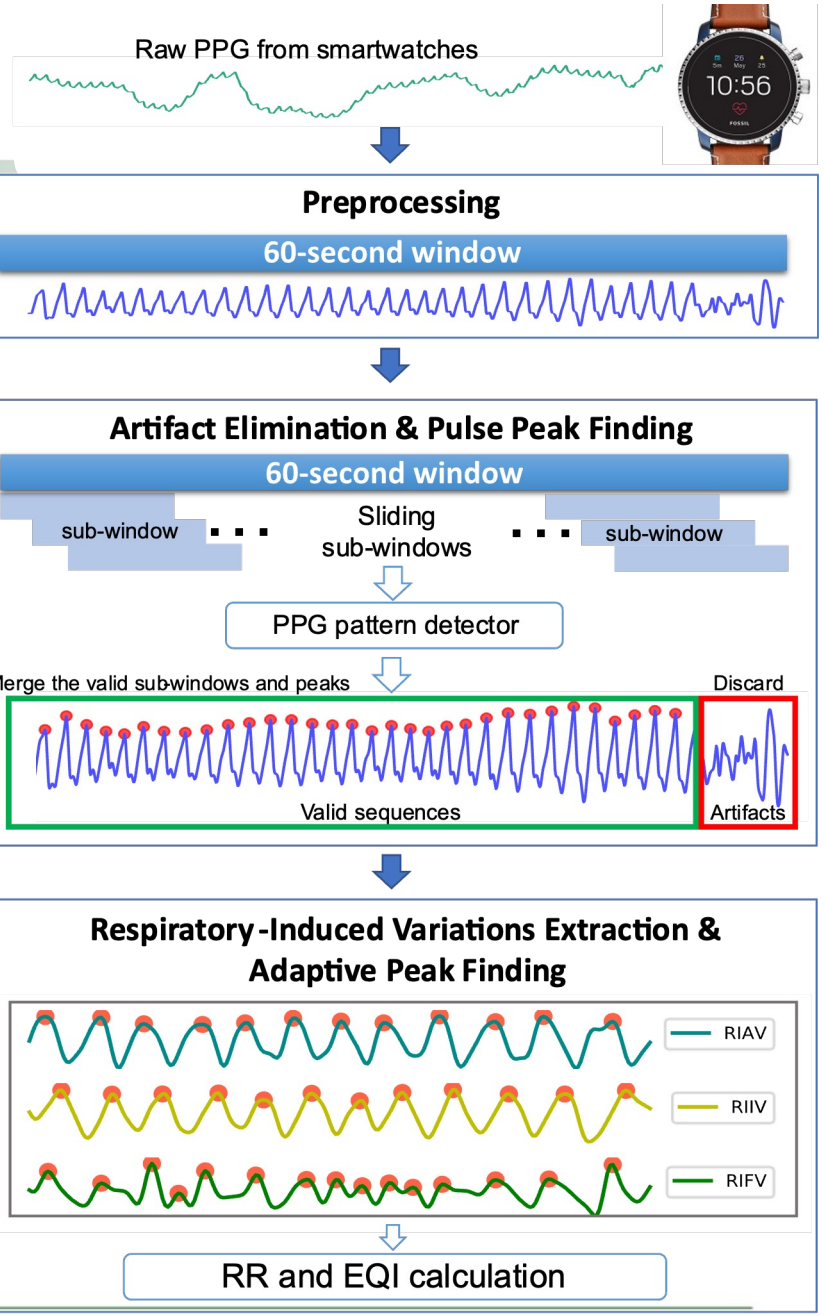
RespWatch Approaches

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

Approaches	Accuracy	Efficiency
Signal processing estimator	**High** under **moderate noise**	**Highly efficient**
Deep learning estimator	**Robust** to **significant noise**	Not efficient
Hybrid estimator	**High** under **moderate noise** **Robust** to **significant noise**	**Efficient**

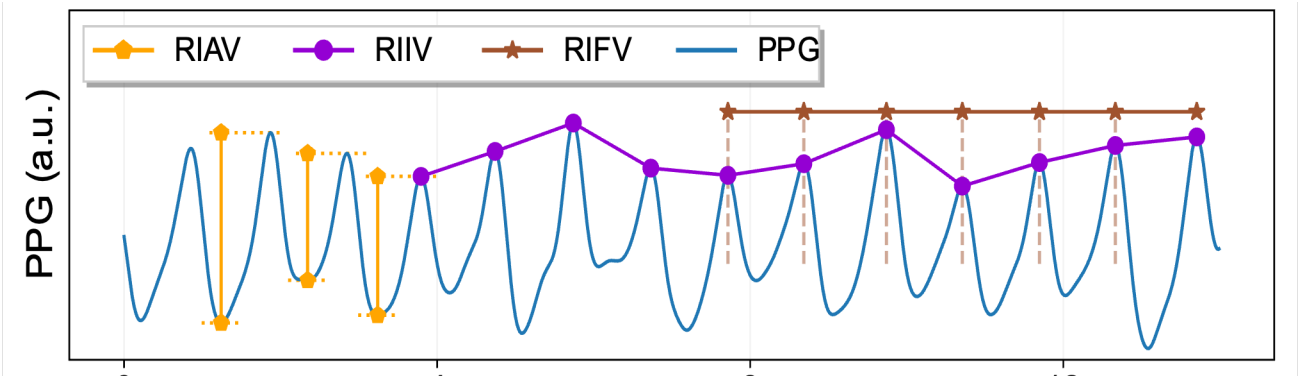
Signal Processing Estimator

- **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

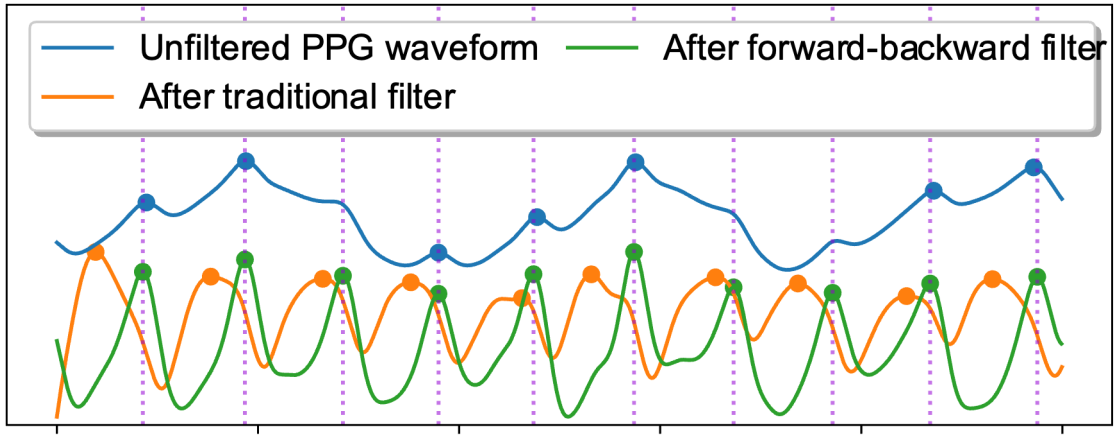


Forward-Backward (FB) Filter

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

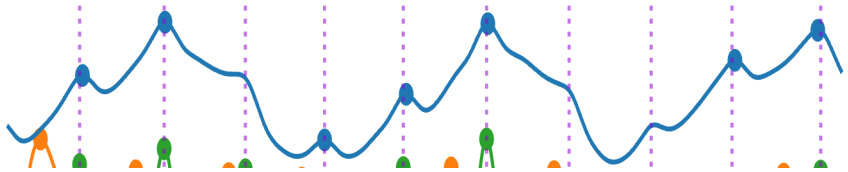


- Challenge: Find the pulse peaks in the presence of noise
- Forward-backward filter allows pulse peaks to be mapped back to unfiltered PPG

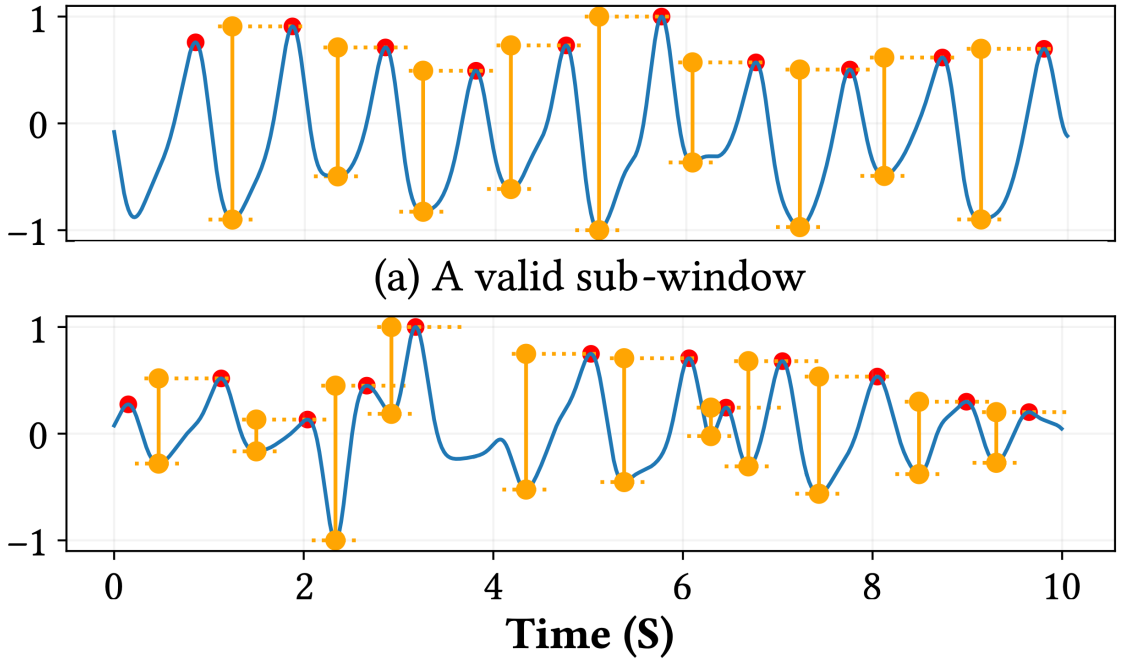


Artifact Elimination & Pulse Peak Finding

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



FB filter



(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.)

- Keep peaks in valid sub-windows
  - Fine-grained noise elimination
- Those peaks are used to
  - construct the respiration signals
  - find peaks to estimate RR

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 → more accurate

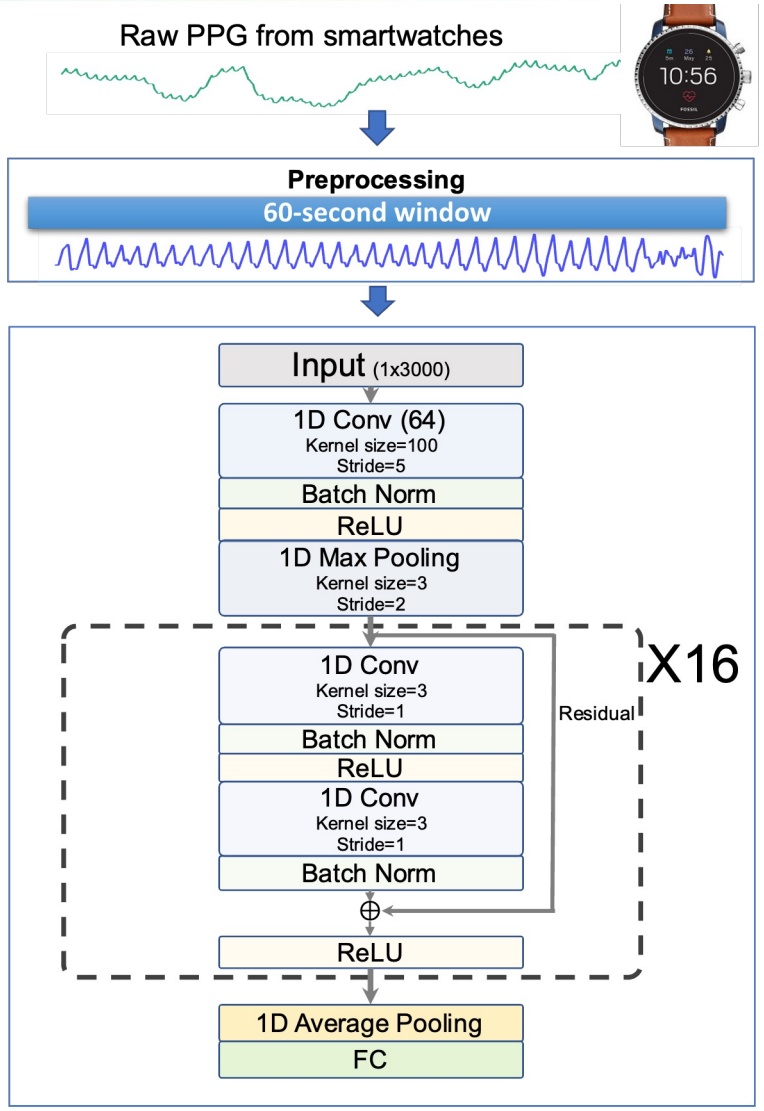
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RespWatch: Deep learning Estimator

- **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



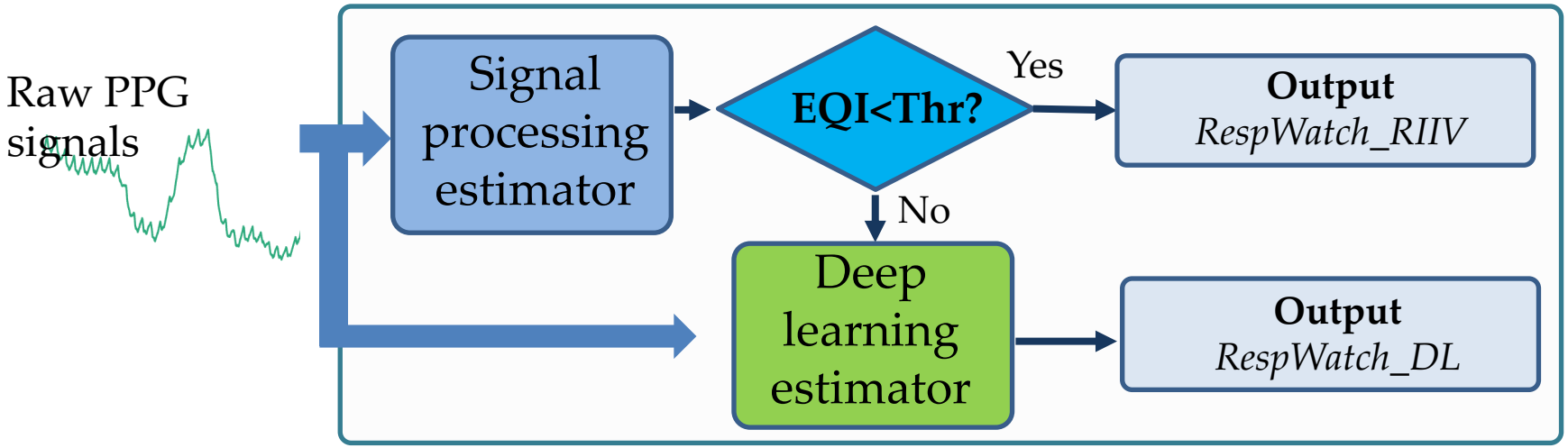
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Hybrid Approach

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

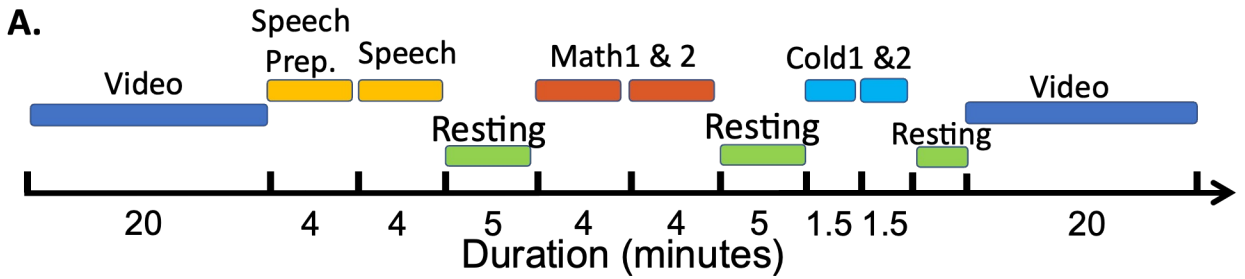


Combine complementary advantages

- 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



B.



Fossil Gen4 Explorist
- PPG at 200Hz
- IMU at 50Hz

C.

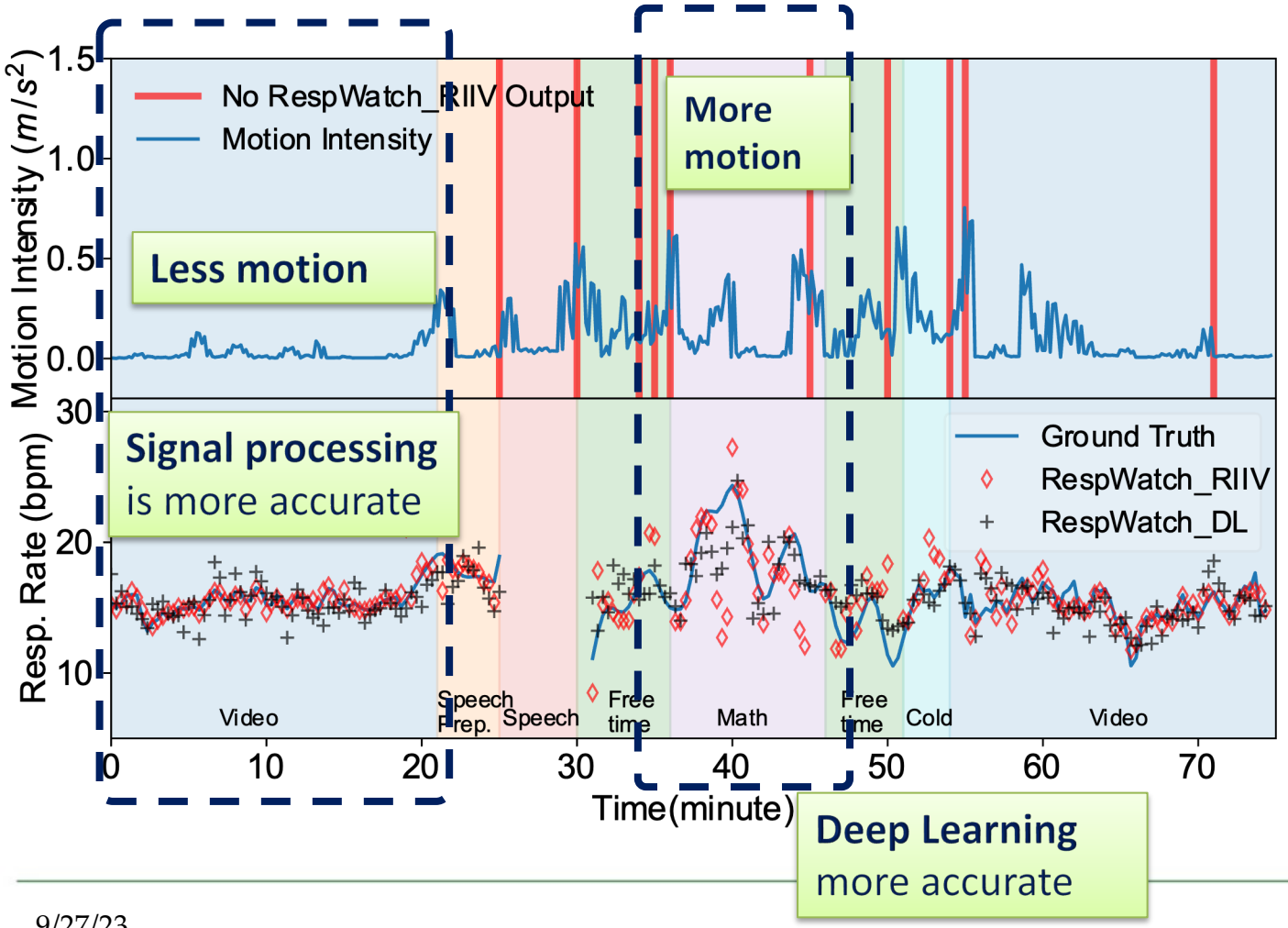


Vernier Respiration Belt as ground truth

- We recruited **32 healthy subjects** (2 subjects' data discarded)
  - In total: 1.5 X 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

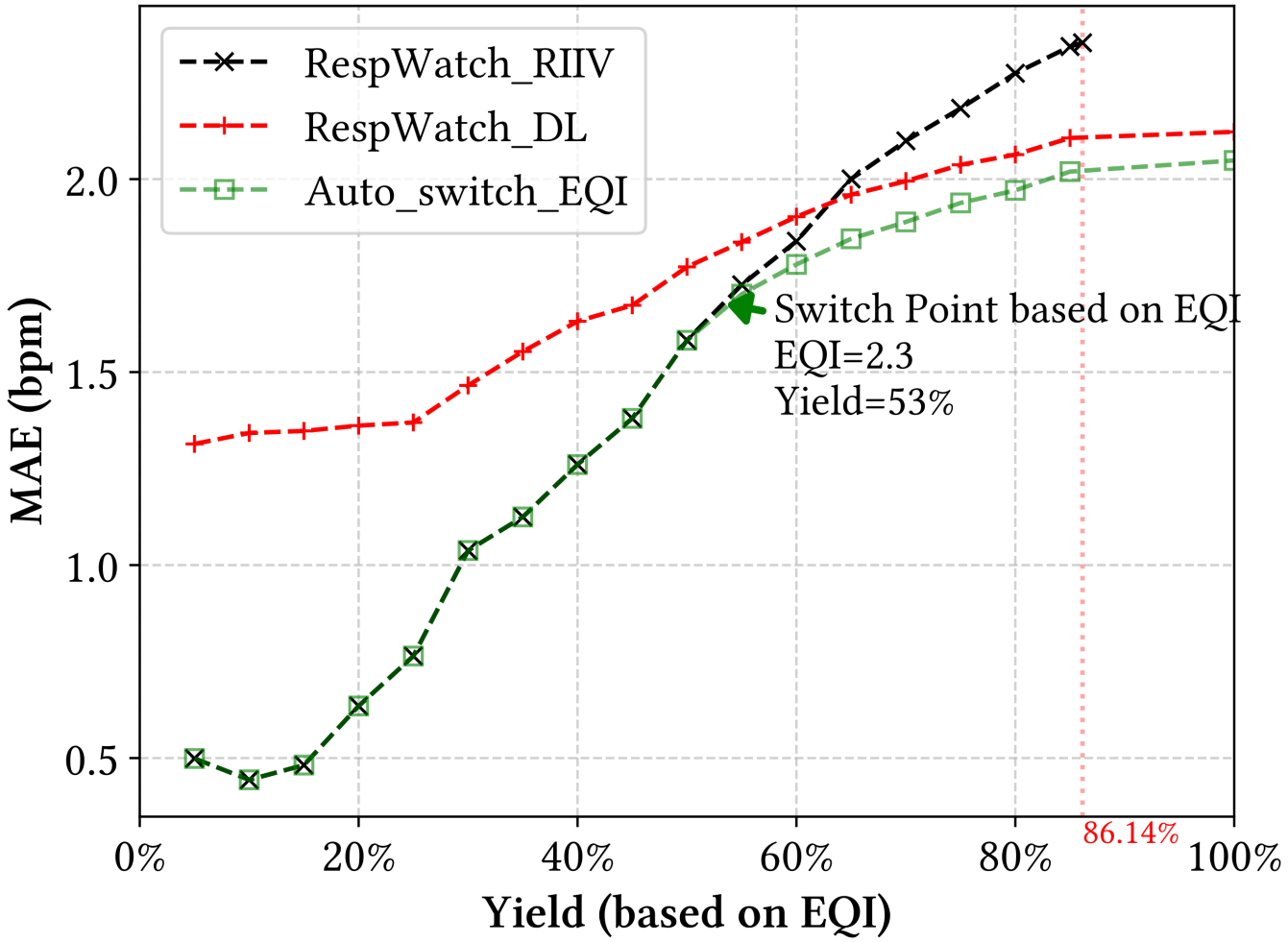


- Speech period is excluded
- Red vertical lines marks intervals when signal processing failed

RespWatch_RIIV: signal processing
RespWatch_DL: deep learning

Accuracy vs. Yield

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



Sort the data windows based on the EQI

Empirical Evaluation on Smartwatches

- Implementation on commercial smartwatches

Device	Platform	RAM	System	PPG Sensor
Fossil Gen4	Wear 2100[1]	512MB	H	PAH8011[2](200Hz)
Fossil Sport	Wear 3100[3]	512MB	H	PAH8011 (100Hz)

- Running time on the smartwatch

Devices	**Signal processing running time**	**Deep learning running time**	**Hybrid expected running time**
Fossil Gen4 (H)	44.895ms	6592.828ms	2879.811ms
Fossil sport (H)	38.064ms	7943.434ms	3453.740ms

- 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.