RespEar: Earable-Based Robust Respiration Rate Monitoring

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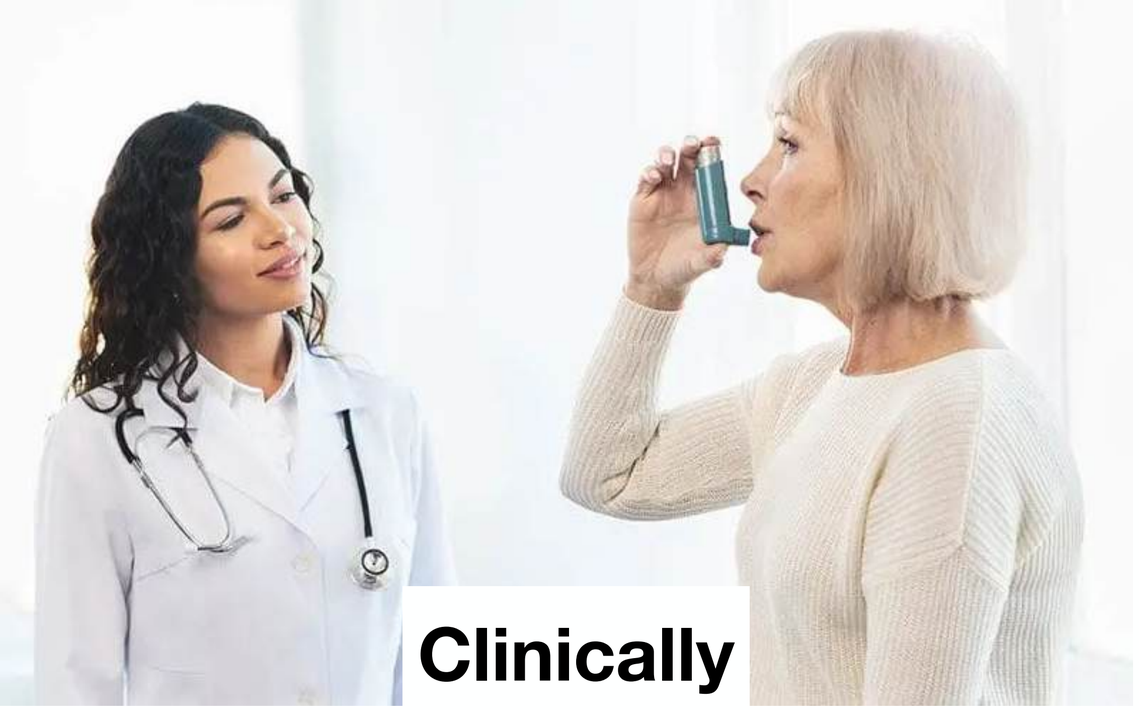
> 20 breaths per minute
Fever, asthma, heart conditions…

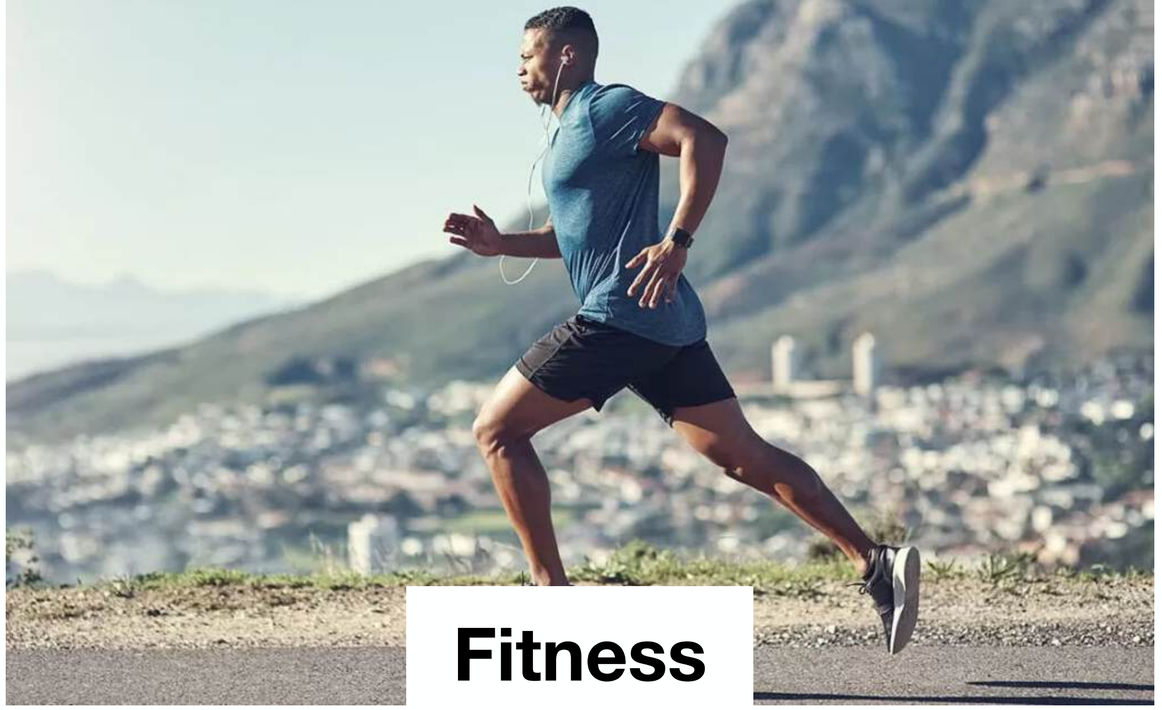
< 12 breaths per minute
Abnormal metabolic processes, sleep apnoea, neurological conditions…

Hill, Barry, and Sarah H. Annesley. "Monitoring respiratory rate in adults." British journal of nursing 29, no. 1 (2020): 12-16.

Respiration Rate



Clinically



Fitness

Sleeping

Stress

Respiratory Rate Measurements

- Continuous
- Non-obtrusive
- Various activities

Sensing Modality	Continuous	Non-Obtrusive	Various Activities
Pressure Sensor	✓	✗	✓
IMUs	✓	✓	✗
Airflow Sensor	✗	✗	✗
Wireless	✗	✓	✗
Camera	✗	✓	✗
Microphone	✓	✓	✗
PPG/ECG	✓	✓	✗
New Solution	✓	✓	✓

[illegible] Yang, and Shiwen Mao. "Smartphone sonar-based contact-free respiration rate monitoring." ACM Transactions on Computing for Healthcare 2, no. 2 (2021): 1-26.
[illegible] PervasiveHealth, IEEE, 2015.

Earables

Unobtrusive sensing

(Non-obtrusive)

Widely Used

(Continuous)

Optimal Location

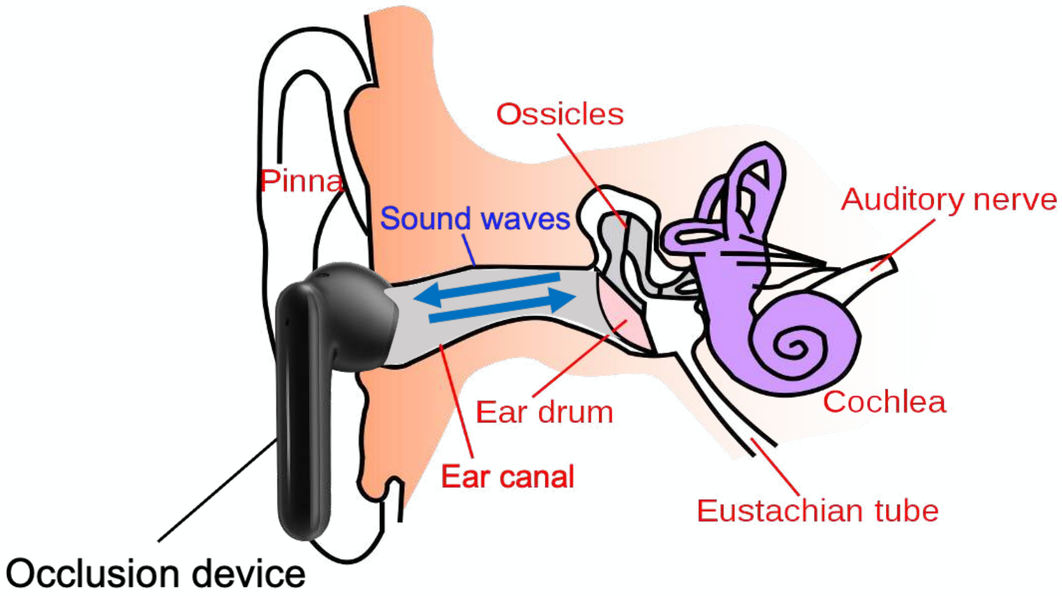
(Various activities)

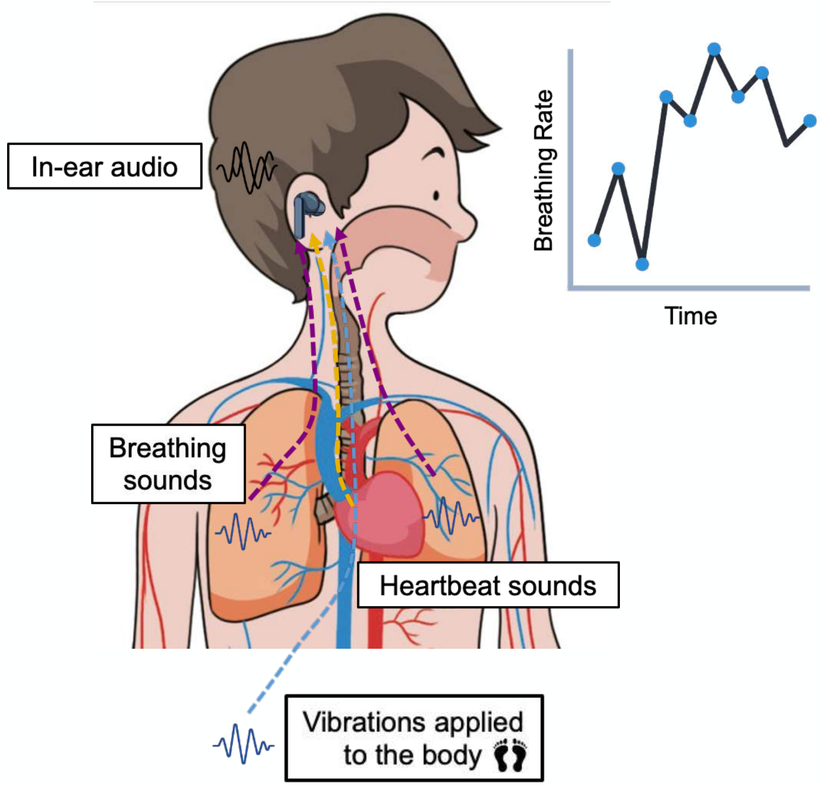
Our solution — RespEar

Earable-based Robust Respiratory Rate Monitoring

- Continuous
- Non-obtrusive
- Various activities

In-ear Acoustic Sensing



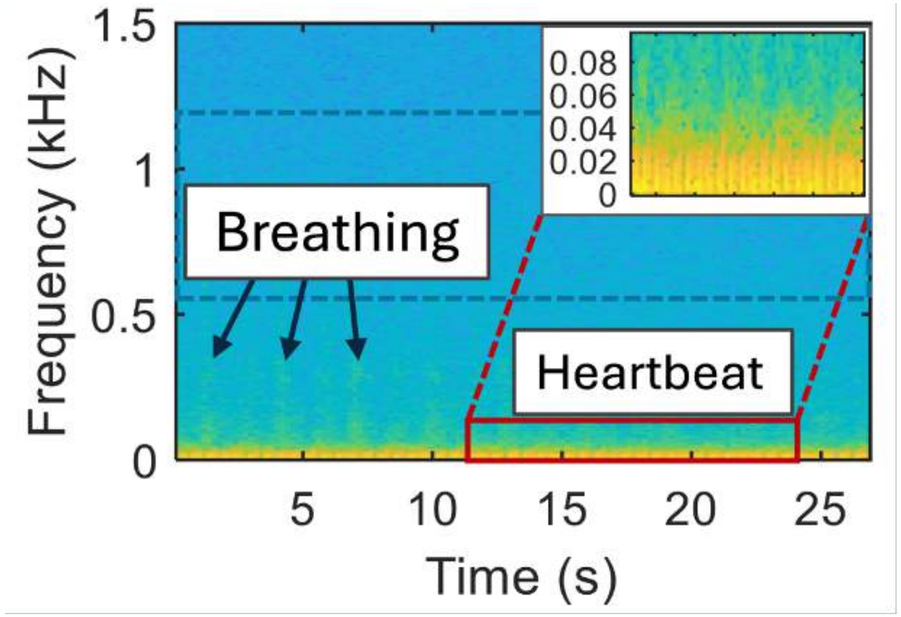


Occlusion effect

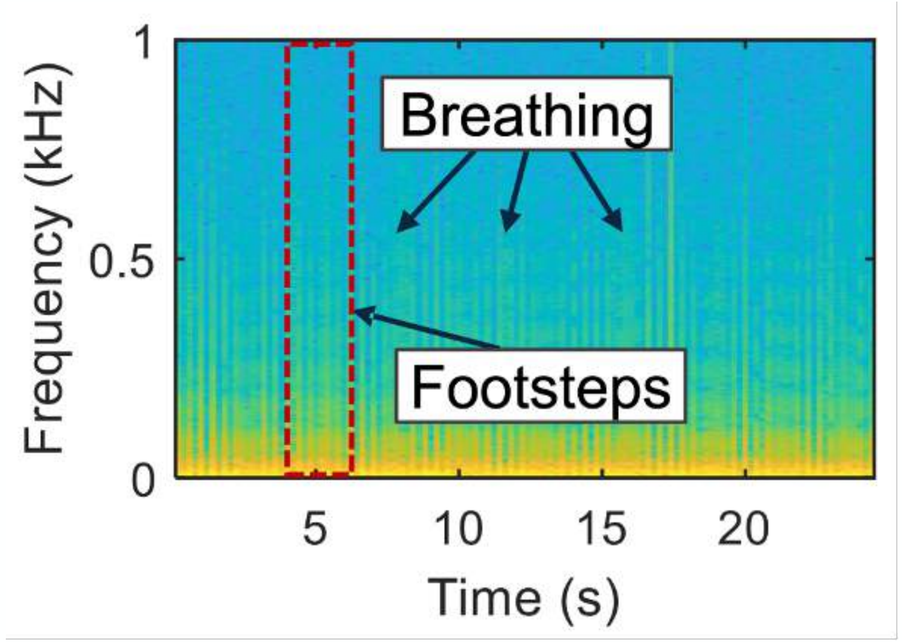
In-ear audio

Ma, Dong, Andrea Ferlini, and Cecilia Mascolo. "Oesense: employing occlusion effect for in-ear human sensing." MobiSys 2021.
Butkow, K. J., Dang, T., Ferlini, A., Ma, D., Liu, Y., & Mascolo, C. An evaluation of heart rate monitoring with in-ear microphones under motion. Pervasive and Mobile Computing, 2024.

In-ear Acoustic Sensing

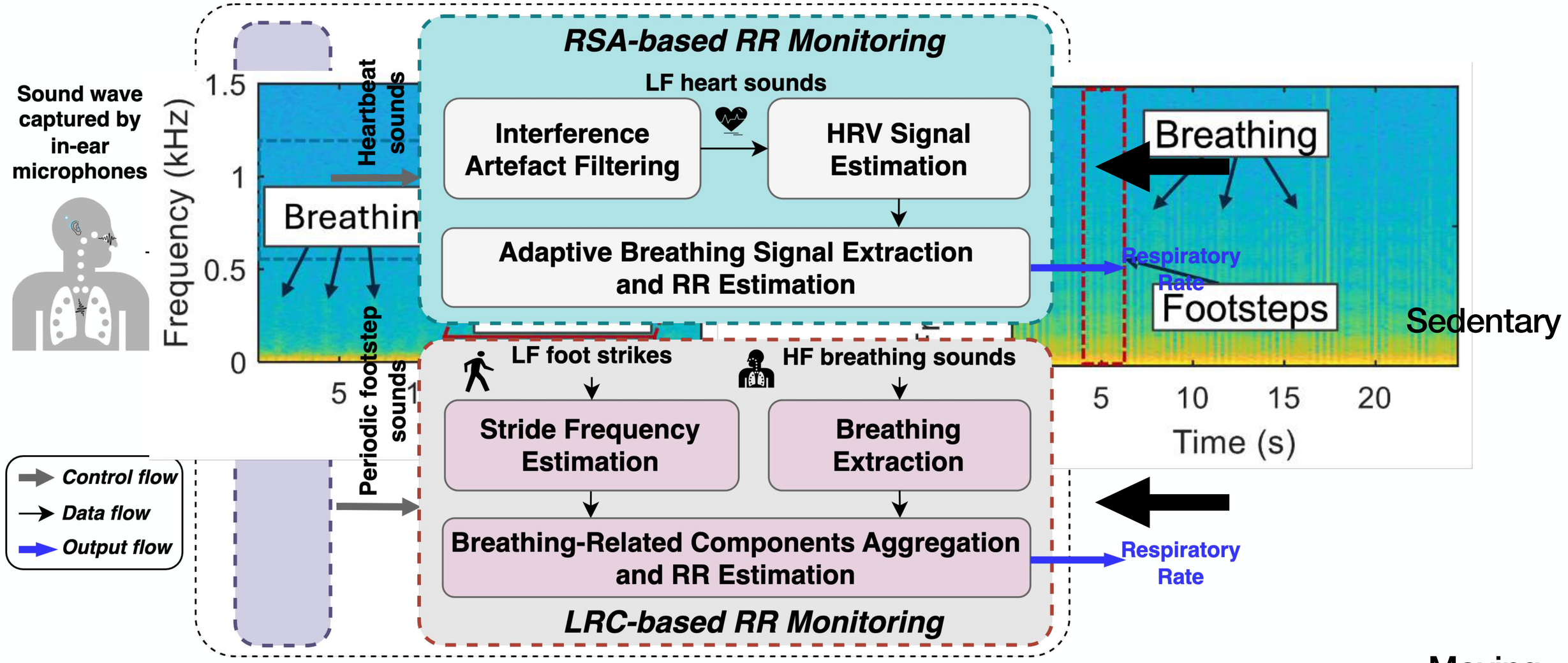


- **Sitting**
- **Clear heartbeat sounds**
- **Breathing low in volume**

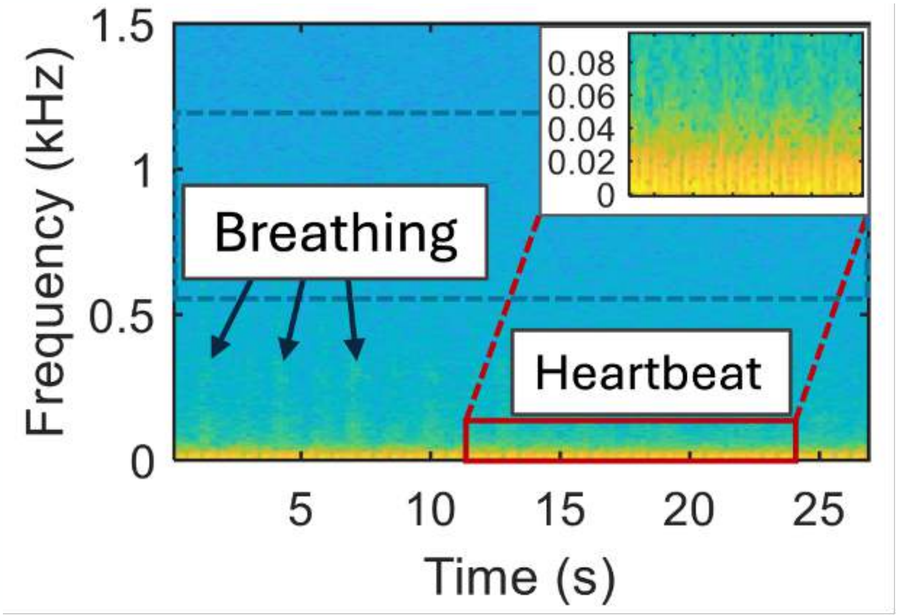


- **Running**
- **Clear footstep sounds**
- **Breathing overwhelmed**

RespEar


Sound wave captured by in-ear microphones
Frequency (kHz)
1.5
1
0.5
0
Heartbeat sounds
Breathing
Periodic footstep sounds
RSA-based RR Monitoring
LF heart sounds
Interference Artefact Filtering
HRV Signal Estimation
Adaptive Breathing Signal Extraction and RR Estimation
LF foot strikes
HF breathing sounds
Stride Frequency Estimation
Breathing Extraction
Breathing-Related Components Aggregation and RR Estimation
LRC-based RR Monitoring
Respiratory Rate
Breathing
Footsteps
Respiratory Rate
5
10
15
20
Time (s)
Sedentary
Moving
Control flow
Data flow
Output flow

RR Monitoring under Sedentary

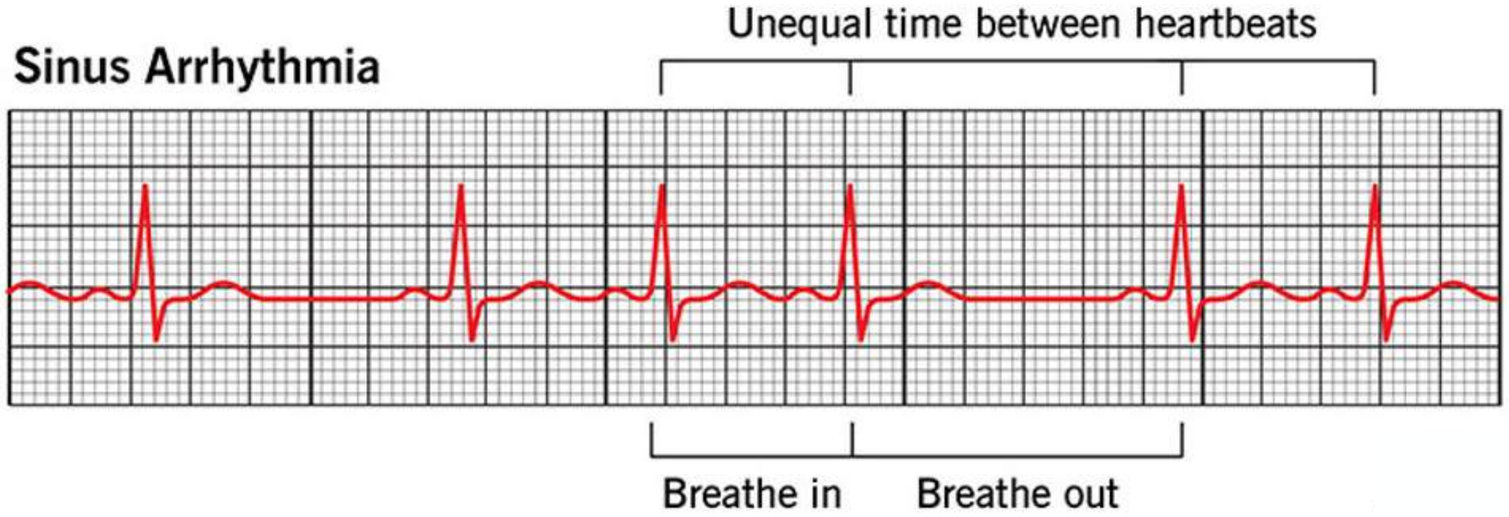


Activity	MAE (BPM)
Sitting	6.49
Cooling down	6.61

- **Clear heartbeat sounds**
- **Breathing low in volume**

BPM: Breaths Per Minute

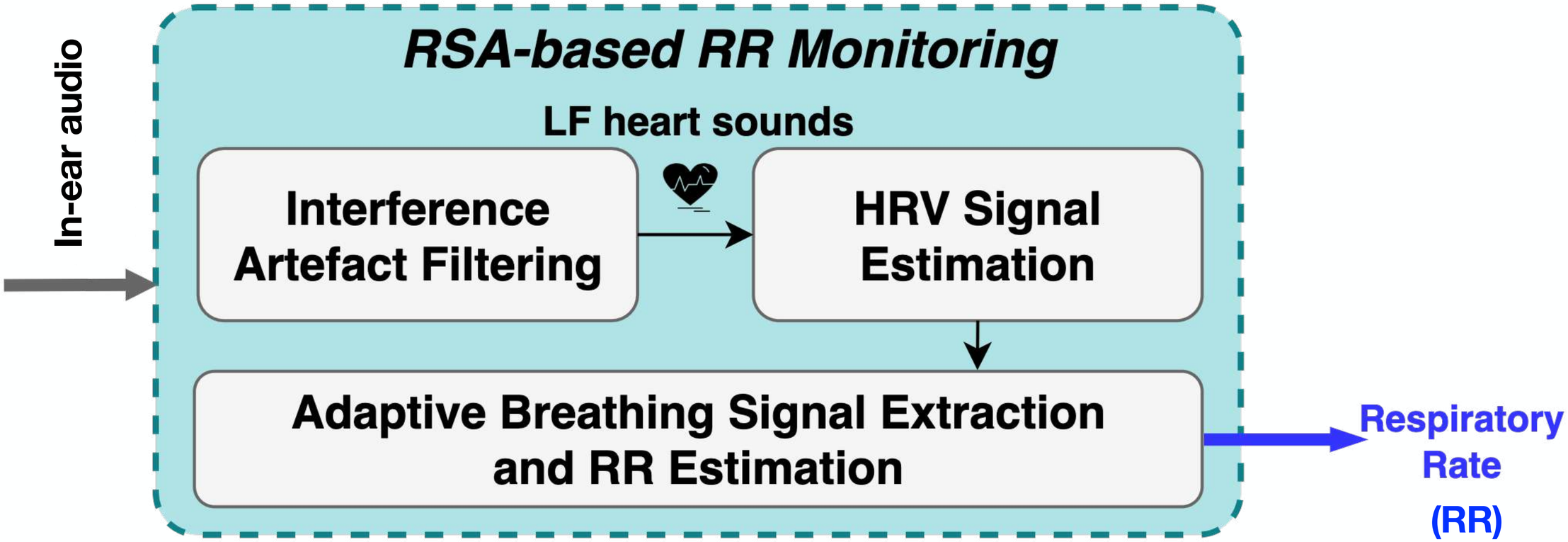
Respiratory Sinus Arrhythmia (RSA)



- **The association between respiratory rate and heart rate variability (HRV)**
- **The high-frequency range in HRV signal is related to respiration**

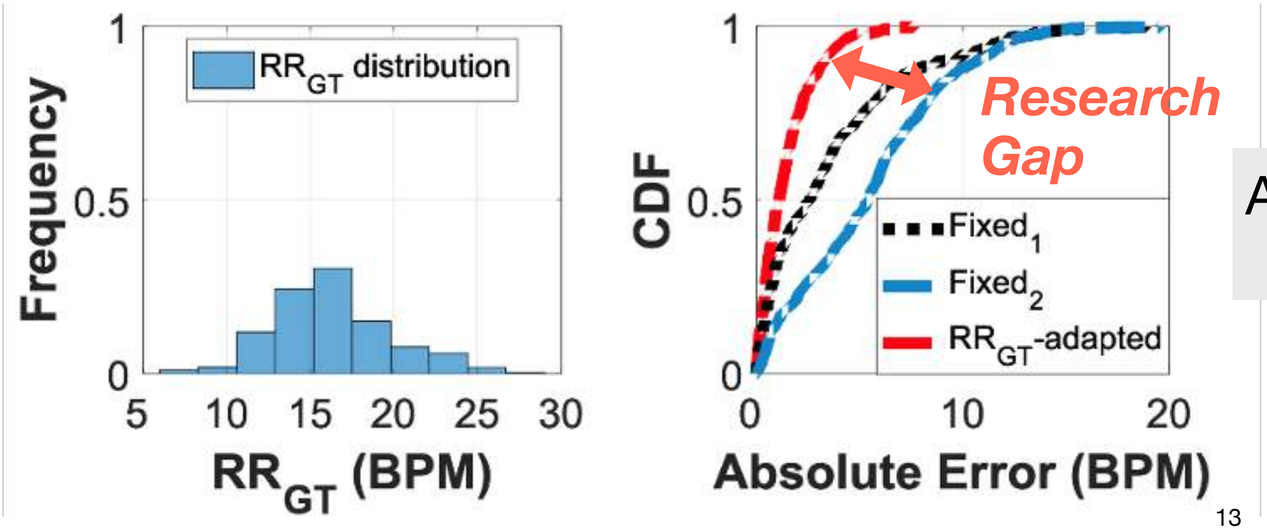
https://my.clevelandclinic.org/health/diseases/21666-sinus-arrhythmia

RR Monitoring under Sedentary

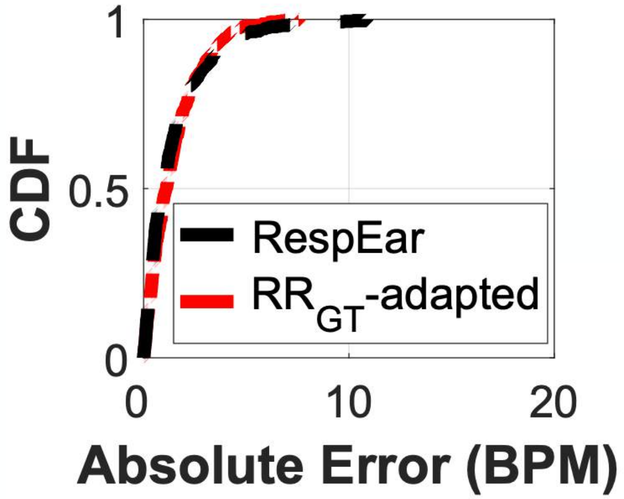


RR Monitoring from HRV Signal

- **Breathing signal extraction**
  - **How to find the high frequency range of HRV signal?**
  - **SOTA: a default range**
- **Our observation**
  - **The ideal high frequency range should be centred around the true RR**

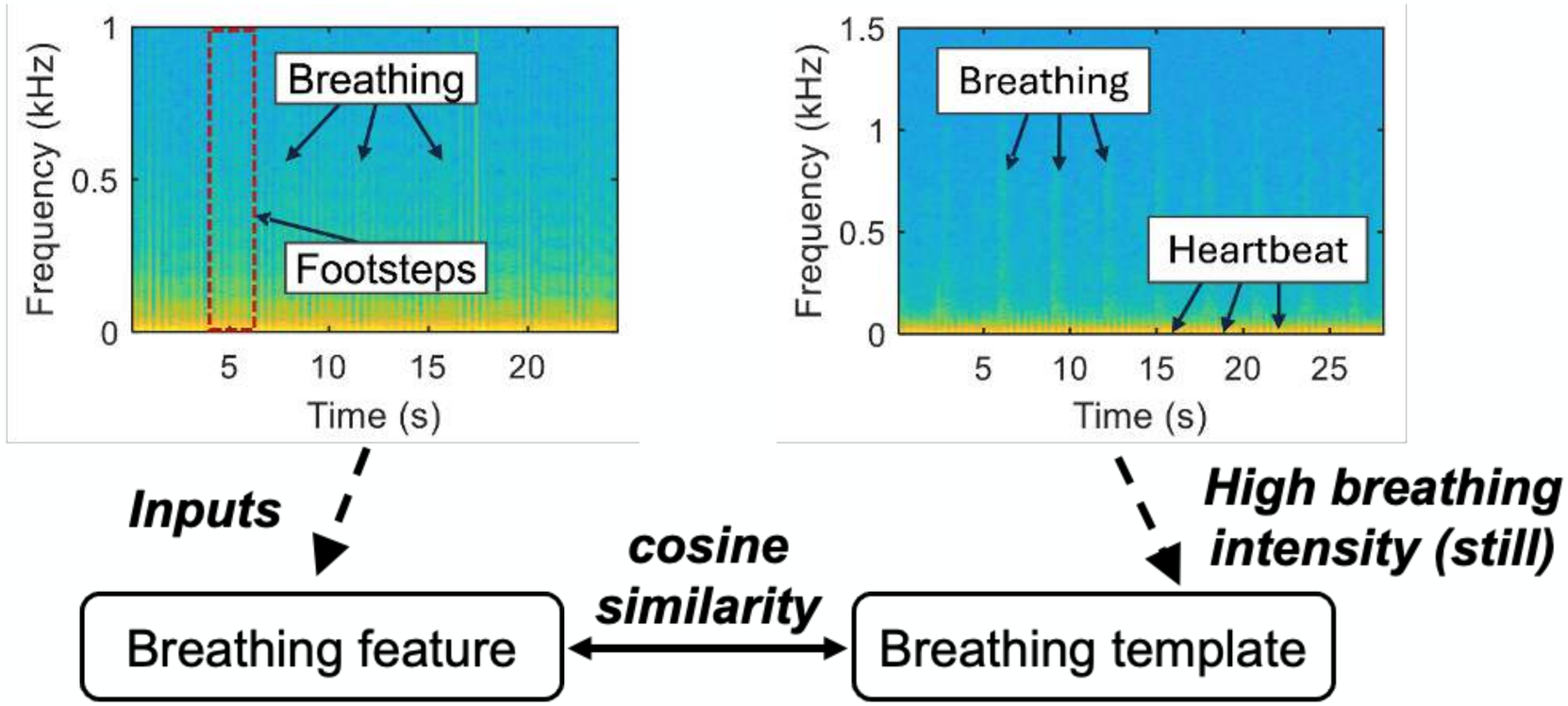


Adaptive Breathing Signal Extraction

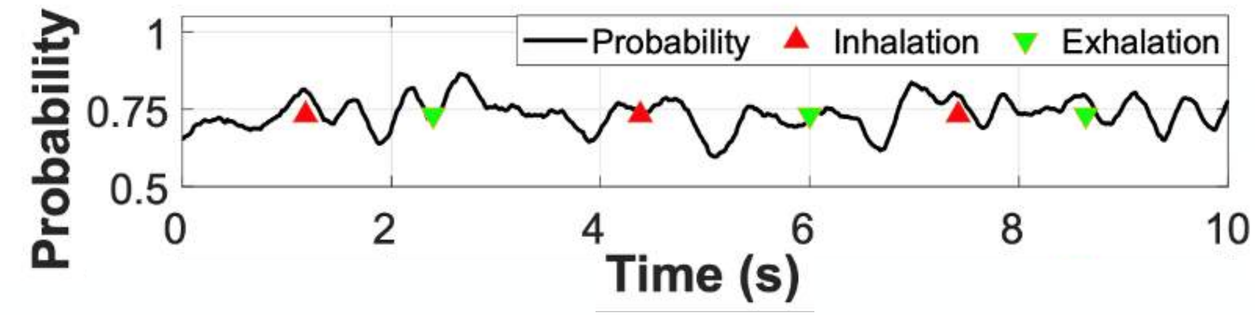


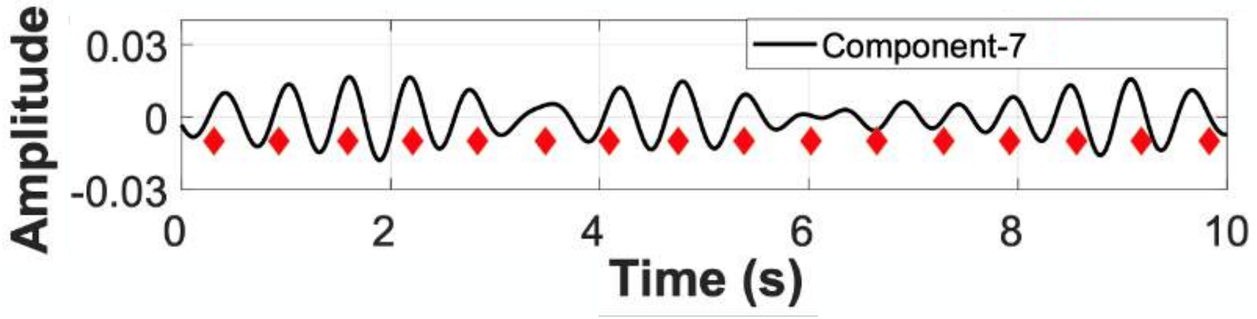
RR Monitoring under Moving

- **Breathing pattern extraction**
  - **Estimating the probability that each audio frame contains breathing**



LRC-based RR Monitoring





Decomposition

Component Selection

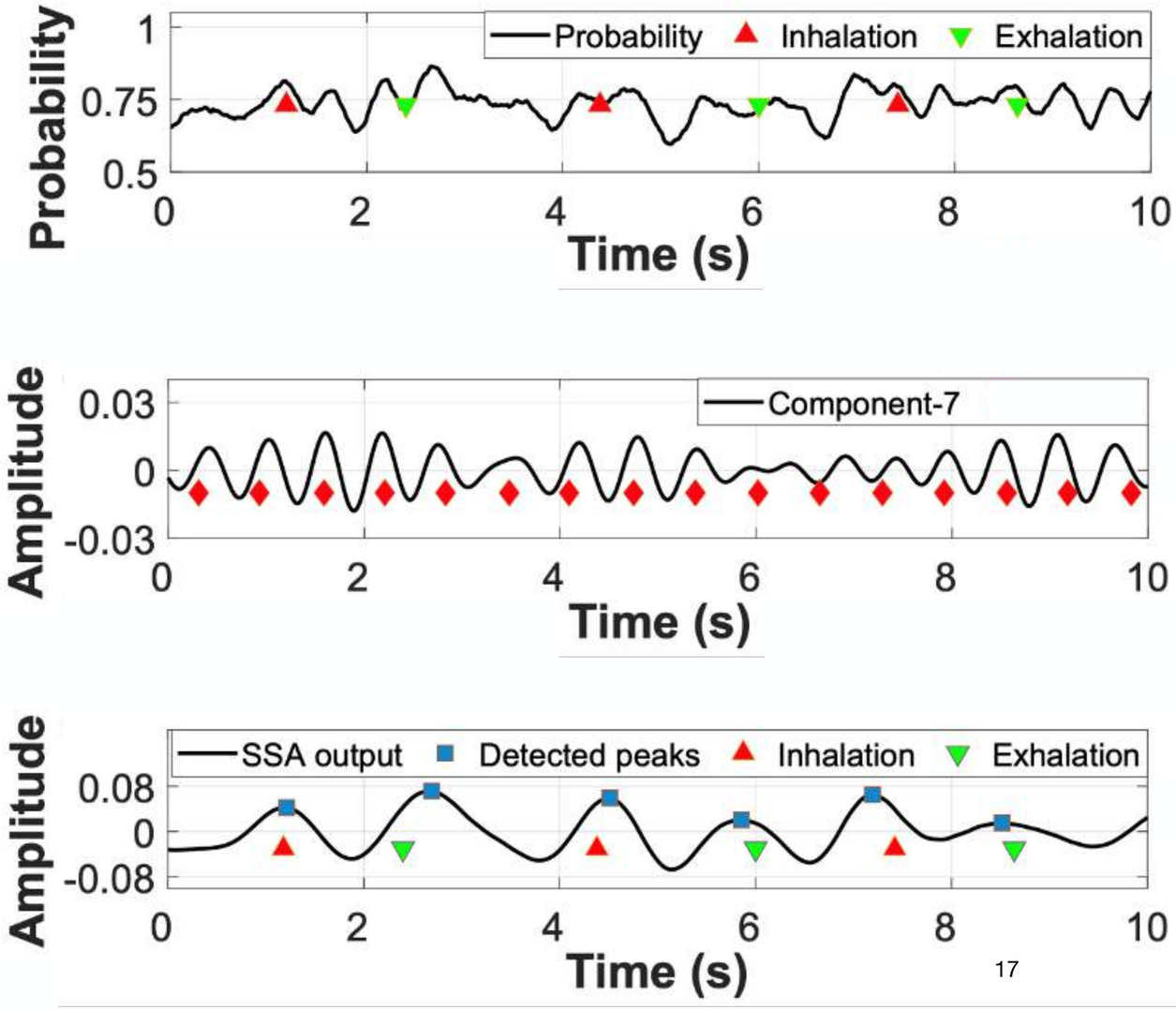
Locomotor Respiratory Coupling (LRC)

One inhalation/exhalation
X steps
X = …, 1, 1.5, 2, …

- **The interaction of respiratory rate with step frequency**
- **LRC ratio = NUM of steps / NUM of breathing cycles**
- **Limited range of human LRC ratios**

Daley M A, Bramble D M, Carrier D R. Impact loading and locomotor-respiratory coordination significantly influence breathing dynamics in running humans[J]. PloS one, 2013, 8(8): e70752.

LRC-based Breathing Component Selection

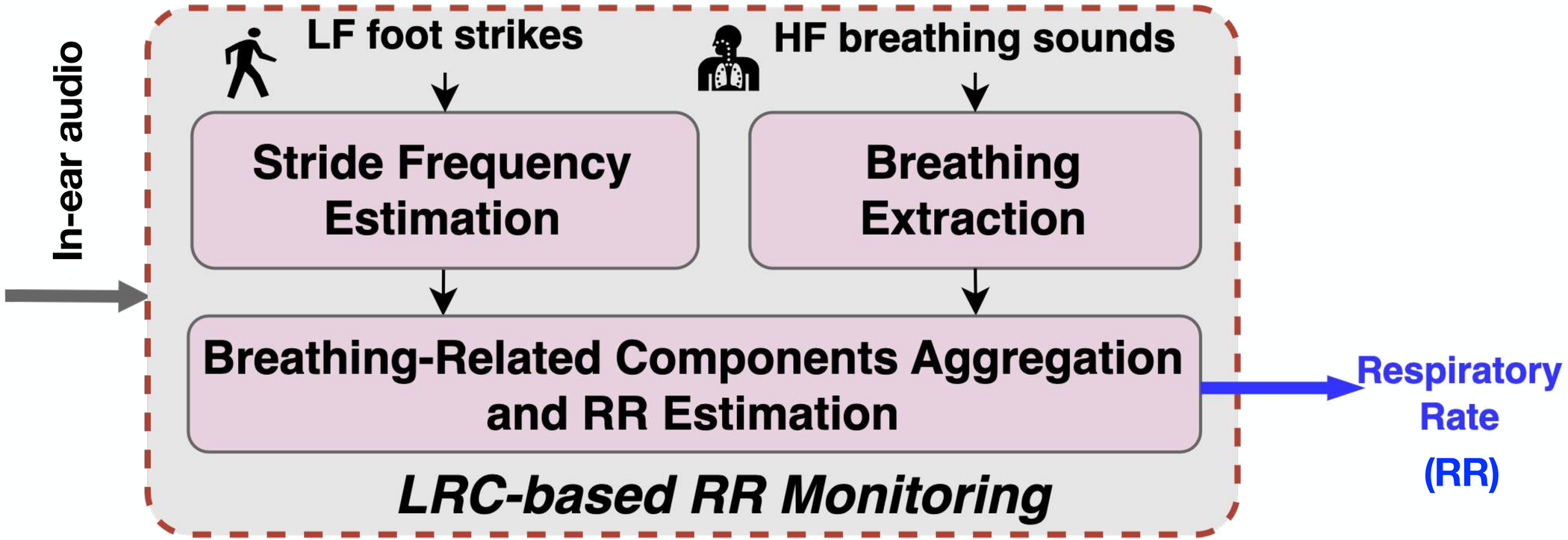


Decomposition

Component Selection

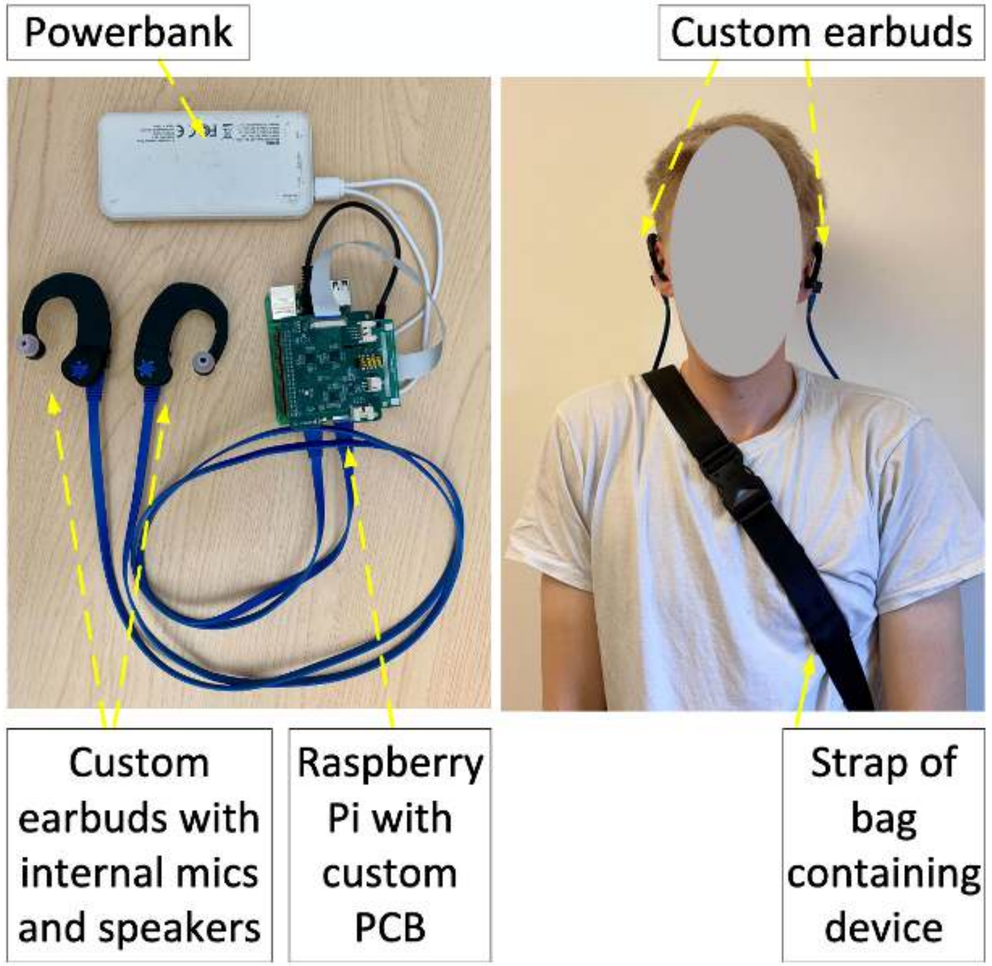
Component Aggregation

RR Monitoring under Moving



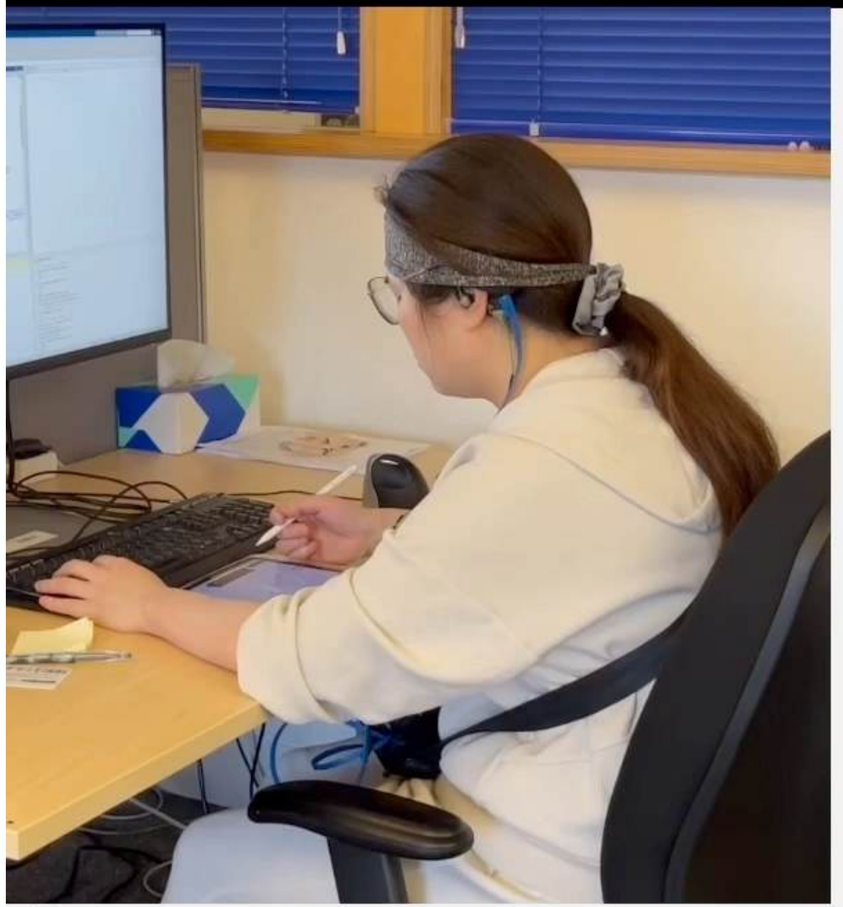
Data Collection

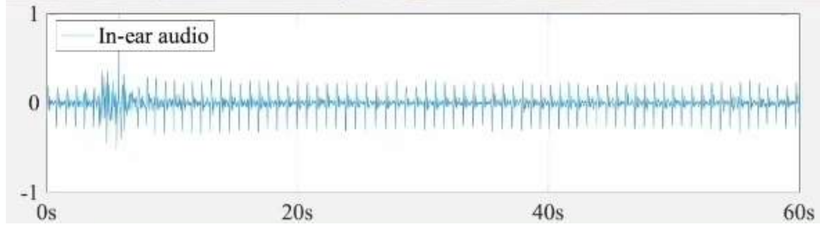
- **18** participants
- **Zephyr** chest strap as ground truth
- 8 **activities** for five minutes
  - Sitting
  - Standing
  - Lying down
  - Listening to music
  - Working
  - Walking
  - Running
  - Cooling down

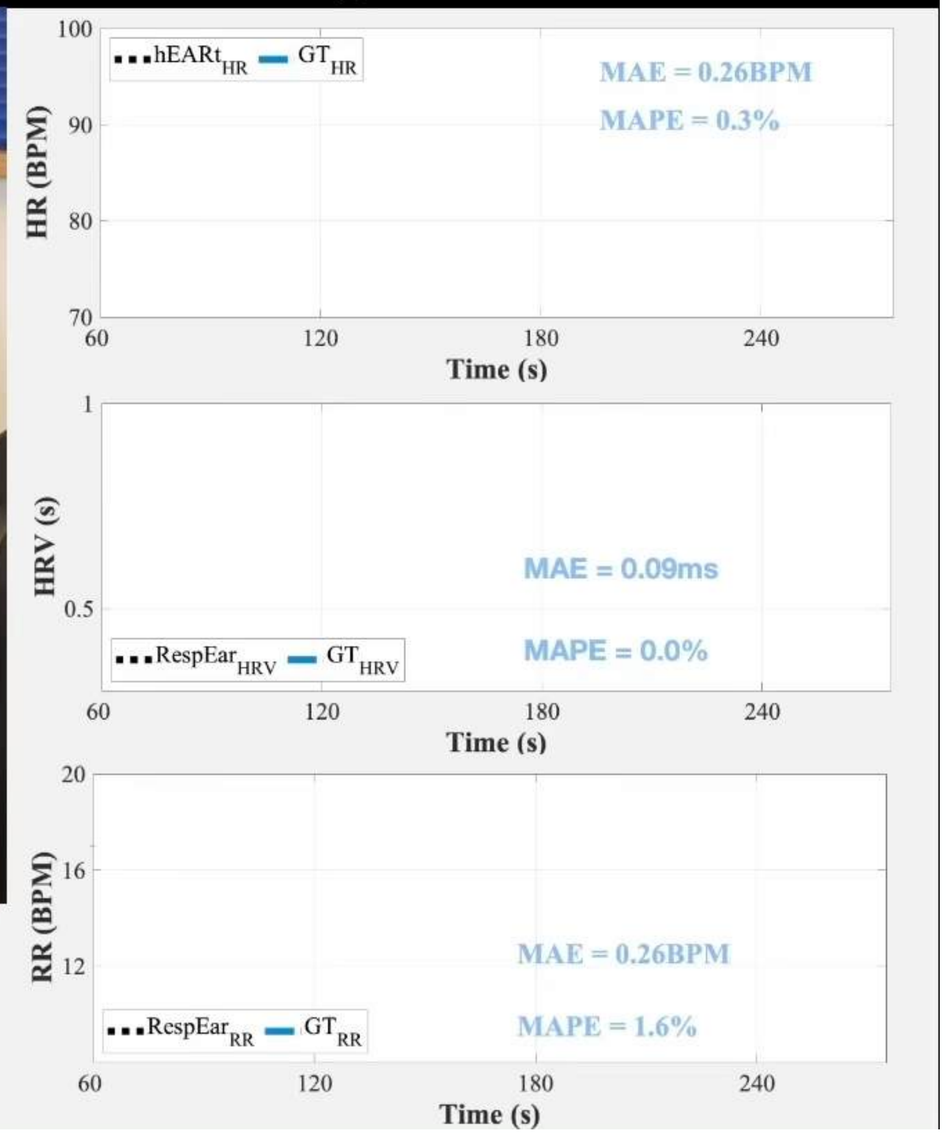


Performance under sedentary

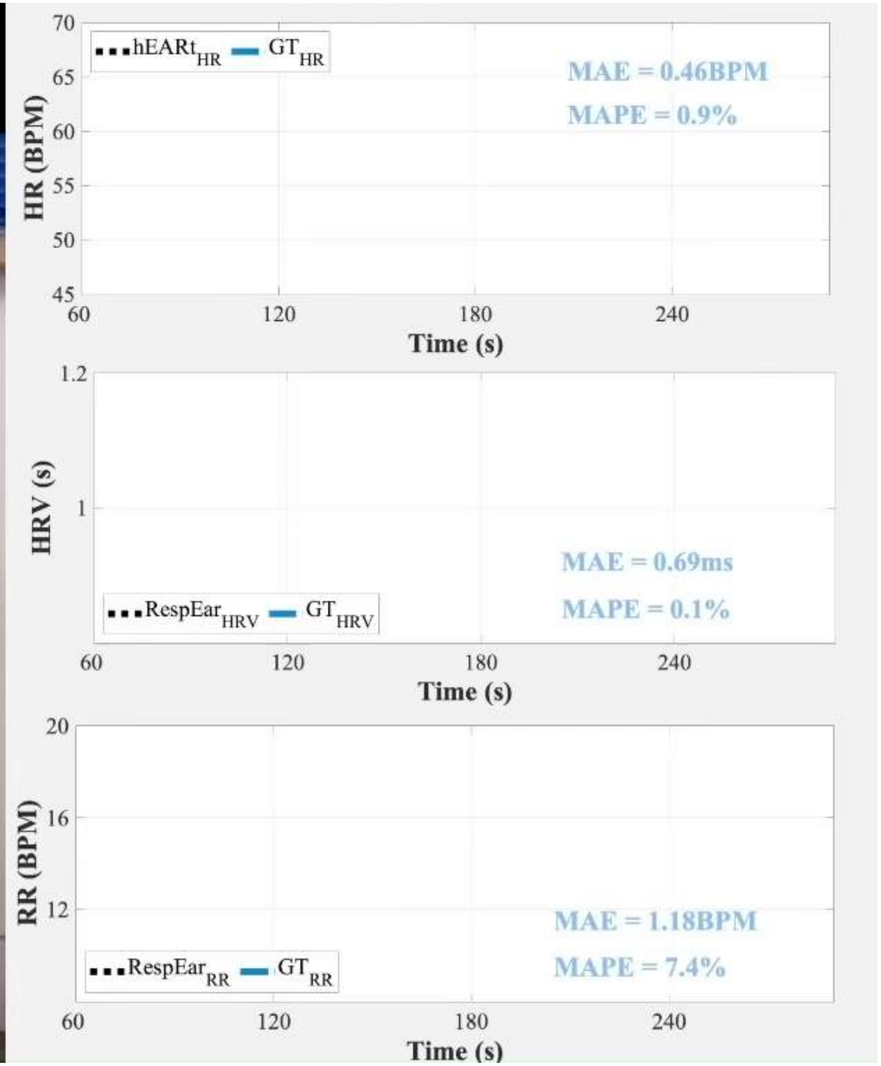
real-time in-the-wild working





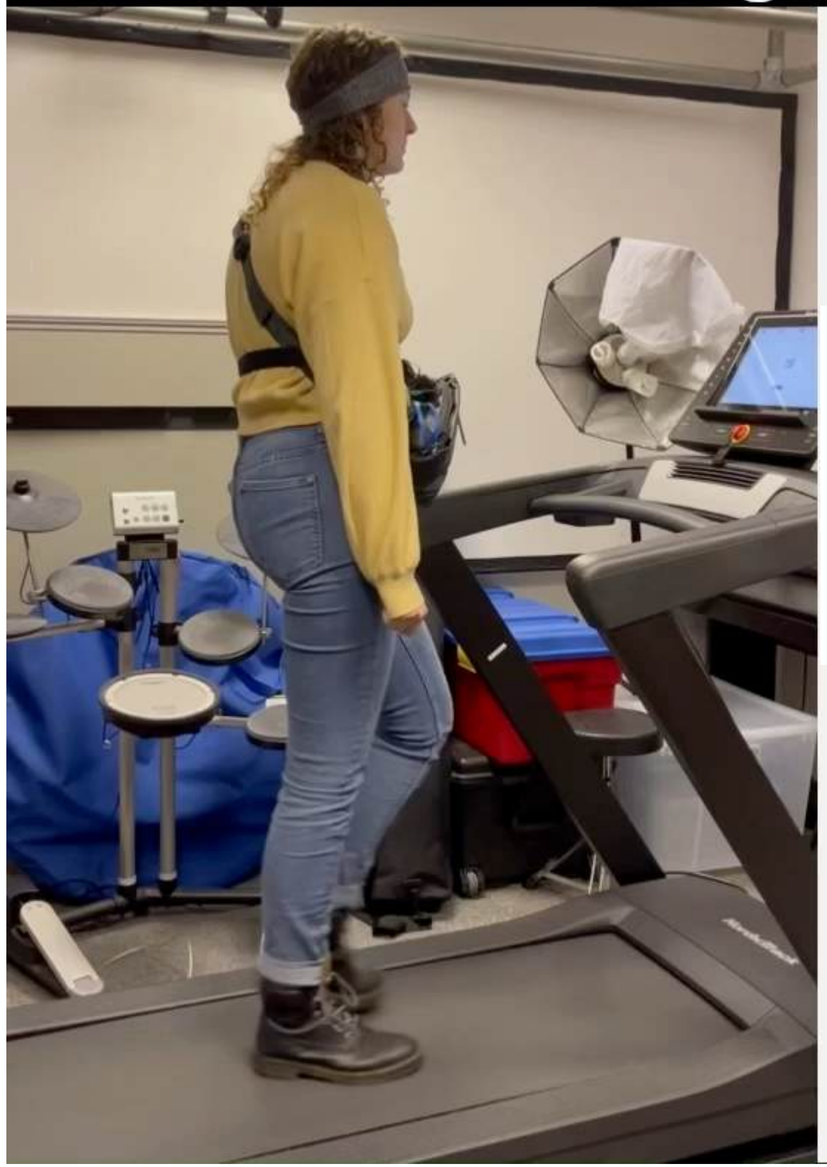


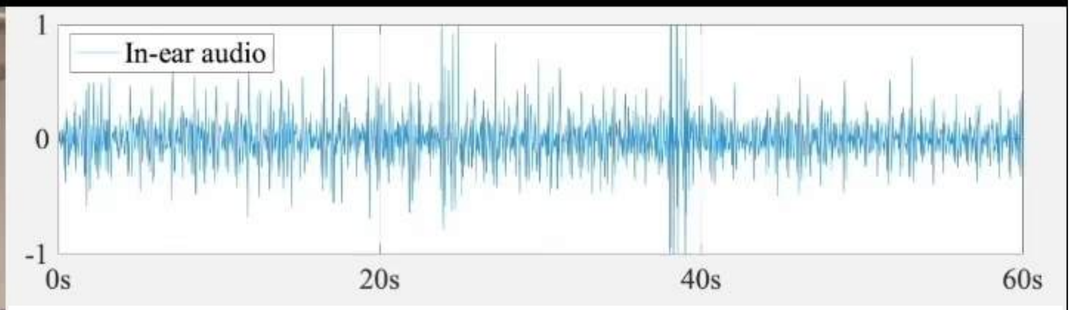
Performance under sedentary



Performance under moving

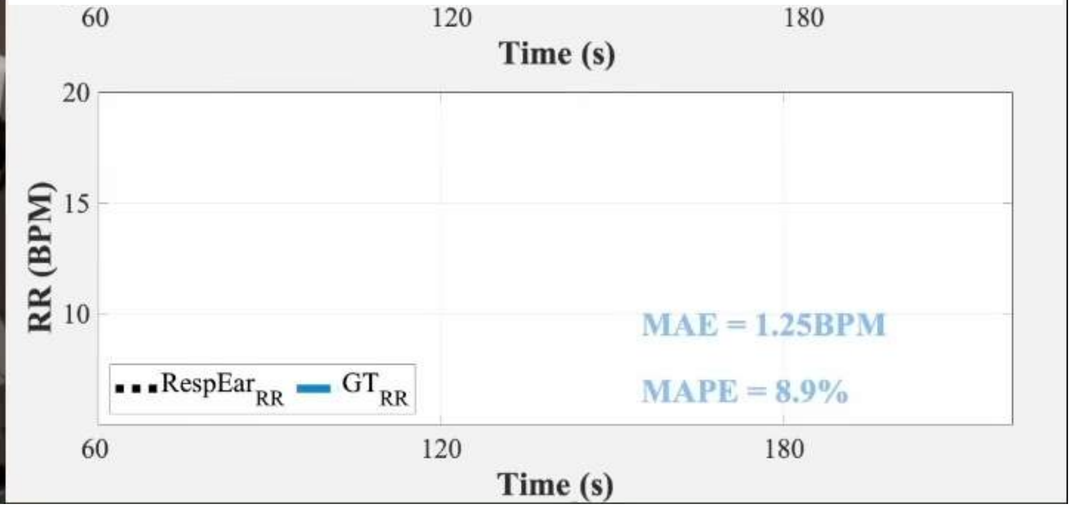
real-time walking





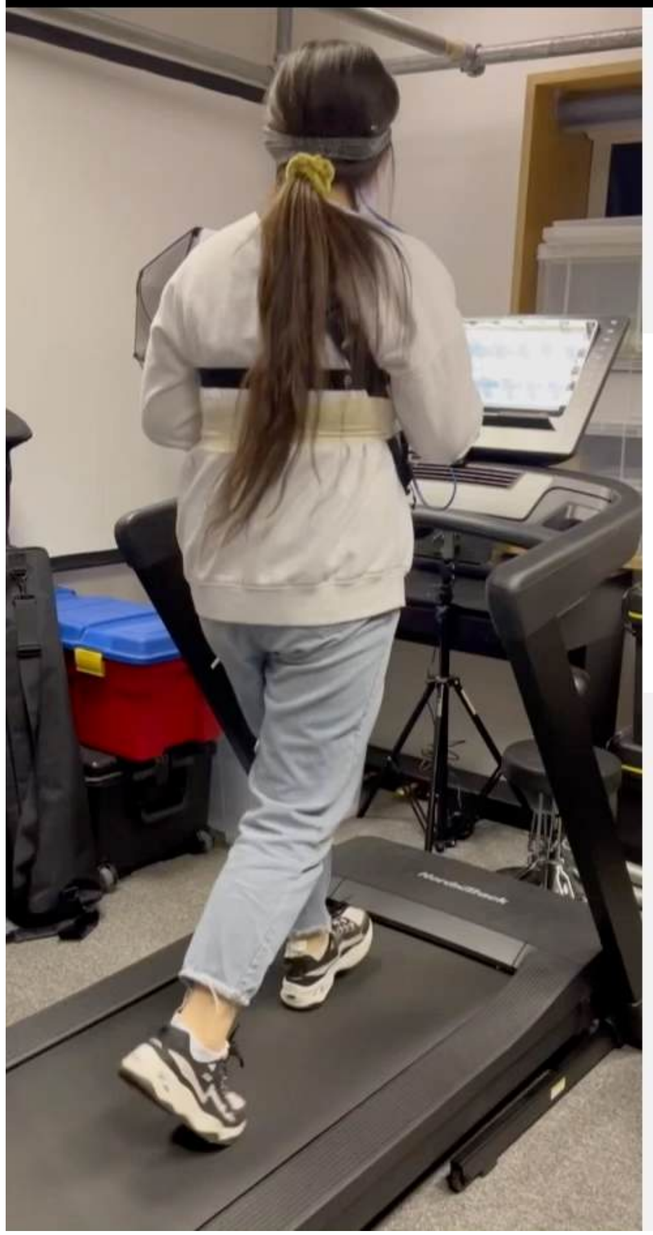
Input window

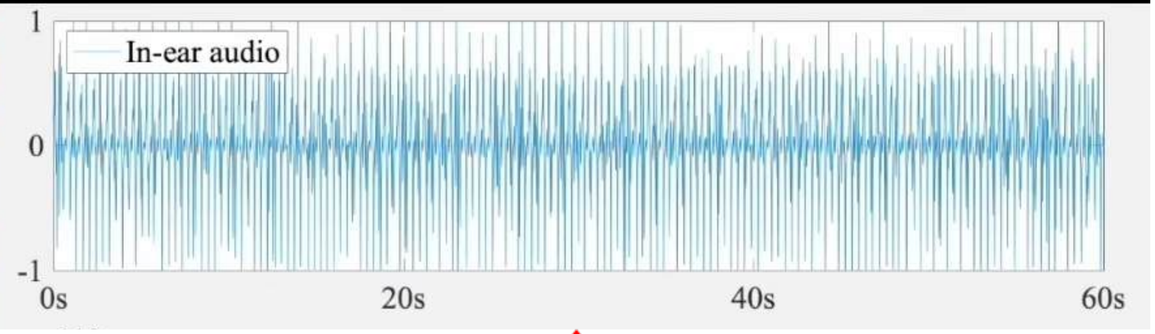
Est. vs GT



Performance under moving

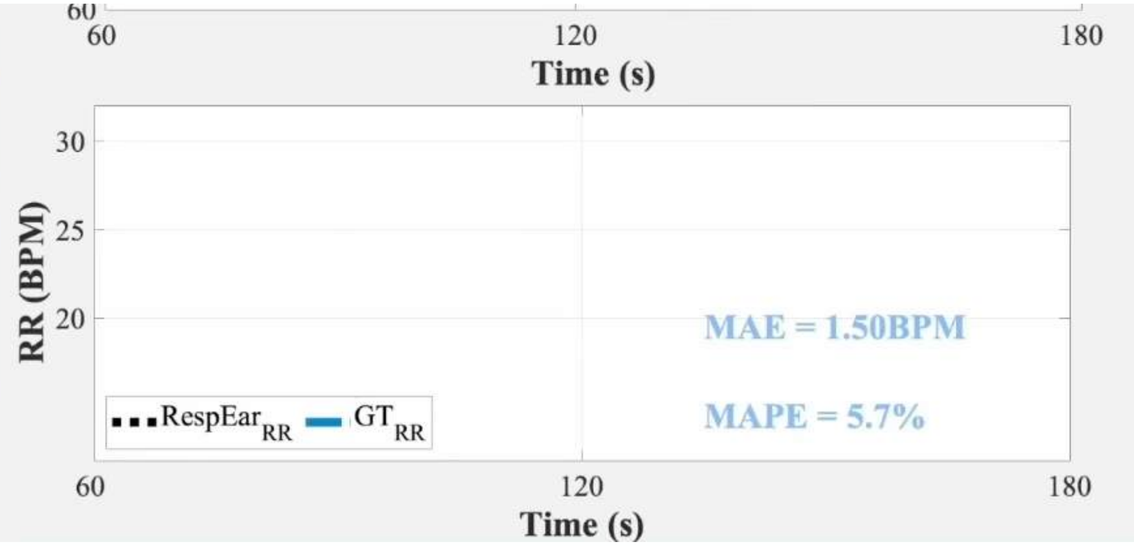
real-time running



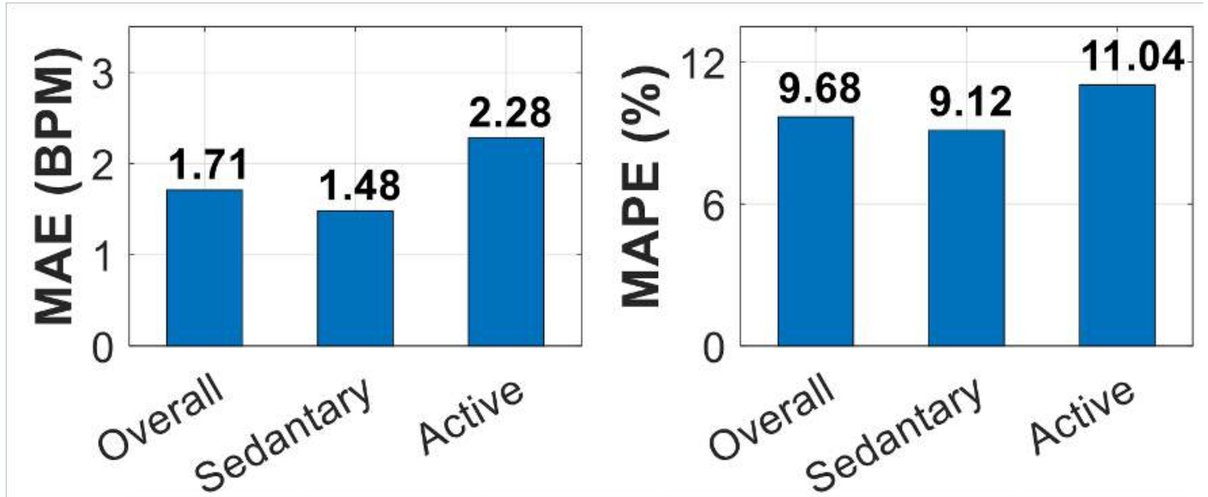


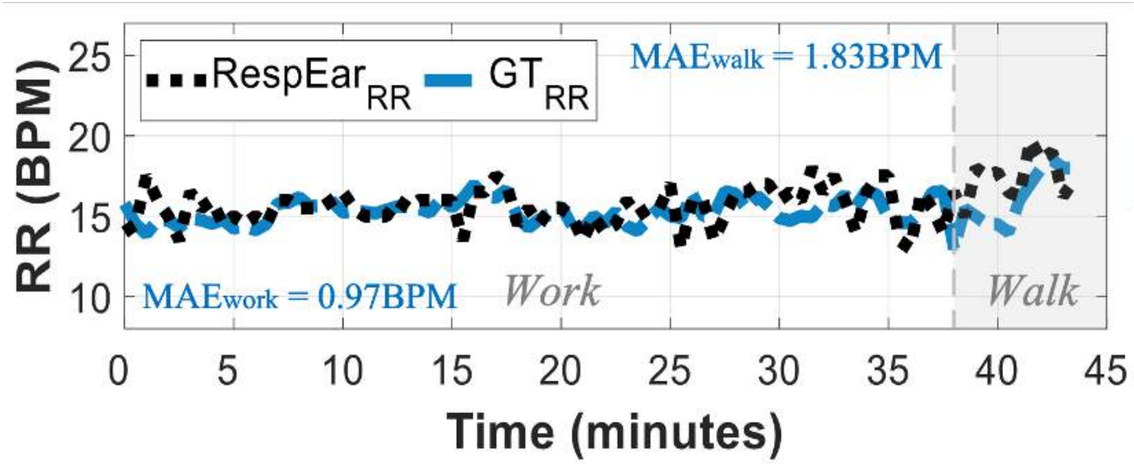
Input window

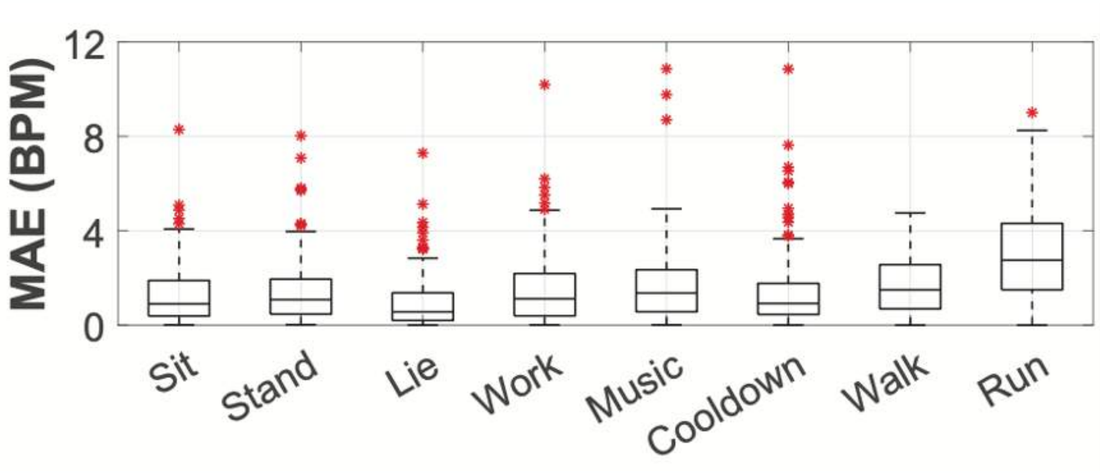
Est. vs GT

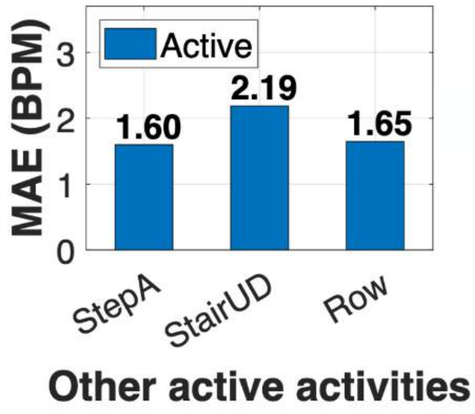


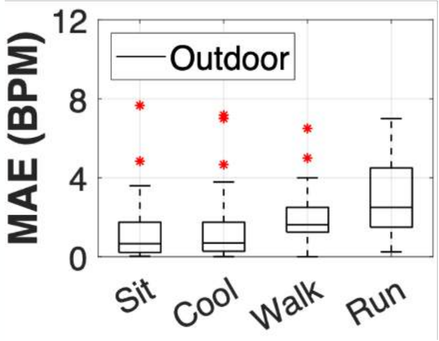
Overall Performance





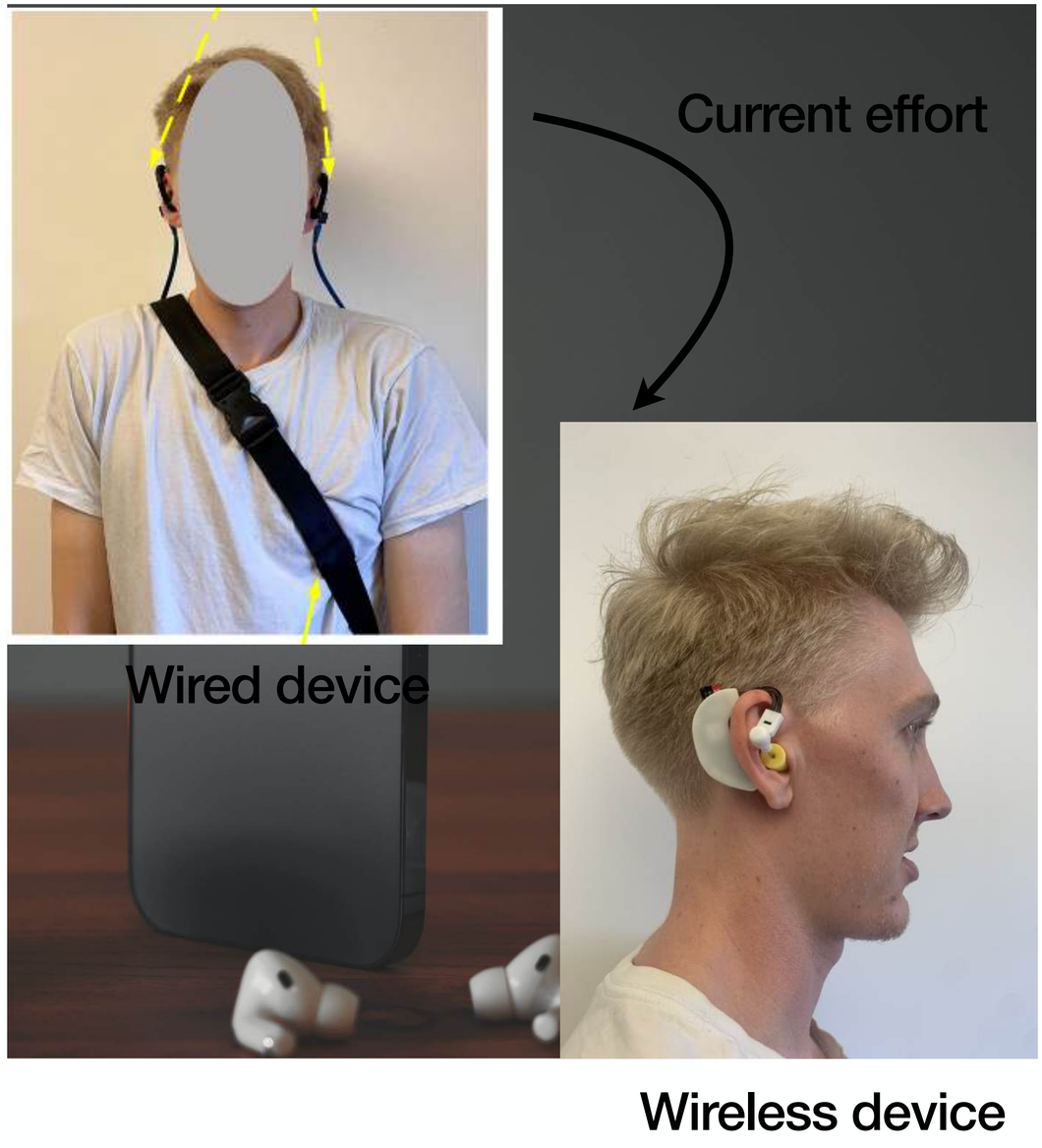






System Considerations

- **Latency:** a new respiratory rate can be estimated
  - Sedentary: every 5s (for 60s window)
  - Moving: every 15s (for 60s window)
- **Energy:** could run continuously on iPhone 12 Pro for
  - Over 24 hours for sedentary
  - Over 7 hours for moving
- **Communication:** future work



Conclusion

- The **first earable RR monitoring** system
  - Continuous
  - Non-obtrusive
  - Diverse daily routines
- A **holistic** and **optimised** solution
  - Leveraging **interplays** among **respiration**, **heart**, and **gait** systems
  - **New algorithms**
- Achieving **SOTA** performance and **uniquely generalising** on conditions

Impact

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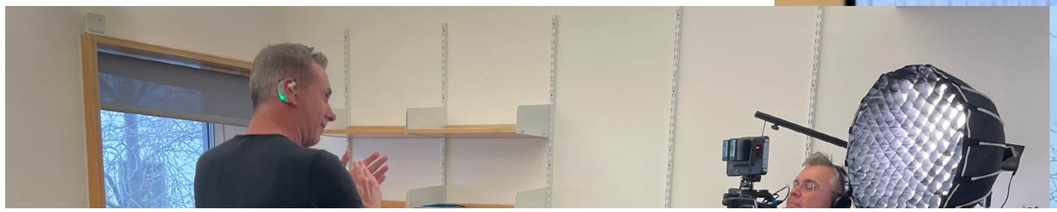

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South Wales
NP10 8QQ

1.	Your reference	**008401010**
2.	Patent application number	
3.	Full name of the first applicant	**CAMBRIDGE ENTERPRISE LIMITED**

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