Nov. 07, 2024

Keynote

Applications of Radar Sensors in Remote Health Monitoring

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SENSORDEVICES 2024, Nov. 03-07, Nice, France

Outlines

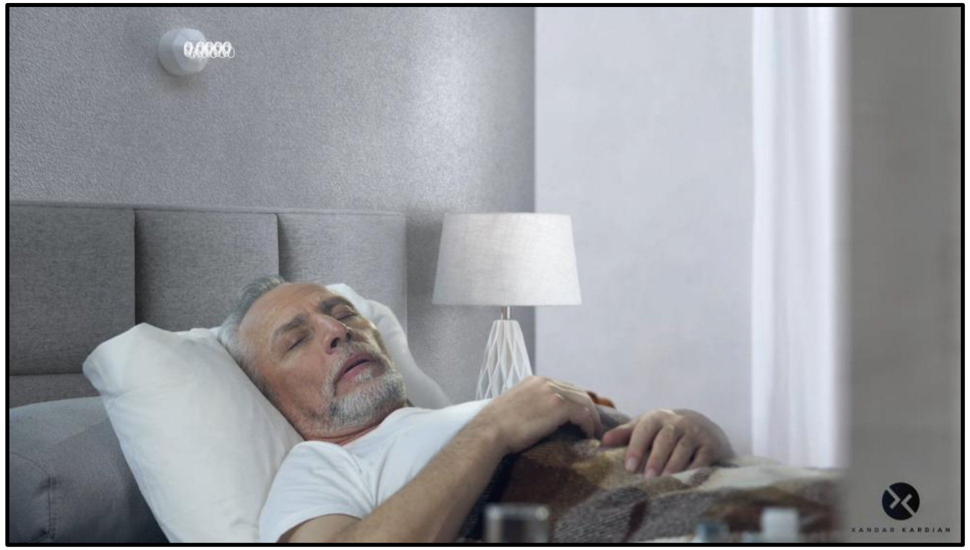
Vital Sign Monitoring

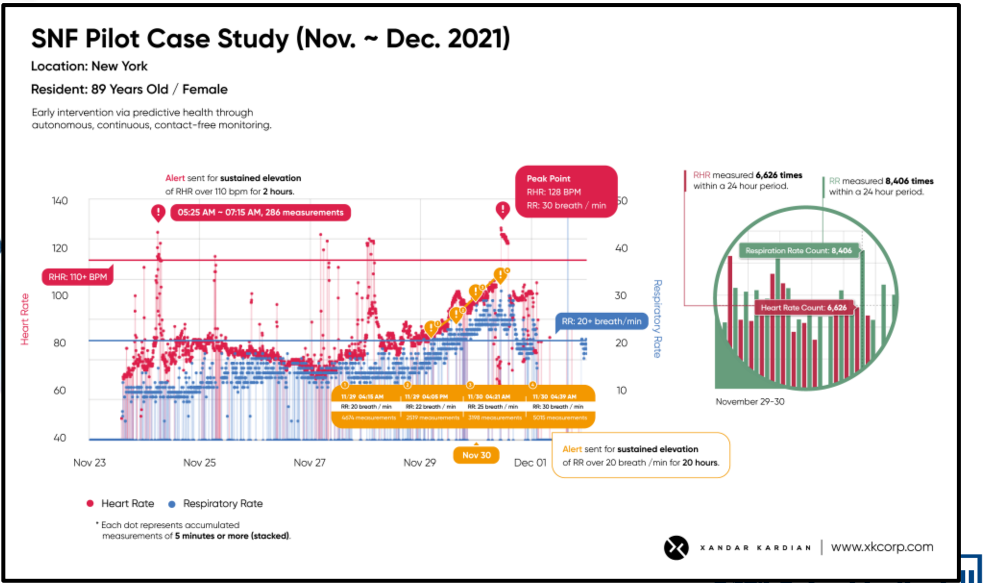
- "Machine Learning for Healthcare Radars: Recent Progresses in Human Vital Sign Measurement and Activity Recognition," *IEEE COMST*, First Quarter 2024.
- "Effects of Receiver Beamforming for Vital Sign Measurements Using FMCW Radar at Various Distances and Angles," *Sensors*, Sep. 2022.
- "Preclinical Evaluation of Noncontact Vital Signs Monitoring Using Real-Time IR-UWB Radar and Factors Affecting Its Accuracy," *Scientific Reports*, Dec. 2021.
- "Experimental Comparison of IR-UWB Radar and FMCW Radar for Vital Signs," *Sensors*, Nov. 2020.
- "An Overview of Signal Processing Techniques for Remote Health Monitoring using Impulse Radio UWB Transceiver," *Sensors*, Apr. 2020.
- "Preclinical Evaluation of a Noncontact Simultaneous Monitoring Method for Respiration and Carotid Pulsation Using Impulse-Radio Ultra-Wideband Radar," *Scientific Reports*, Aug. 2019.
- "A Novel Non-Contact Heart Rate Monitor Using Impulse-Radio Ultra-Wideband (IR-UWB) Radar Technology," *Scientific Reports*, Aug. 2018.
- "A Detailed Algorithm for Vital Sign Monitoring of a Stationary/Non-Stationary Human through IR-UWB Radar," *Sensors*, Feb. 2017.

Non-Contact Vital Sign Monitoring (1/3)

- *Respiration Rate (RR)*
- *Heart Rate (HR)*
- *Movement Monitoring*

Acute Care Space, Nursing Home, Assisted Living Facility, Long-Term Care Facility





SNF Pilot Case Study (Nov. ~ Dec. 2021)

Location: New York

Resident: 89 Years Old / Female

Early intervention via predictive health through autonomous, continuous, contact-free monitoring.

Alert sent for **sustained elevation** of RHR over 110 bpm for **2 hours**.

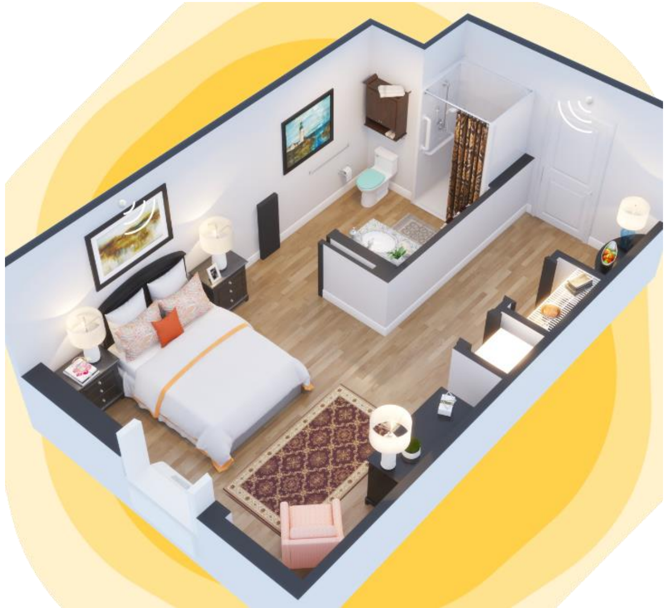
Alert sent for **sustained elevation** of RR over 20 breath /min for **20 hours**.

RHR measured **6,626 times** within a 24 hour period.

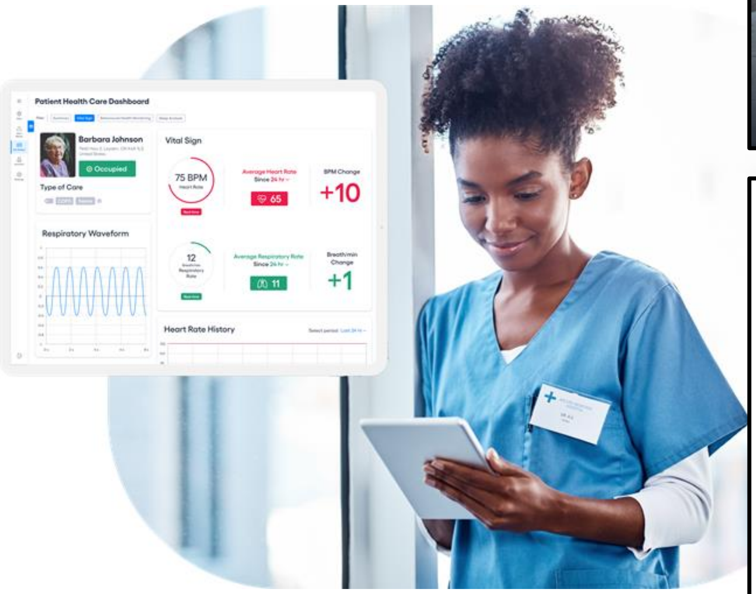
RR measured **8,406 times** within a 24 hour period.

* Each dot represents accumulated measurements of **5 minutes or more (stacked)**.

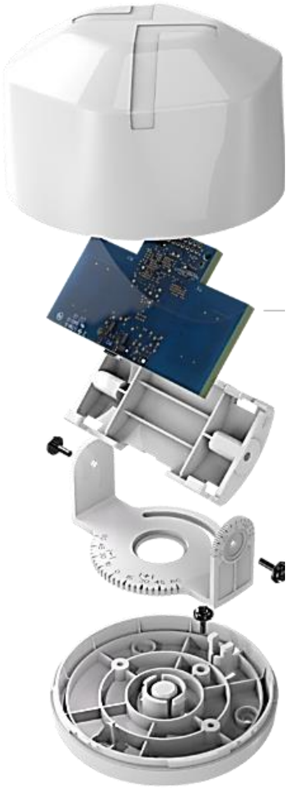
Home Health

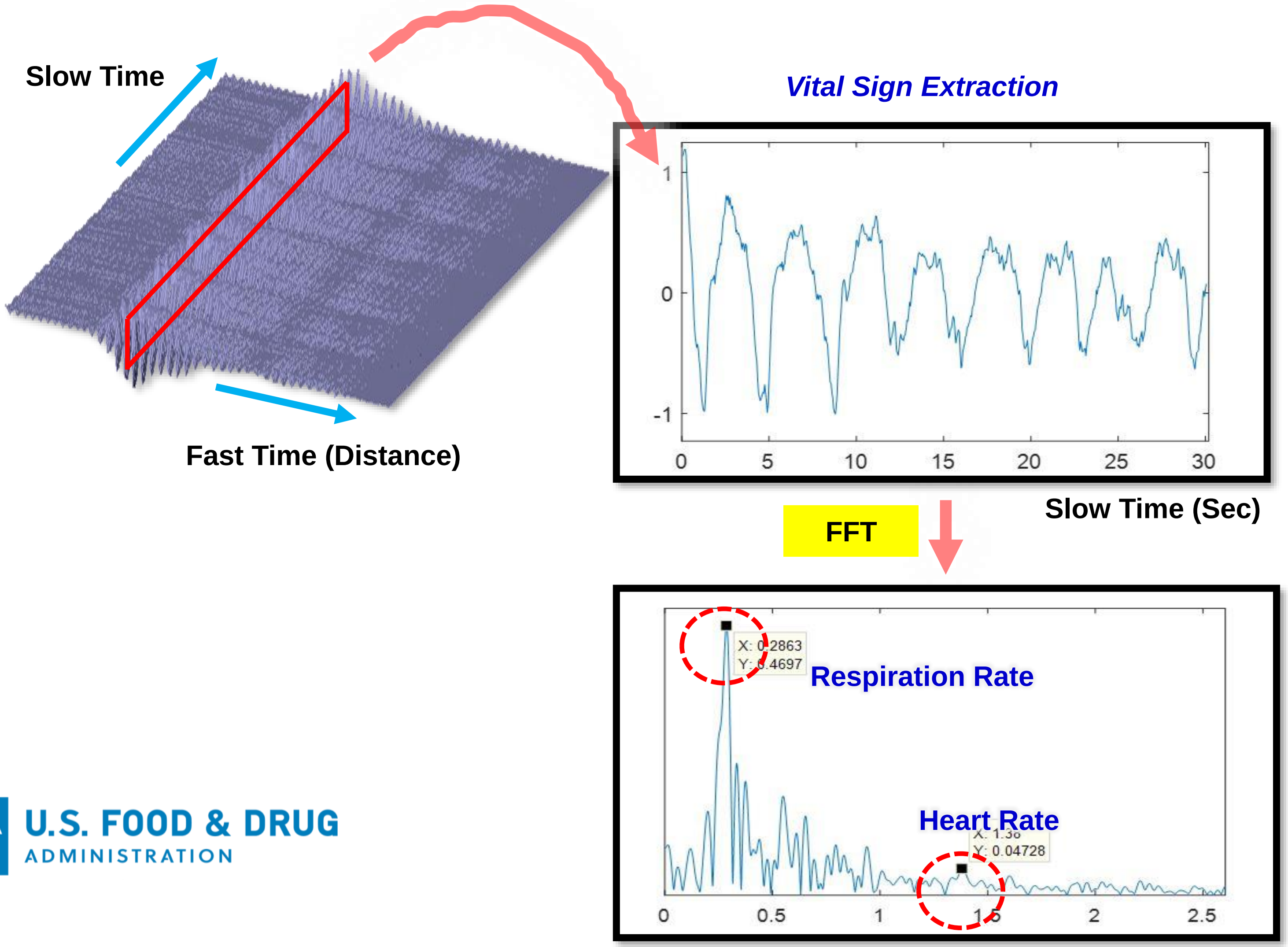


Reduce Staff Turnover Rates



Non-Contact Vital Sign Monitoring (2/3)

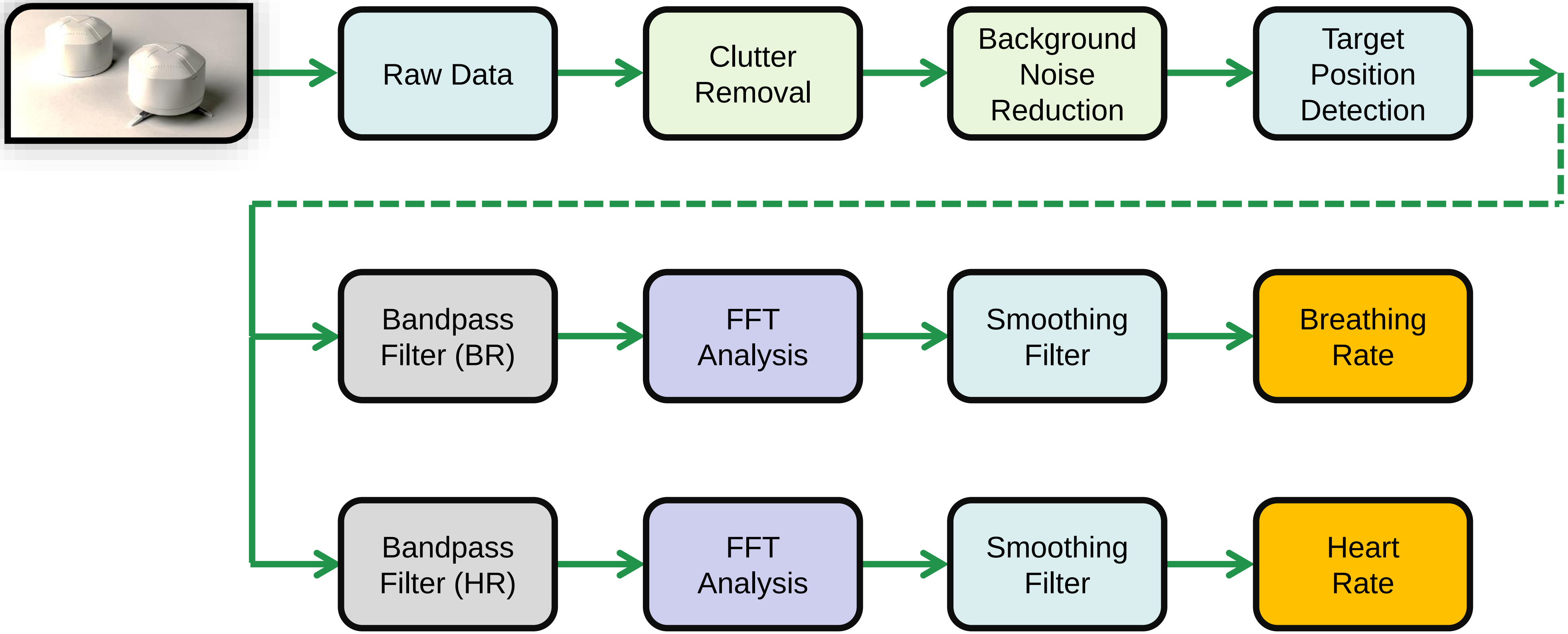




FDA U.S. FOOD & DRUG ADMINISTRATION

Non-Contact Vital Sign Monitoring (3/3)

❖ *Detection of RR and HR*



Raw Data

Clutter Removal

Background Noise Reduction

Target Position Detection

Bandpass Filter (BR)

FFT Analysis

Smoothing Filter

Breathing Rate

Bandpass Filter (HR)

FFT Analysis

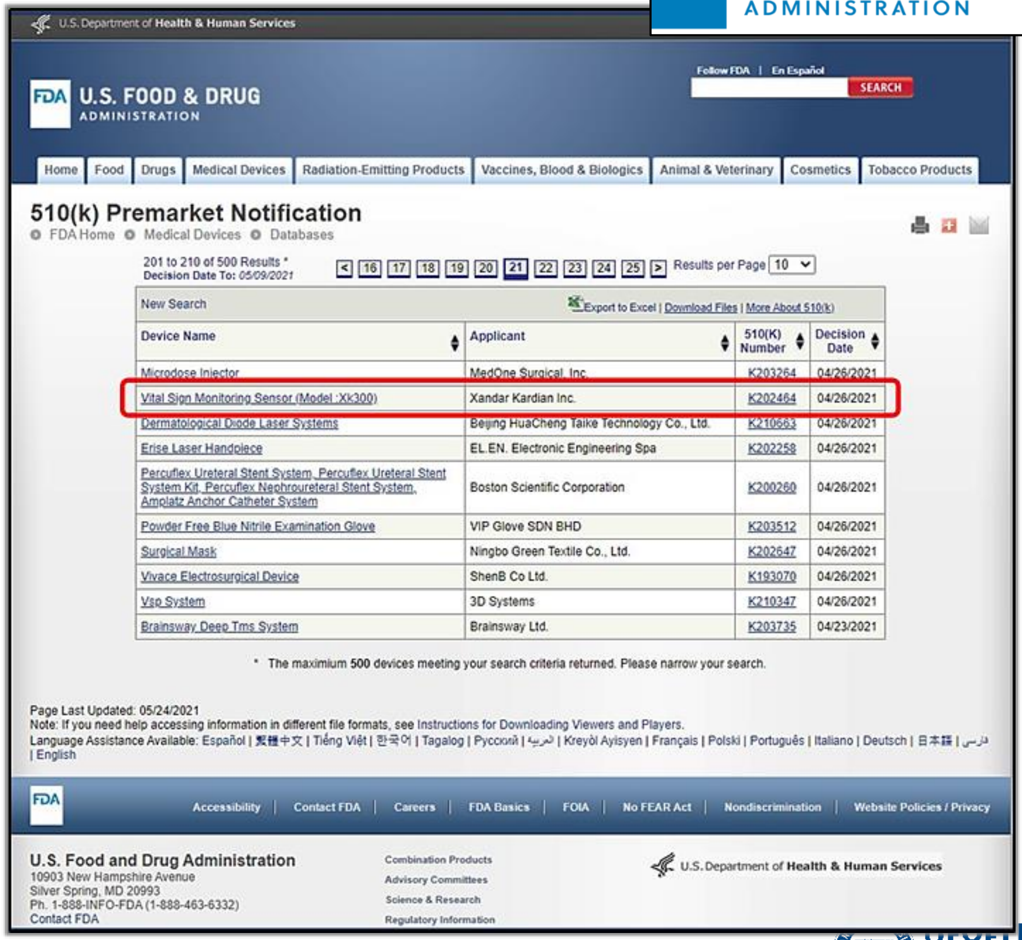
Smoothing Filter

Heart Rate

Acknowledgments and Awards of Non-Contact Vital Sign Monitoring (1/4)

- ***Innovation Awards (Honoree)*** *at CES 2021~2024, USA*
  - Health & Wellness Category
  - Digital Health Category
  - In-Vehicle Entertainment & Safety Category
  - Correctional, Human Security for All Category

- ***FDA Clearance*** *for Vital Sign Monitoring Sensor, USA (April 2021)*



510(k) Premarket Notification

FDA Home · Medical Devices · Databases

201 to 210 of 500 Results *
Decision Date To: *05/09/2021*

< 16 17 18 19 20 21 22 23 24 25 > Results per Page 10

New Search — Export to Excel | Download Files | More About 510(k)

Device Name	Applicant	510(K) Number	Decision Date
Microdose Injector	MedOne Surgical, Inc.	K203264	04/26/2021
Vital Sign Monitoring Sensor (Model :Xk300)	Xandar Kardian Inc.	K202464	04/26/2021
Dermatological Diode Laser Systems	Beijing HuaCheng Taike Technology Co., Ltd.	K210663	04/26/2021
Erise Laser Handpiece	EL.EN. Electronic Engineering Spa	K202258	04/26/2021
Percuflex Ureteral Stent System, Percuflex Ureteral Stent System Kit, Percuflex Nephroureteral Stent System, Amplatz Anchor Catheter System	Boston Scientific Corporation	K200260	04/26/2021
Powder Free Blue Nitrile Examination Glove	VIP Glove SDN BHD	K203512	04/26/2021
Surgical Mask	Ningbo Green Textile Co., Ltd.	K202647	04/26/2021
Vivace Electrosurgical Device	ShenB Co Ltd.	K193070	04/26/2021
Vsp System	3D Systems	K210347	04/26/2021
Brainsway Deep Tms System	Brainsway Ltd.	K203735	04/23/2021

* The maximium **500** devices meeting your search criteria returned. Please narrow your search.

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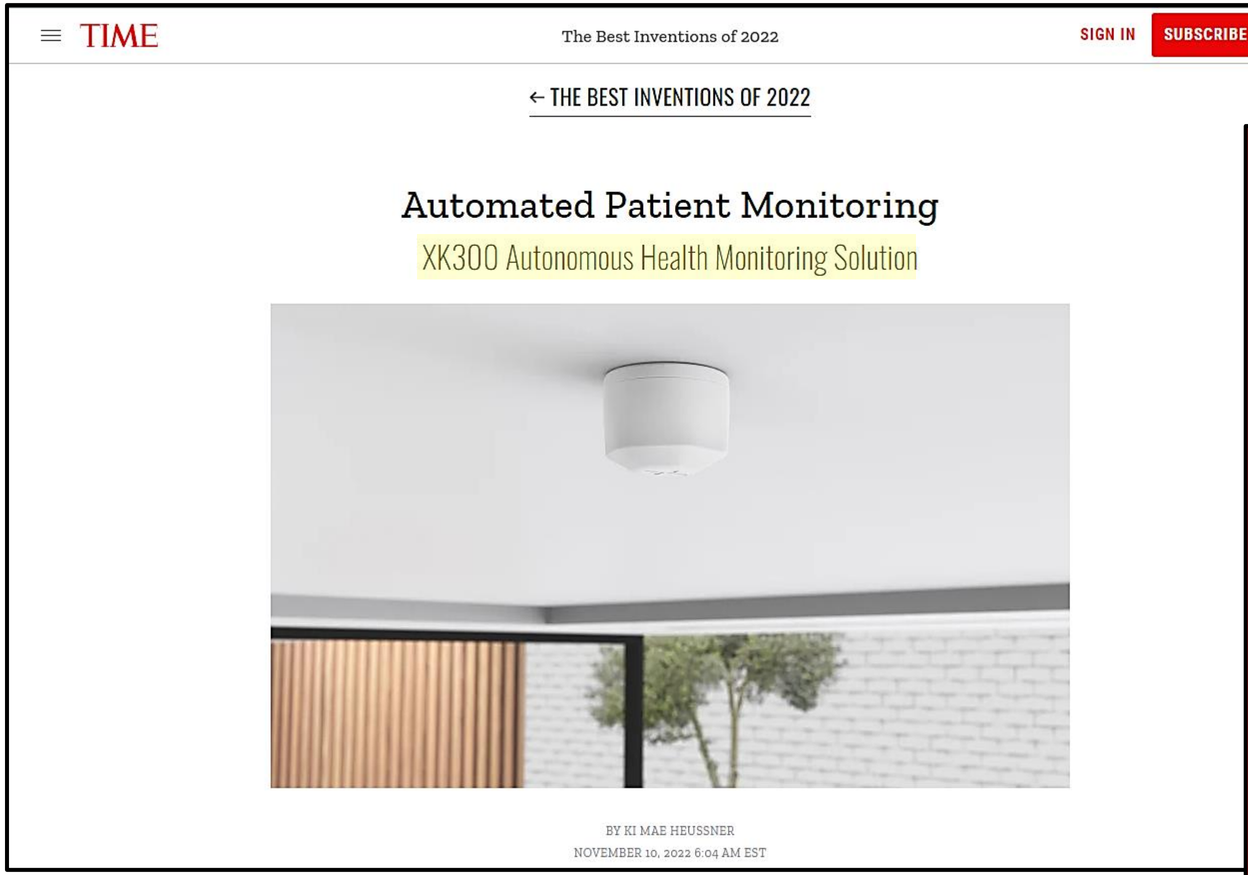
Acknowledgments and Awards of Non-Contact Vital Sign Monitoring (2/4)

- *Selected as one of “**The Best Inventions of 2022**” by TIME MAGAZINE, USA (November 2022)*



The Best Inventions of 2022

← THE BEST INVENTIONS OF 2022

Automated Patient Monitoring

XK300 Autonomous Health Monitoring Solution

BY KI MAE HEUSSNER

NOVEMBER 10, 2022 6:04 AM EST

Acknowledgments and Awards of Non-Contact Vital Sign Monitoring (3/4)

- ***"Radar-based Vital Sign Monitoring on KETV News"*** *for Installation at Midlands Living Center in Council Bluffs, Iowa, USA (February 2023)*

https://youtu.be/QLQosf2lW50

Acknowledgments and Awards of Non-Contact Vital Sign Monitoring (4/4)

- *Recognized as One of the* ***“5 New Innovations to Help Seniors Live Better,”*** *FOX News, USA (January 2024)*

TECH

5 new innovations to help seniors live better

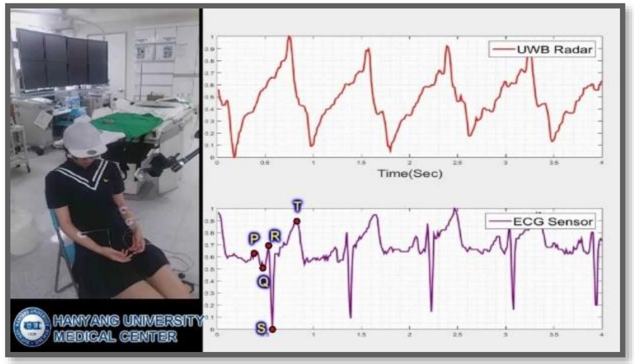
How this technology can improve the quality of life and independence for older adults

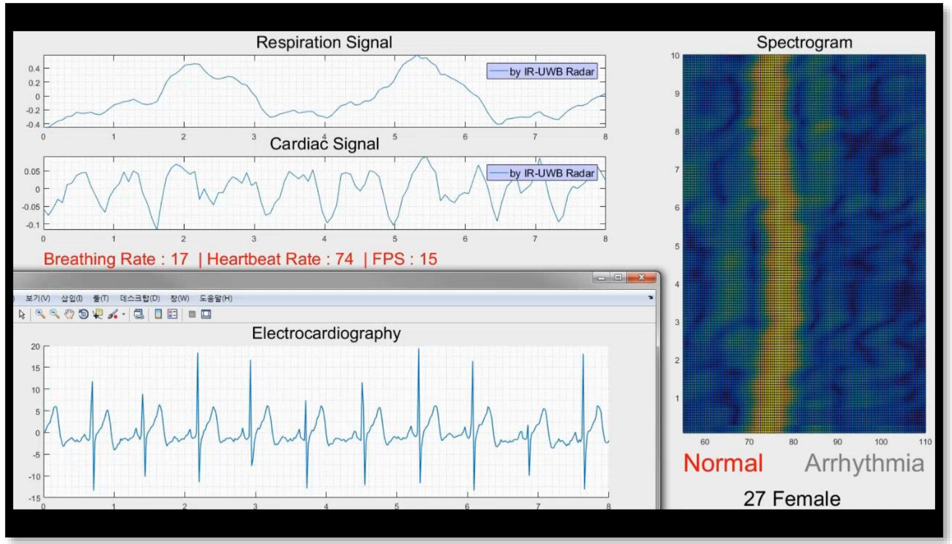
By **Kurt Knutsson, CyberGuy Report** · **Fox News**

Published January 13, 2024 6:00am EST

Arrhythmia Detection

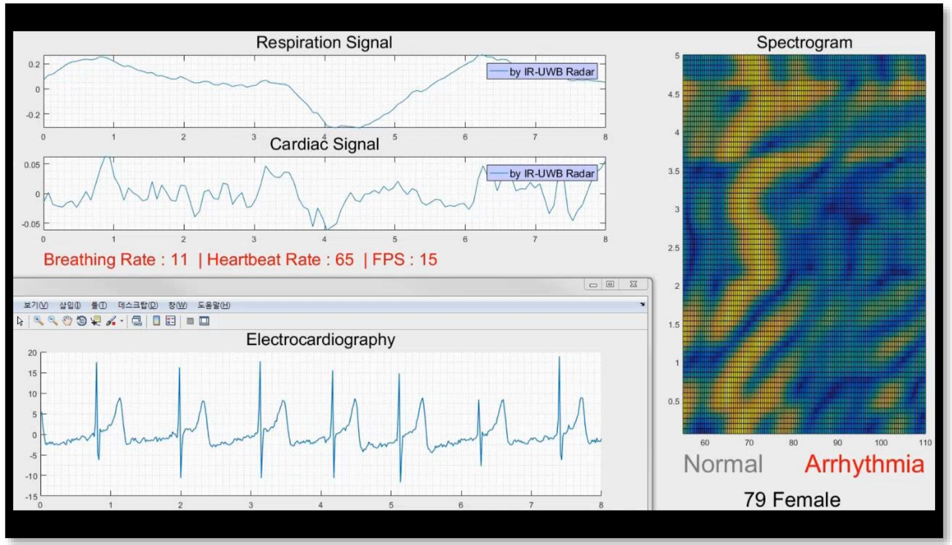
- *Normal - Female / 27*





Breathing Rate : 17 | Heartbeat Rate : 74 | FPS : 15

- *Arrhythmia Patient - Female / 79*

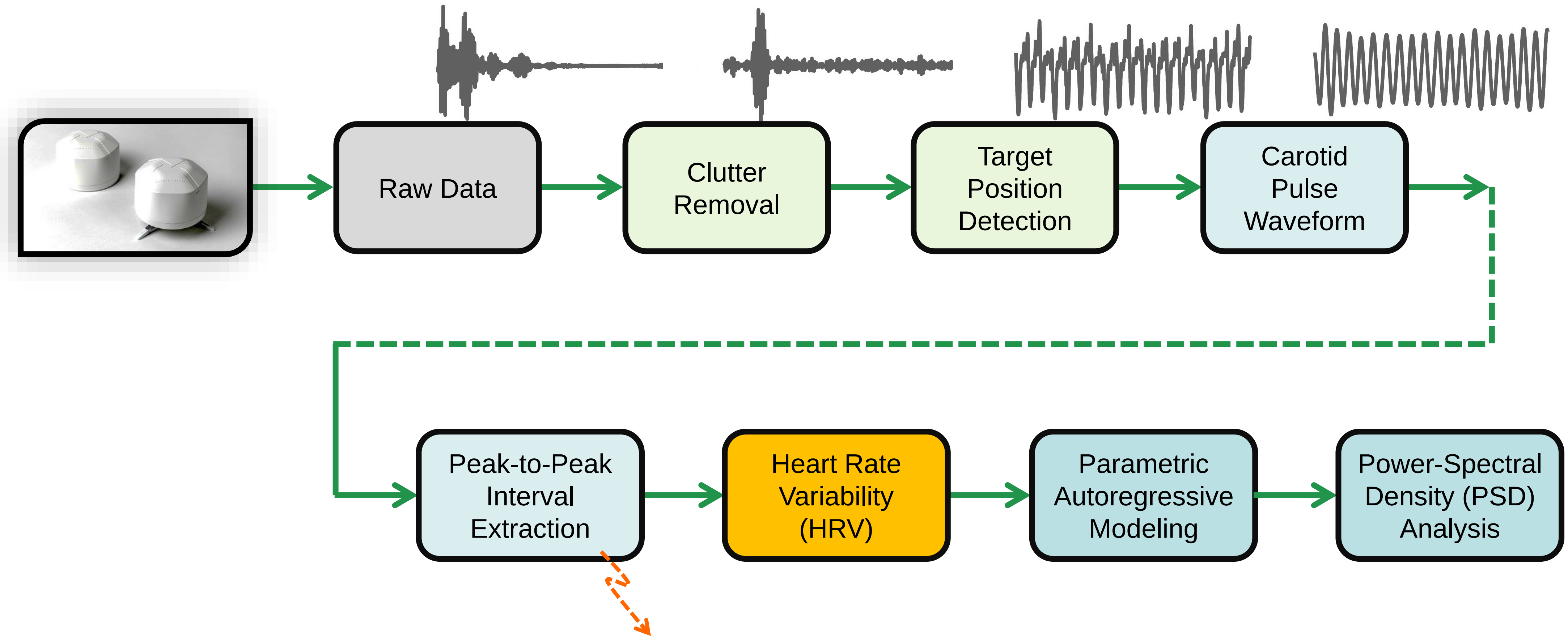


Breathing Rate : 11 | Heartbeat Rate : 65 | FPS : 15

Heart Rate Variability (HRV) Monitoring

- "Feasibility of Early Assessment for Psychological Distress: HRV-Based Evaluation Using IR-UWB Radar," *Sensors*, Sep. 2024.
- "Noncontact Assessment for Fatigue Based on Heart Rate Variability Using IR-UWB Radar," *Scientific Reports*, Aug. 2022.

HRV Detection



Raw Data

Clutter Removal

Target Position Detection

Carotid Pulse Waveform

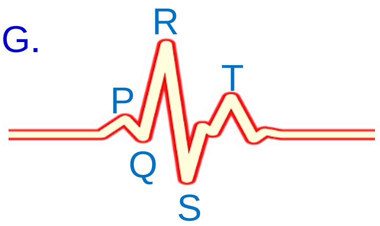
Peak-to-Peak Interval Extraction

Heart Rate Variability (HRV)

Parametric Autoregressive Modeling

Power-Spectral Density (PSD) Analysis

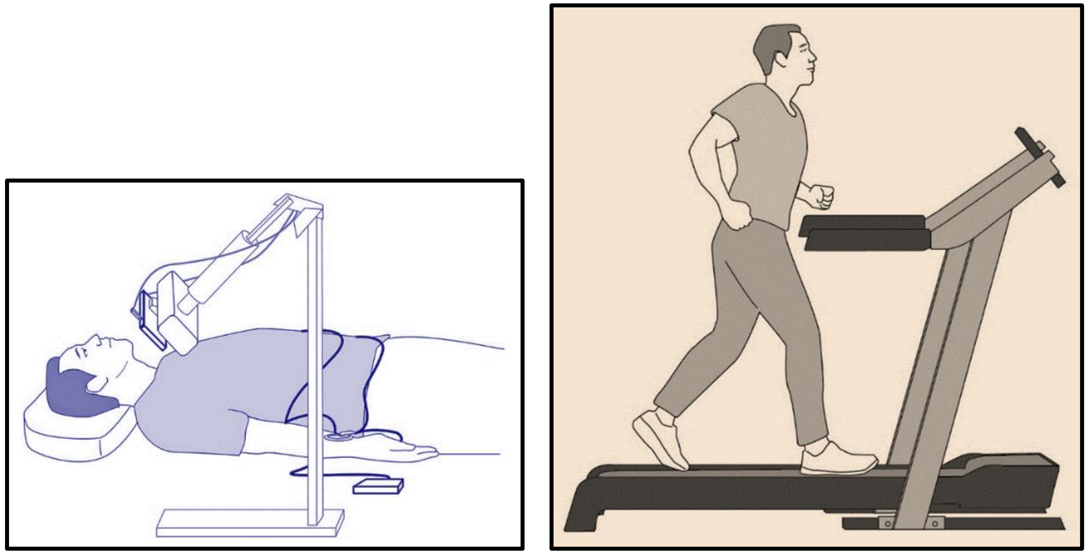
This corresponds to the RR interval in ECG.



Test Example #1: Fatigue Assessment (1/4)

- HRV is related to interaction between sympathetic and parasympathetic influences in the heart.

- *1-Hour, 3-Step Experiment Protocol*
  - HRV measurement for 10 min before exercise
  - Treadmill running at 8 Km/hour speed for 20 min
  - HRV measurement for 30 min after exercise



- *Sampling Rate of Radar & ECG: 250 samples/sec*

- *Using HRV, we want to*
  - Estimate a *recovery time* of each participant using HRV after exercise.
  - Find the relationship between the *"body fat percentage"* and *"patterns of recovery"* from exercise-induced fatigue

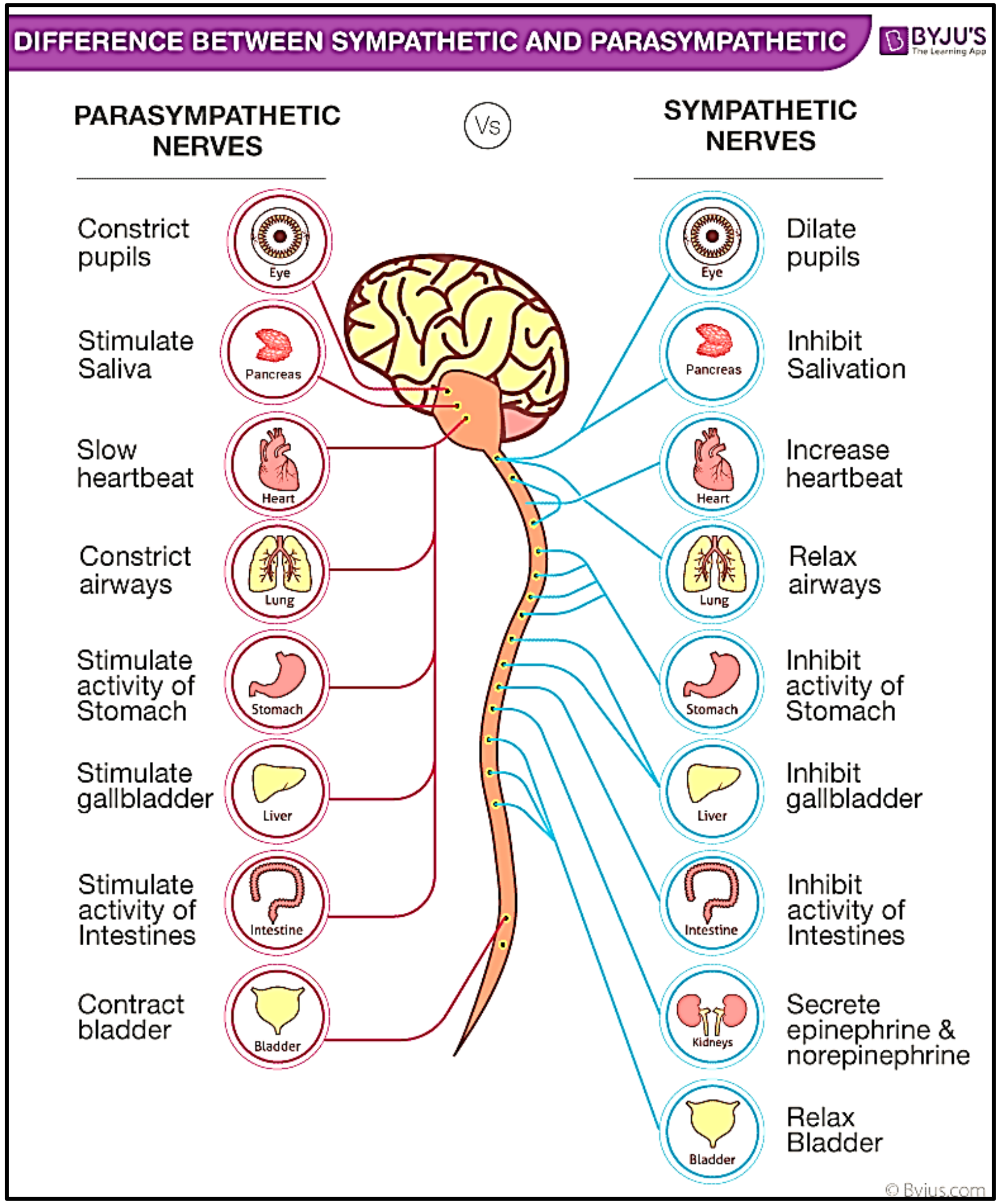
Test Example #1: ***Fatigue Assessment*** ***(2/4)***

- *HRV Frequencies*
  - Quantify modulation of the sympathetic and parasympathetic branches of the autonomic nervous system.
  - Very Low Frequency (VLF): 0~0.04 Hz
  - *Low Frequency* (LF): 0.04~0.15 Hz
  - *High Frequency* (HF): 0.15~0.4 Hz

- *LF/HF Ratio*
  - Shows autonomic nervous system (ANS) balance.
  - Low LF/HF ratio:
    - *Parasympathetic nervous system* (PSNS) dominance
    - Allows repair and healing while we are relaxing, assists with digestion.
  - High LF/HF ratio:
    - *Sympathetic nervous system* (SNS) dominance
    - Triggers when we feel highly stressed, emotional, tired, over-worked.

Relax Mode

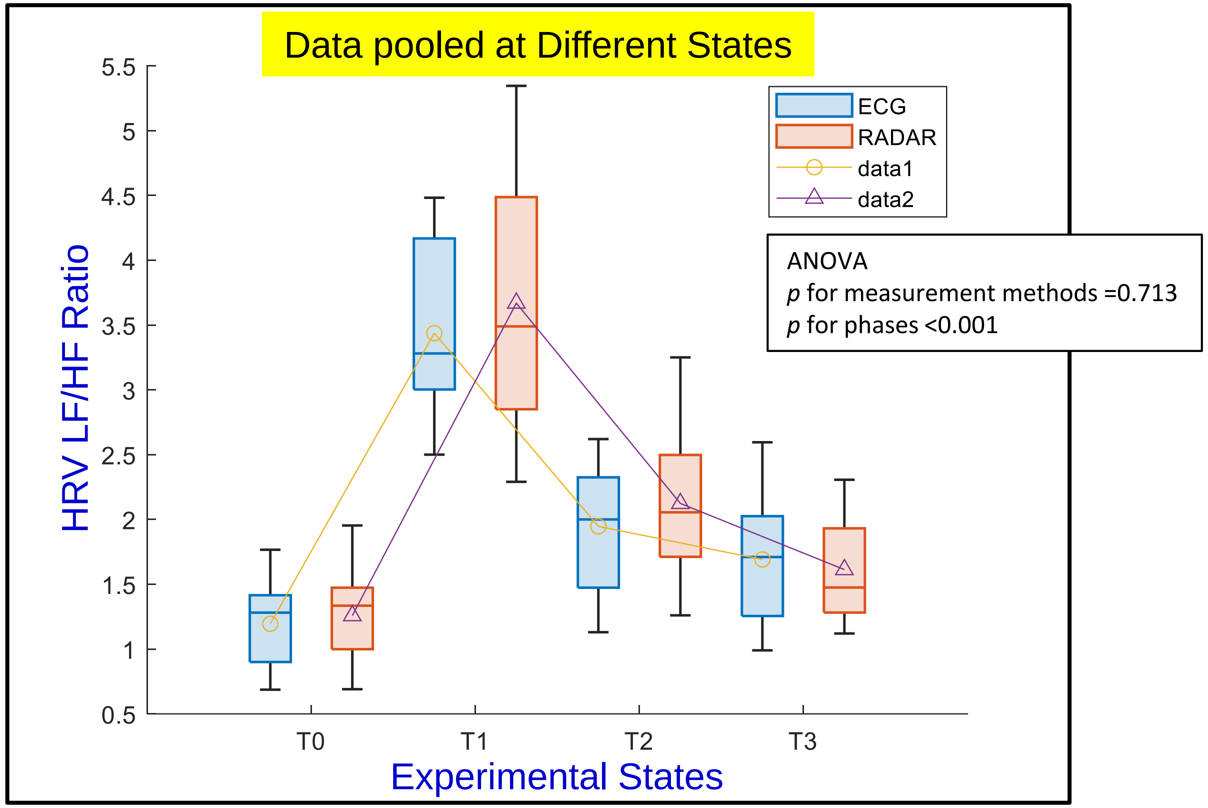
Agitated Mode



https://byjus.com/biology/difference-between-sympathetic-and-parasympathetic/

Test Example #1: *Fatigue Assessment* (3/4)

ANOVA Analysis



Standardized Mean Difference

Subject Characteristics

Clinical characteristics	**Values (N=15)**
Age (years)	27.2 ± 3.7
Gender (male/female)	13/2
Weight (kg)	70.9 ± 10.8
Height (cm)	172.7 ± 6.5
BMI (kg/m^2)	23.54 ± 2.6
Total body fat mass (kg)	18.3 ± 3.9
Percent body fat (%)	24.6 ± 5.1

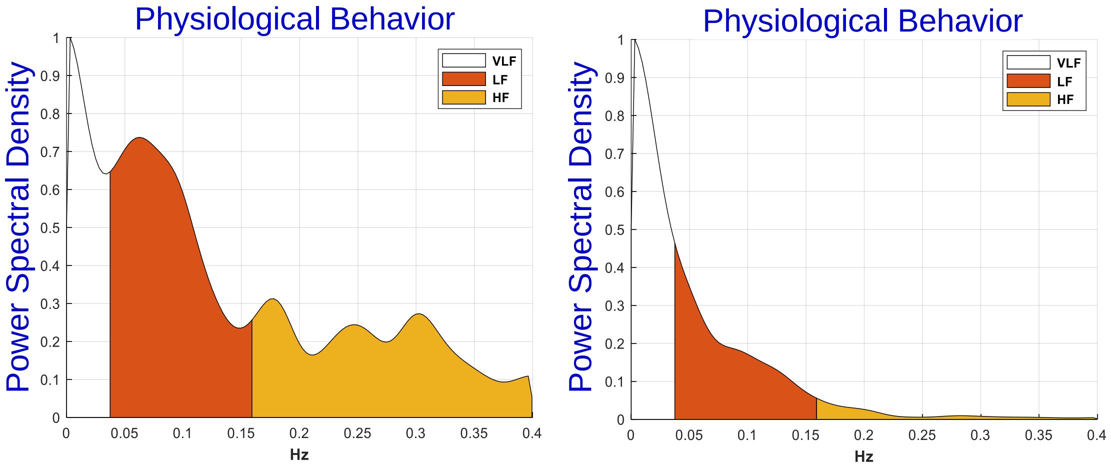
HRV variable	**ECG**	**Radar**	**SMD**
T0: Rest (before exercise)			
LF (second^2/Hz)	12.9 ± 4.2	10.1 ± 3.5	0.771
HF (second^2/Hz)	11.5 ± 4.0	8.62 ± 4.0	0.739
LF/HF	1.20 ± 0.3	1.25 ± 0.4	-0.189
T1: Fatigue 1 (0~10 min after exercise)			
LF (second^2/Hz)	8.61 ± 6.5	8.67 ± 7.10	-0.089
HF (second^2/Hz)	2.68 ± 2.2	2.60 ± 2.35	0.030
LF/HF	3.43 ± 0.7	3.67 ± 0.95	-0.293
T2: Fatigue 2 (10~20 min after exercise)			
LF (second^2/Hz)	4.56 ± 1.2	5.1 ± 2.4	-0.312
HF (second^2/Hz)	2.40 ± 0.5	2.4 ± 0.8	-0.020
LF/HF	1.95 ± 0.4	2.1 ± 0.5	-0.355
T3: Recovery (20~30 min after exercise)			
LF (second^2/Hz)	11.7 ± 4.8	9.7 ± 5.5	0.383
HF (second^2/Hz)	7.70 ± 4.1	6.8 ± 4.58	0.217
LF/HF	1.70 ± 0.5	1.6 ± 0.40	0.184

Data were shown as the mean ± SD.
SMD: Standardized Mean Difference

Test Example #1: Fatigue Assessment (4/4)

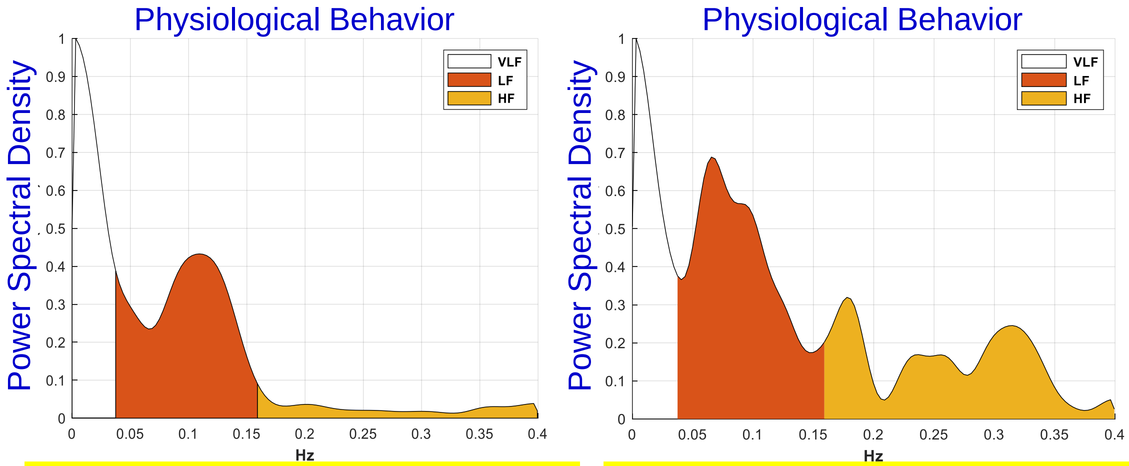
Nov. 07, 2024

HRV Distributions in LF and HF Region



Before exercise

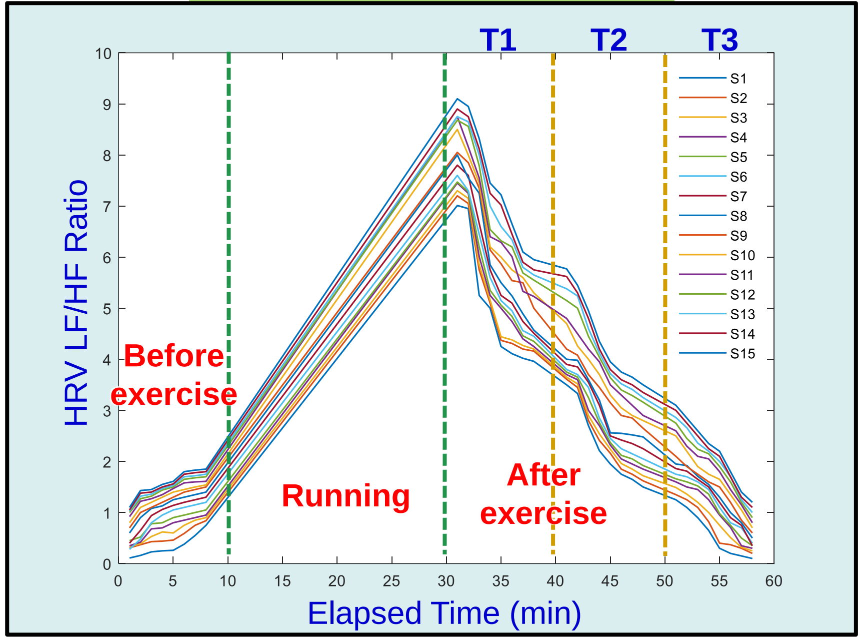
During 0~10 min after exercise (T1)



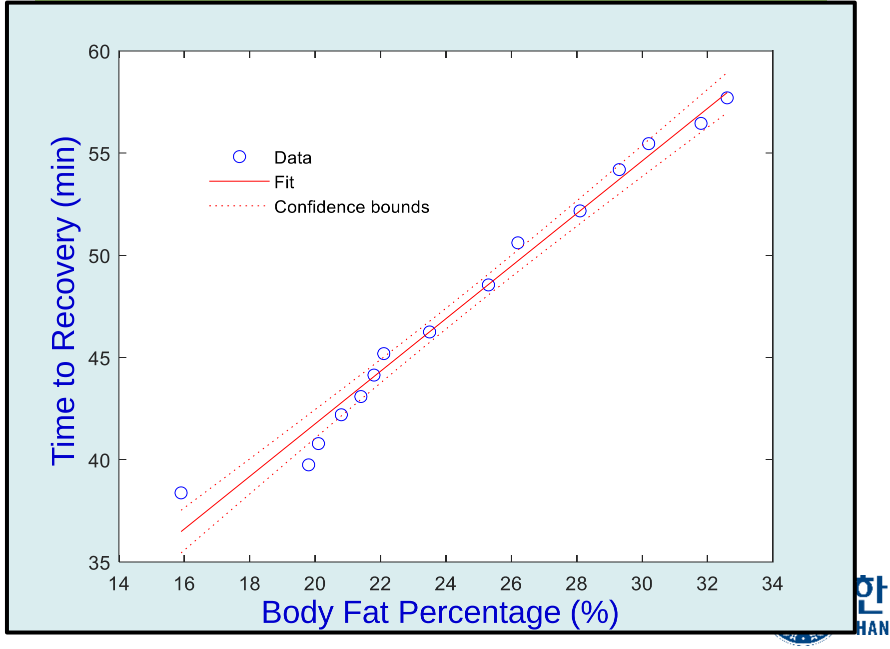
During 10~20 min after exercise (T2)

During 20~30 min after exercise (T3)

Changes of LF/HF Ratios



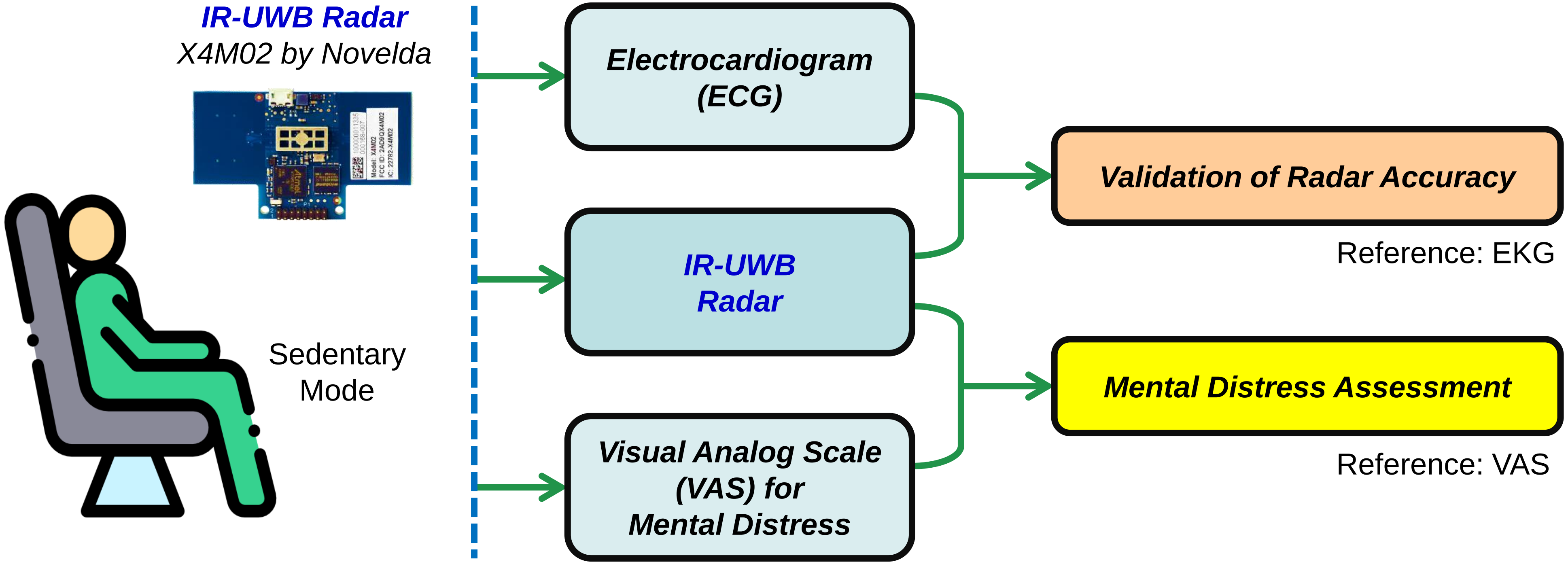
Body Fat Percentage vs. Time to Recovery



Test Example #2: Mental Distress Assessment (1/4)

Experimental Setup

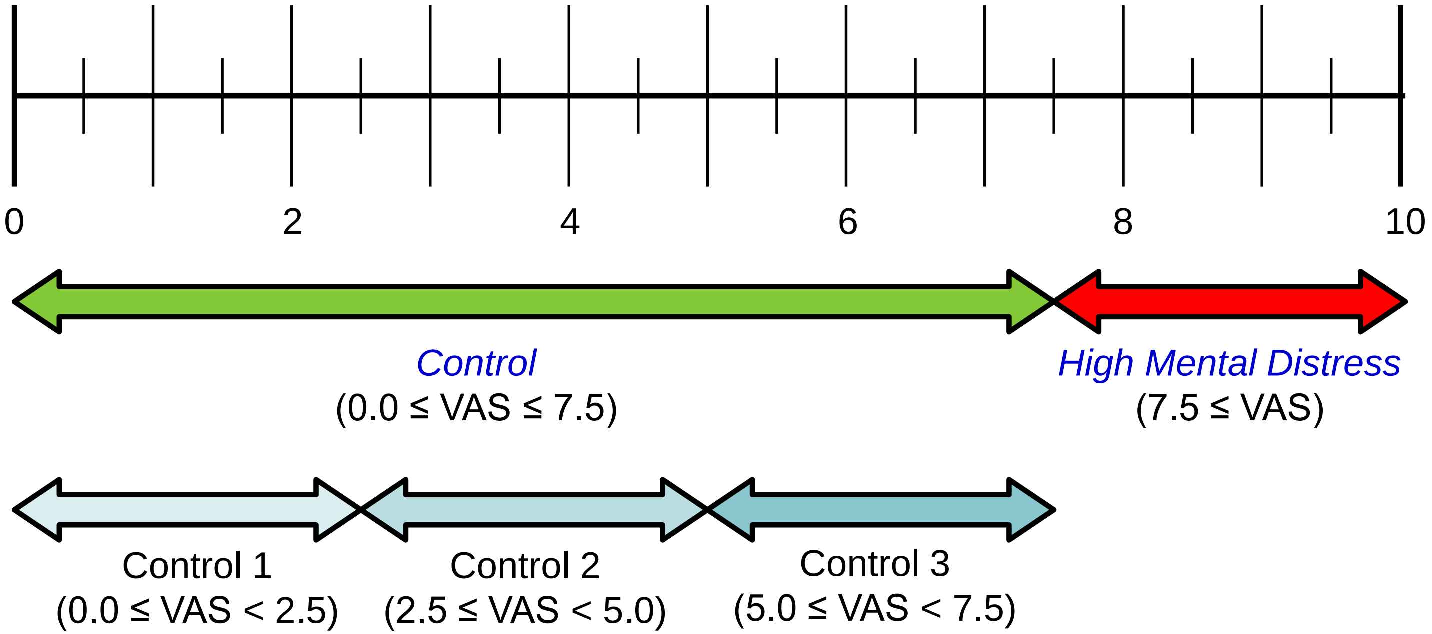
- 15 employees in a software startup company in Seoul, South Korea.
- Age: 23~43 years old (average = 30.9 years)
- 15 employees x 8 independent times = 120 measurements



Test Example #2: Mental Distress Assessment (2/4)

Visual Analog Scale (VAS)

- A *questionnaire* in which participants rate their levels of conditions such as *pain*, *mood* and *worry* by selecting a point on a line between two opposite extremes.
- Participants were requested to rate their level of mental distress prior to the HRV measurement, with *a response resolution set at 0.5 sec*.



Control
(0.0 ≤ VAS ≤ 7.5)

High Mental Distress
(7.5 ≤ VAS)

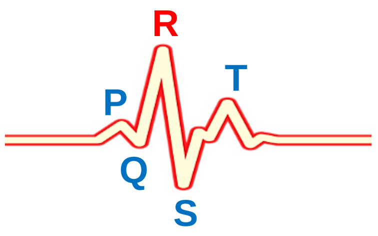
Control 1
(0.0 ≤ VAS < 2.5)

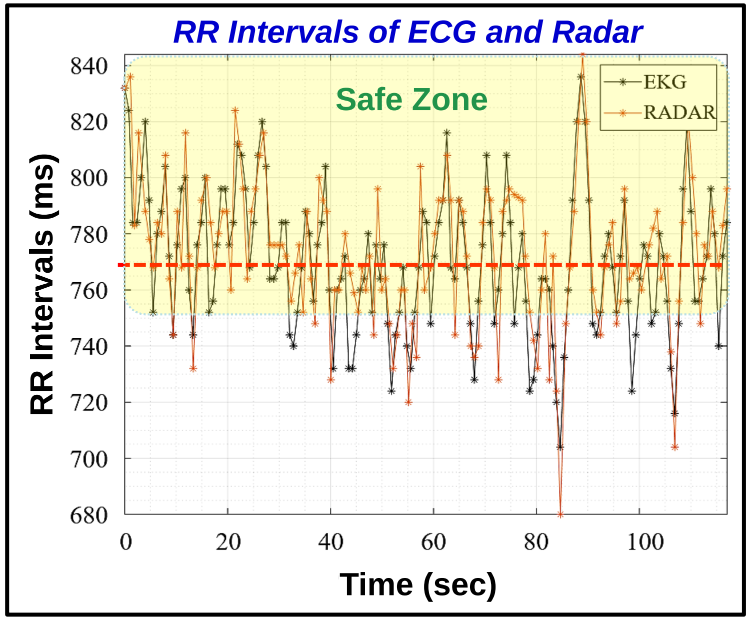
Control 2
(2.5 ≤ VAS < 5.0)

Control 3
(5.0 ≤ VAS < 7.5)

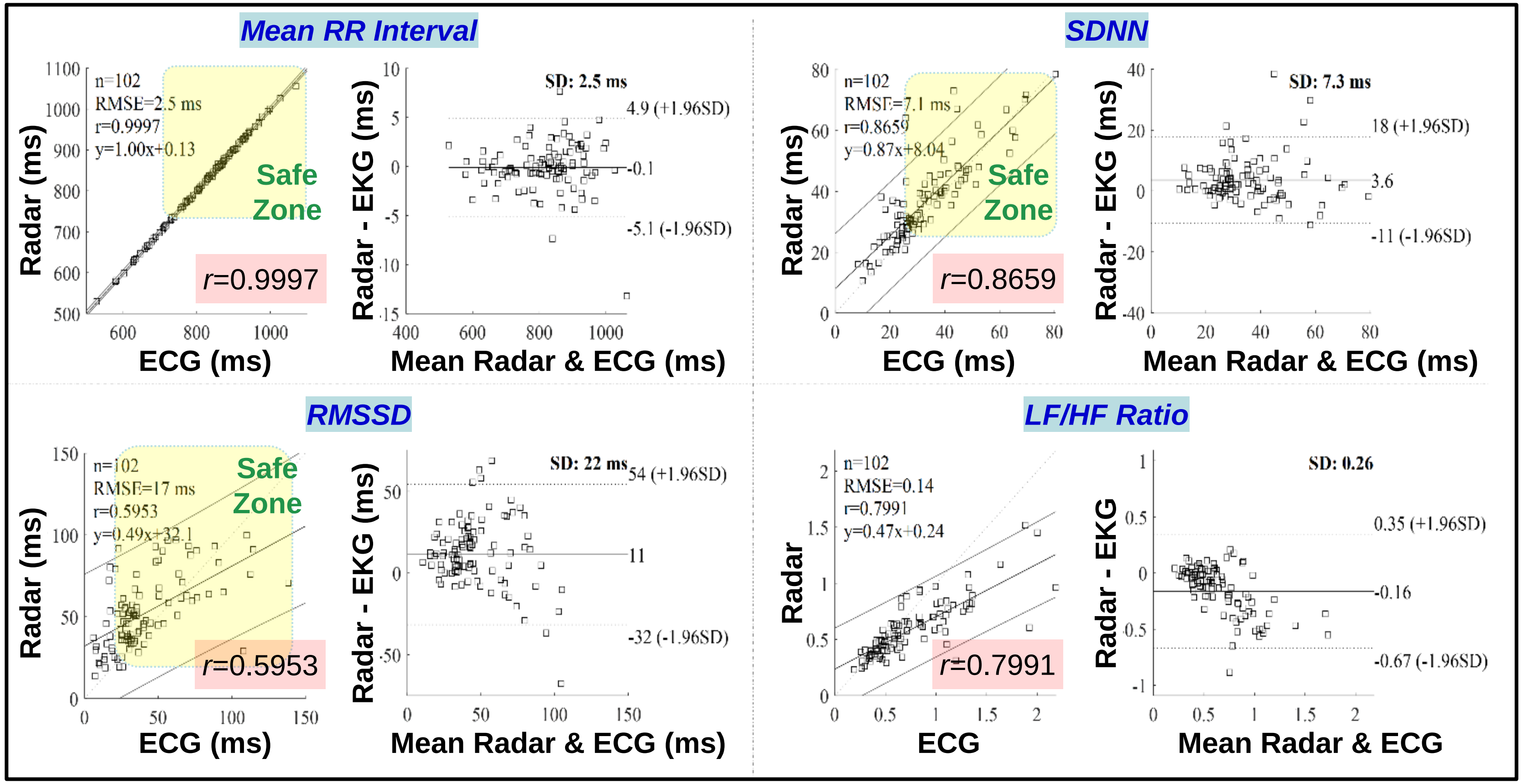
Test Example #2: Mental Distress Assessment (3/4)

- *Validation of Radar Accuracy*





102 evaluations, excluding 18 outliers



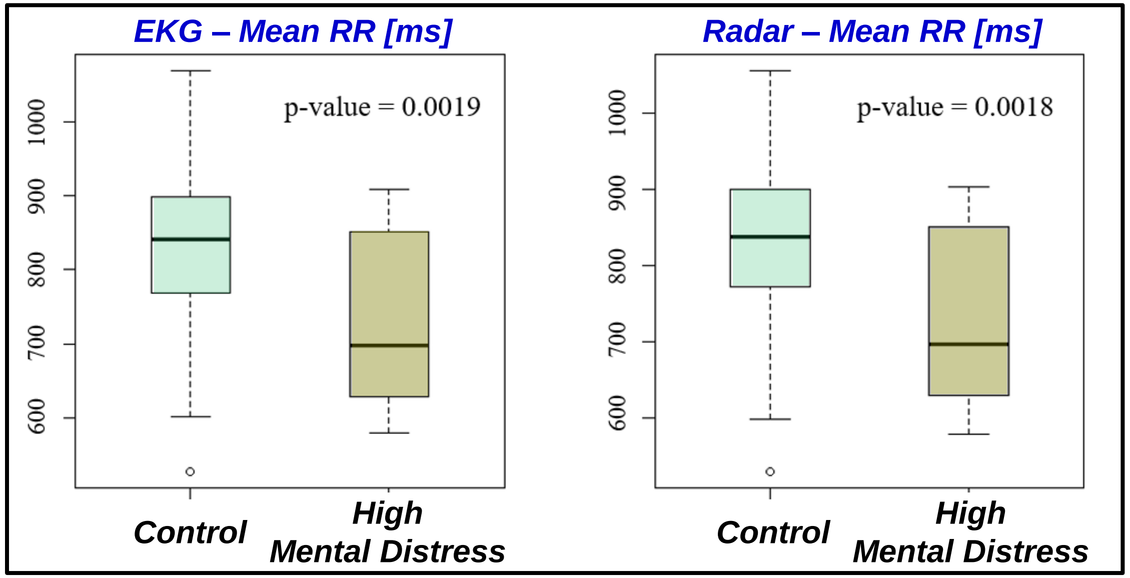
SDNN: Standard Deviation of Normal to Normal (NN) Interval (*Stress Resistance*)

RMSSD: Root Mean Square of Successive Differences between Adjacent NN Intervals (*Vitality of Parasympathetic Nervous System*)

LF/HF Ratio: Low-Frequency to High-Frequency Ratio (*Balance of Autonomic Nervous System*)

Test Example #2: Mental Distress Assessment (4/4)

- *Mental Distress Assessment*



102 evaluations, excluding 18 outliers

Group	***VAS Score Range***	***N***	***ECG***		***IR-UWB radar***	
			Mean RR [ms]	***SDNN [ms]***	***Mean RR [ms]***	***SDNN [ms]***
Control 1	0 ≤ VAS < 2.5	21	840.76	34.99	840.61	37.71
Control 2	2.5 ≤ VAS < 5.0	20	832.15	36.31	831.81	37.86
Control 3	5.0 ≤ VAS < 7.5	49	821.93	33.10	822.08	36.50
Control (all)	**0 ≤ VAS < 7.5**	**90**	**828.59**	**34.25**	**828.56**	**37.08**
High mental distress	**7.5 ≤ VAS < 10.0**	**12**	**726.75**	**22.29**	**726.12**	**31.72**

"Significantly lower"

Sleep Monitoring

- "Non-contact Sleep/Wake Monitoring Using Impulse-Radio Ultrawideband Radar in Neonates," *Frontiers in Pediatrics*, Dec. 2021.
- "Non-Contact Diagnosis of Obstructive Sleep Apnea Using Impulse-Radio Ultra-Wideband Radar," *Scientific Reports*, Mar. 2020.
- "Validation of Noncontact Cardiorespiratory Monitoring Using Impulse-Radio Ultra-Wideband Radar against Nocturnal Polysomnography," *Sleep and Breathing*, Aug. 2019.

Sleep Monitoring with Radar

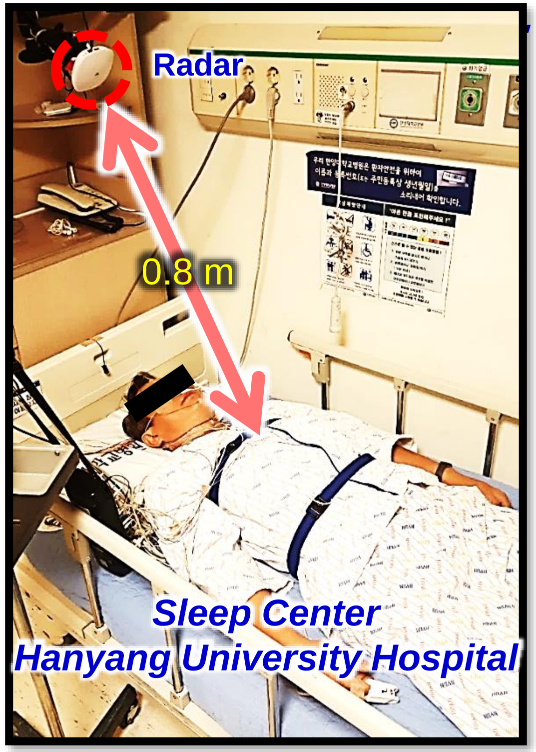
- *Vital Sign Monitoring*
  - Respiration Rate (RR)
  - Heart Rate (HR)
- *Sleep Apnea*
  - Central Apnea
  - Obstructive Apnea
  - Hypopnea
  - Apnea Hypopnea Index (AHI)

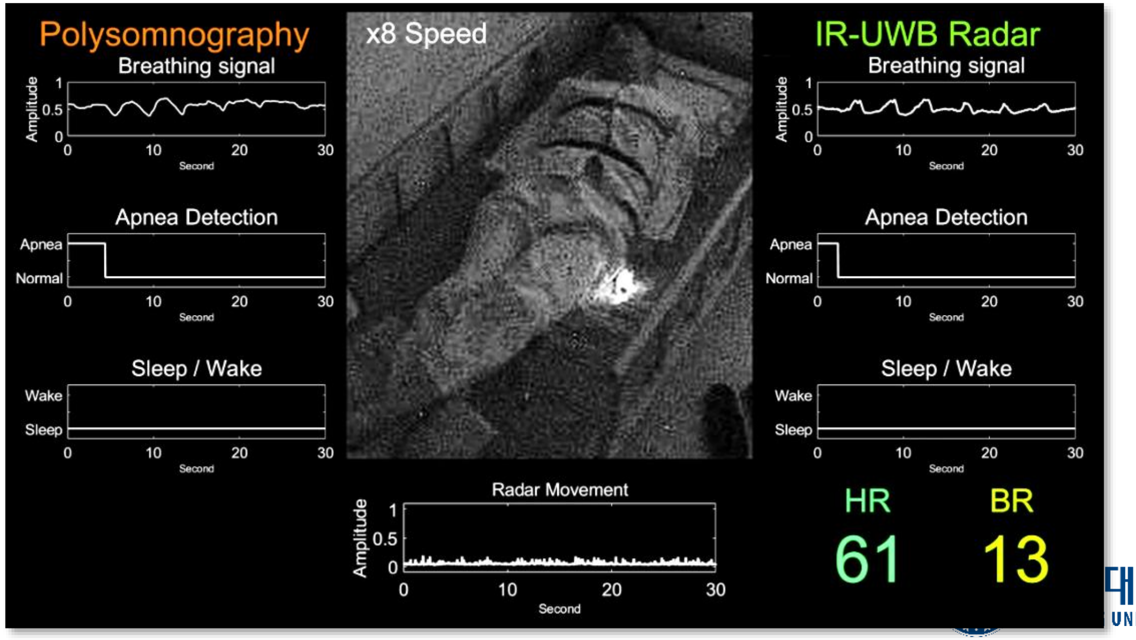
Easy to use

Daily

Non-contact

No privacy issue

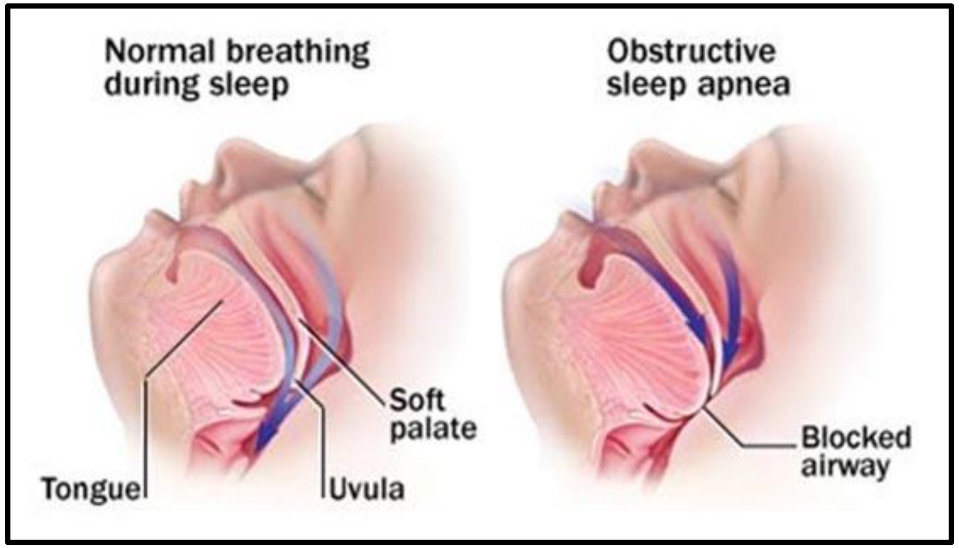




Sleep Apnea (1/6)

- *Apnea/Hypopnea*
  - ***Apnea***: No breathing for over 10 sec
    - Central Apnea (Brain doesn't tell to breathe during sleep)
    - ***Obstructive Apnea*** (Airway collapse)
    - Mixed Apnea
  - ***Hypopnea***: Shallowed breathing

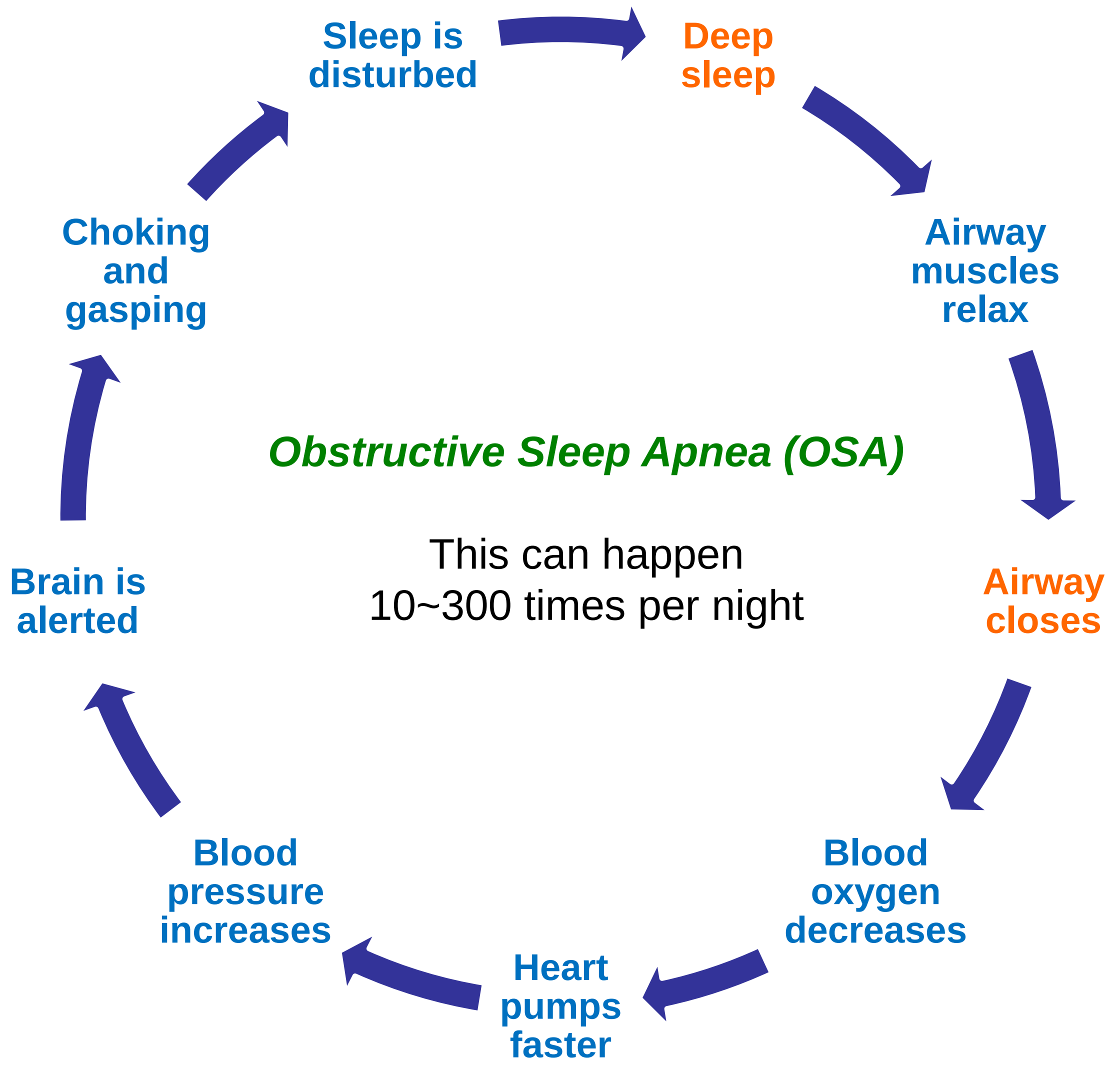
- *Common Causes*
  - Obesity
  - Large neck size
  - Abnormal upper airway anatomy
  - Using medications, drugs, or alcohol
  - Aging
  - Sleeping on the back
  - REM or dreaming sleep
  - Smoking



Sleep Apnea (2/6)

Common Symptoms of Sleep Apnea

- Loud or frequent snoring
- Choking or gasping sounds
- Witnessed pauses in breathing during sleep
- Dry mouth or throat
- Morning headache
- Memory loss
- Attention deficit
- Depression
- Excessive daytime sleepiness
- Fatigue
- Nocturia
- Impotence
- Insomnia



Obstructive Sleep Apnea (OSA)

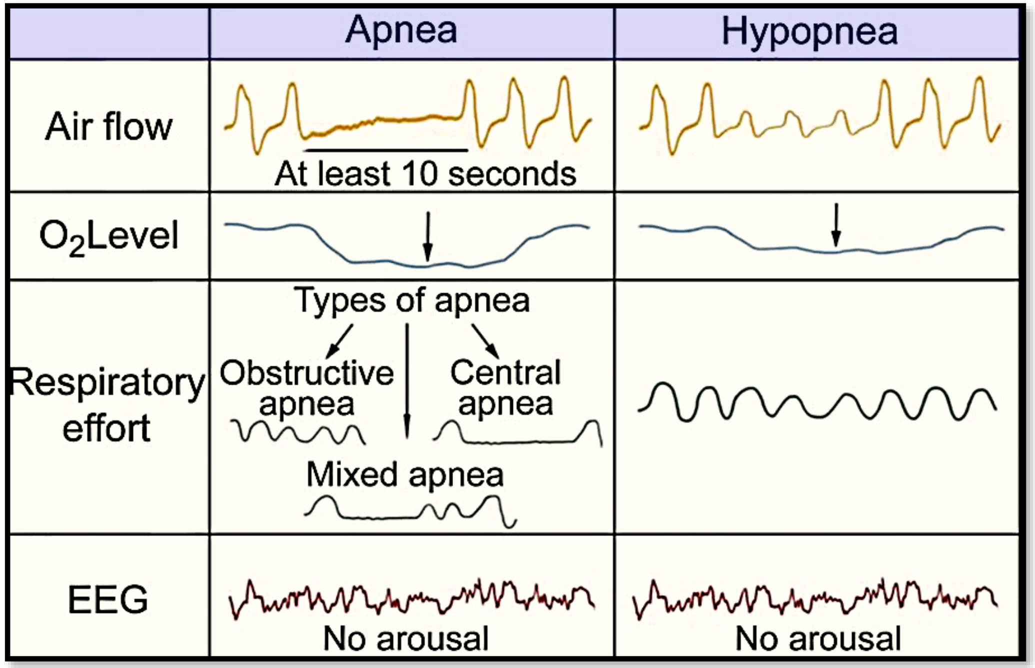
This can happen
10~300 times per night

Sleep Apnea (3/6)

- *Apnea Hypopnea Index (AHI)*
  - Average number of apnea & hypopnea per hour

$$\text{AHI} = \frac{\text{\# of Apneas} + \text{\# of Hypopneas}}{\text{Total Sleep Time (Hour)}}$$

- ***Normal:*** ***AHI<5***
- ***Mild:*** ***5≤AHI<15***
- ***Moderate:*** ***15≤AHI<30***
- ***Severe:*** ***AHI≥30***



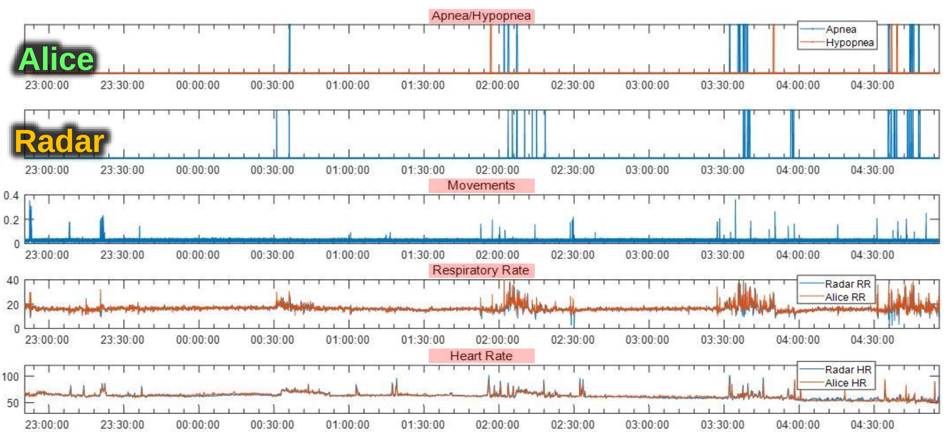
	Apnea	Hypopnea
Air flow	At least 10 seconds	
O_2Level		
Respiratory effort	Types of apnea Obstructive apnea Central apnea Mixed apnea	
EEG	No arousal	No arousal

Continuous Positive Airway Pressure (CPAP)

Sleep Apnea (4/6)

Nov. 07, 2024

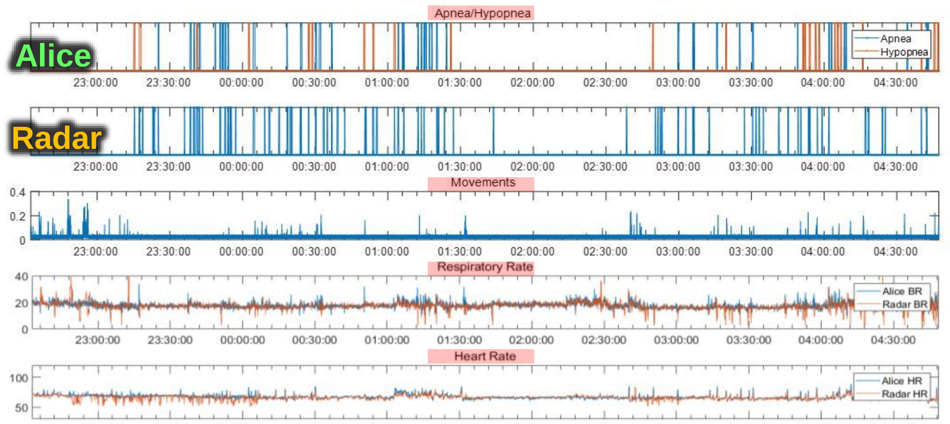
Normal : Male/Age 31



Normal

AHI (Apnea-Hypopnea Index)
3.7 by Alice
4.7 by Radar

Patient #1: Male/Age 54

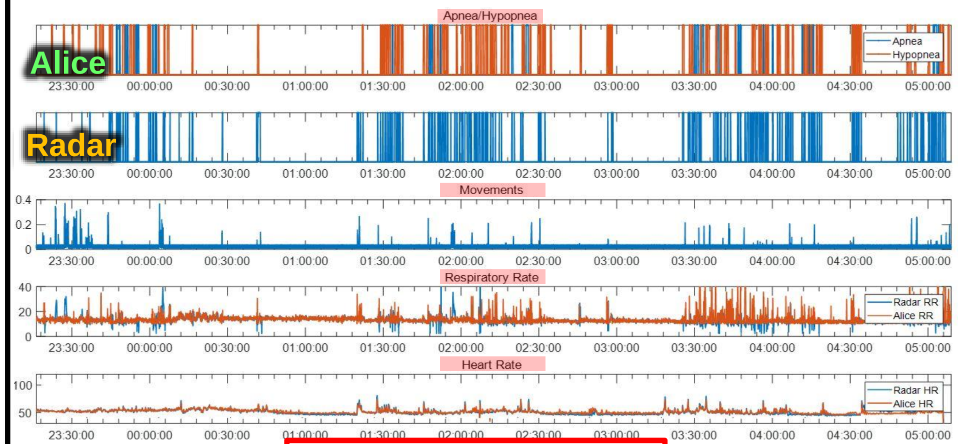


AHI (Apnea-Hypopnea Index)
12.1 by Alice
14.3 by Radar

Moderate

- **Normal: AHI<5**
- **Mild: 5≤AHI<15**
- **Moderate: 15≤AHI<30**
- **Severe: AHI≥30**

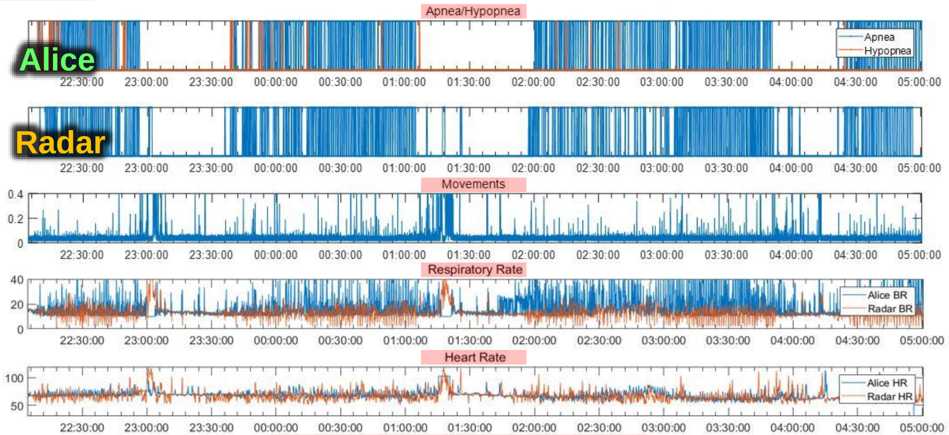
Patient #2: Male/Age 52



Mild

AHI (Apnea-Hypopnea Index)
24.8 by Alice
26.9 by Radar

Patient #3: Male/Age 60



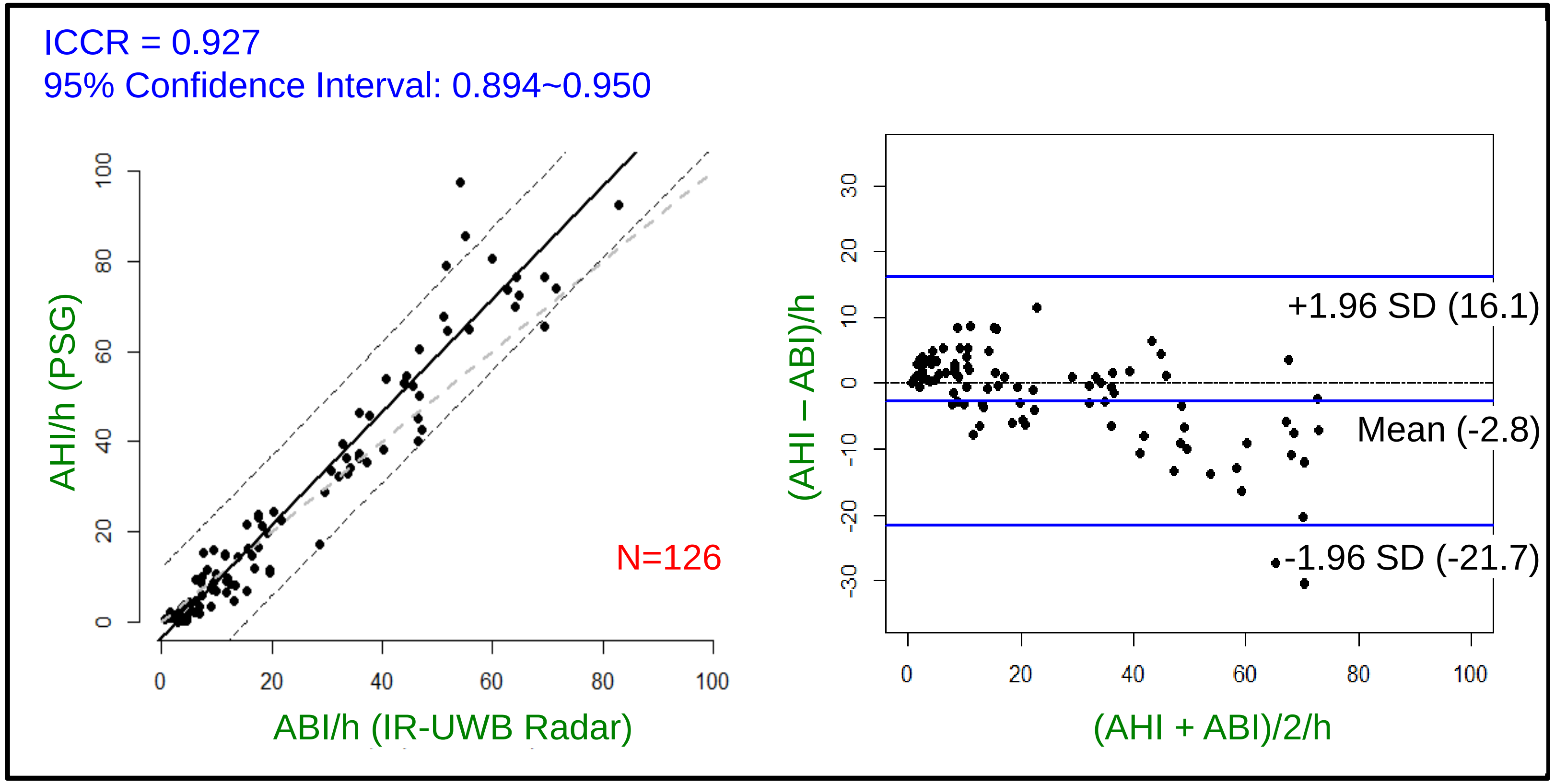
AHI (Apnea-Hypopnea Index)
83.8 by Alice
85.7 by Radar

Severe

Sleep Apnea (5/6)

- *Intraclass Correlation Coefficient R (ICCR)*

Apnea Hypopnea Index (AHI) vs. Abnormal Breathing Index (ABI)



Scatter Plot

Bland-Altman Plot

Sleep Apnea (6/6)

- *Confusion Matrix*

Obstructive Sleep Apnea (OSA)

	Normal (AHI < 5)	Mild (5 ≤ AHI < 15)	Moderate (15 ≤ AHI < 30)	Severe (AHI ≥ 30)	***Recall***
Normal (AHI < 5)	25	5	0	0	0.83
Mild (5 ≤ AHI < 15)	3	26	4	0	0.78
Moderate (15 ≤ AHI < 30)	0	4	20	1	0.80
Severe (AHI ≥ 30)	0	0	2	36	0.95
Precision	0.89	0.74	0.77	0.97	*Overall Agreement* 0.85

Gait Analysis

- "Gait Asymmetry Evaluation Using FMCW Radar in Daily Life Environments," *LNCS (IWBBIO 2023)*, Nov. 2023.
- "Noncontact Extraction of Biomechanical Parameters in Gait Analysis Using a Multi-Input and Multi-Output Radar Sensor," *IEEE Access*, Oct. 2021.

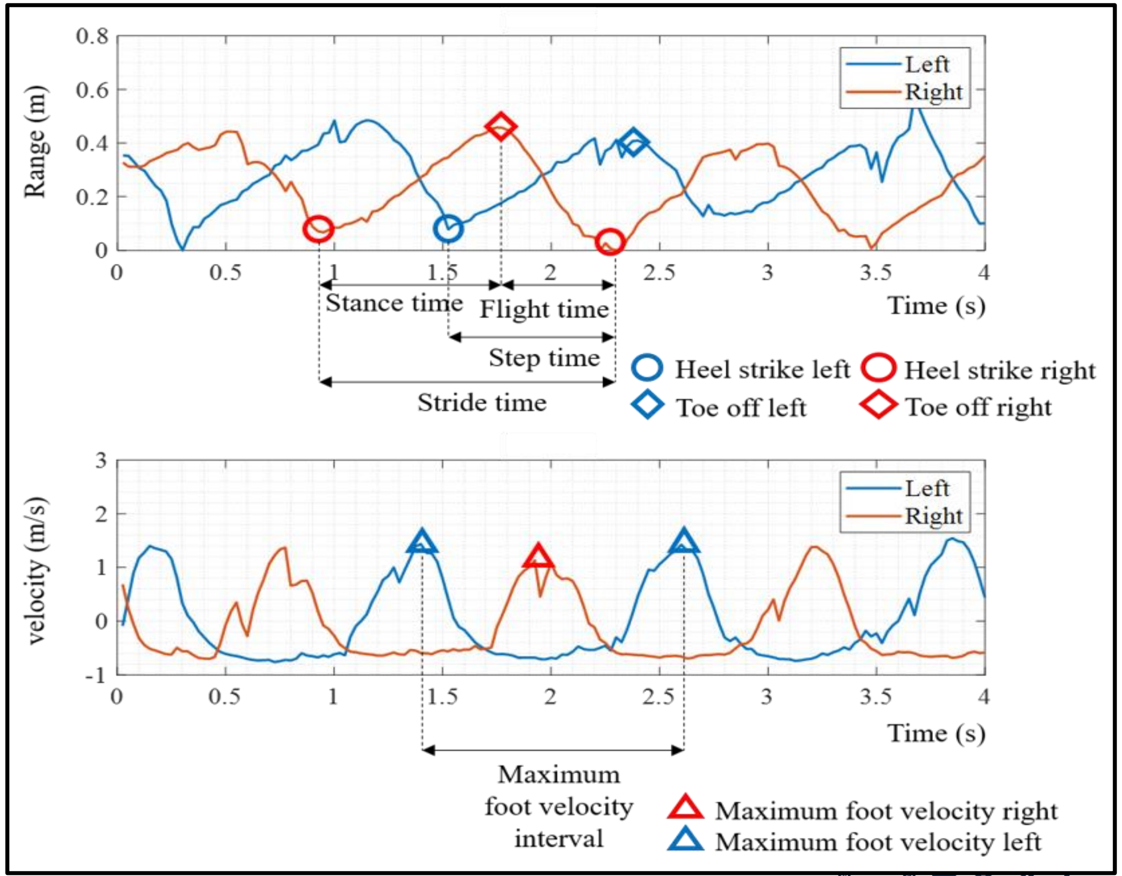
Gait Analysis

❖ *Why Gait?*

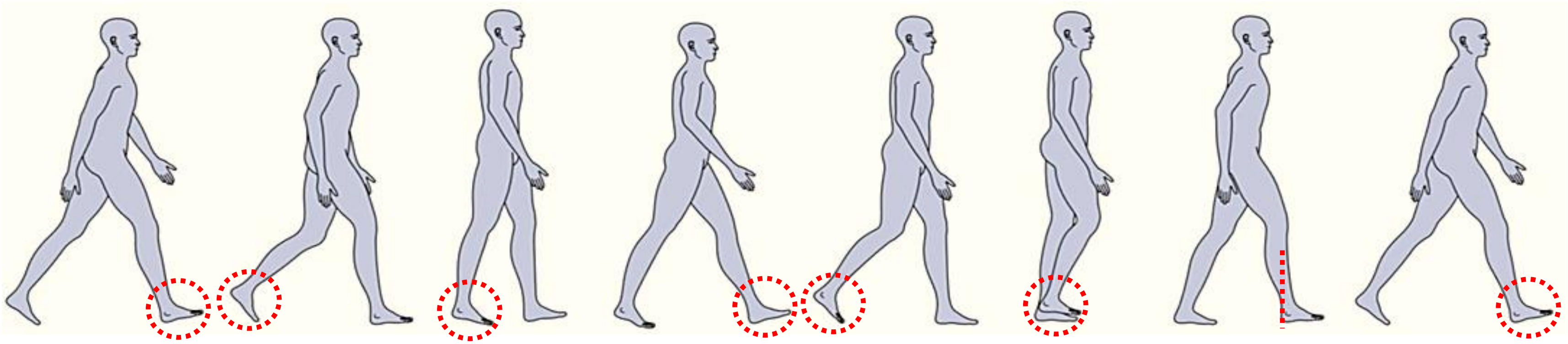
- Early Screening of Neurodegenerative Diseases such as Parkinson’s and Alzheimer’s Diseases
- Senior Mobility Analysis
- Fall Prevention

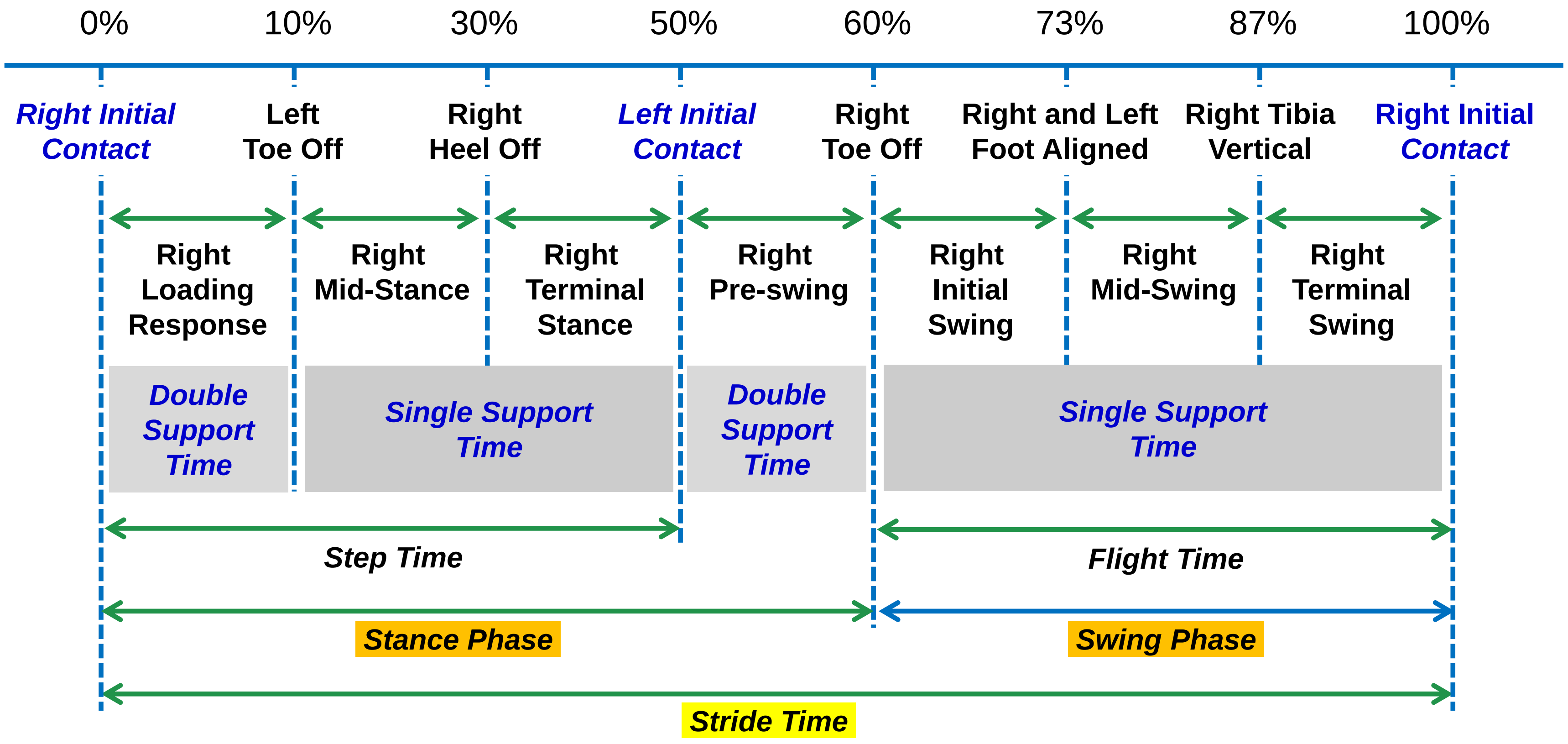
❖ *Gait Parameters*

- Center of Force (CoF)
- Force
- Weight Distribution
- Stride Time
- Stance Time
- Flight Time
- Step Time
- Cadence (steps/minute)
- Maximum Foot Velocity Interval



Gait Cycle





0%	10%	30%	50%	60%	73%	87%	100%
Right Initial Contact	**Left Toe Off**	**Right Heel Off**	***Left Initial Contact***	**Right Toe Off**	**Right and Left Foot Aligned**	**Right Tibia Vertical**	***Right Initial Contact***

Right Loading Response

Right Mid-Stance

Right Terminal Stance

Right Pre-swing

Right Initial Swing

Right Mid-Swing

Right Terminal Swing

Double Support Time

Single Support Time

Double Support Time

Single Support Time

Step Time

Flight Time

Stance Phase

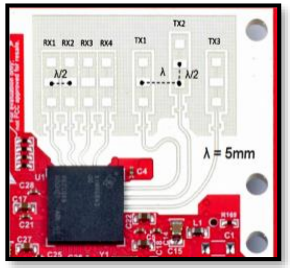
Swing Phase

Stride Time

Experiment #1: Treadmill

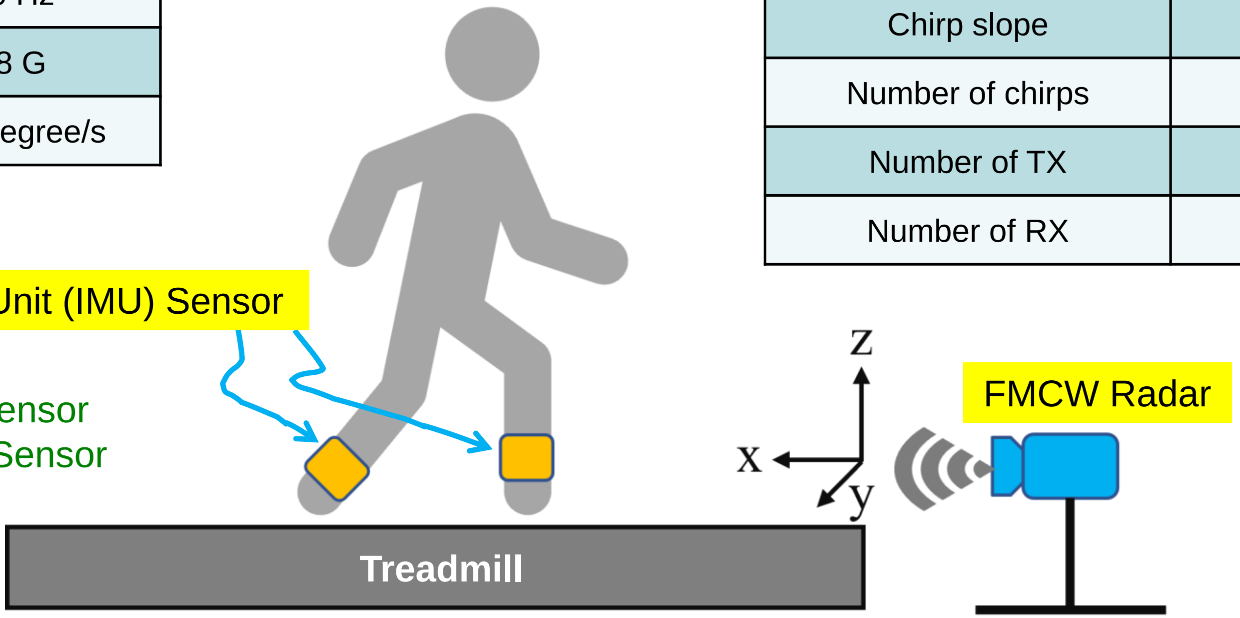
EBIMU-9DOFV5

IMU Chip Set	***EBIMU-9DOFV5***
Acceleration FPS	100 Hz
Angular velocity vector FPS	100 Hz
Absolute orientation FPS	100 Hz
Acceleration range	± 8 G
Angular velocity range	2000 degree/s



IWR6843 by TI

FMCW Chip Set	***TI IWR6843ISK***
Operating frequency	60 GHz
Sweep bandwidth	3.48 GHz
ADC sampling rate	2000 Ksps
Chirp slope	60 MHz/us
Number of chirps	128
Number of TX	2
Number of RX	4



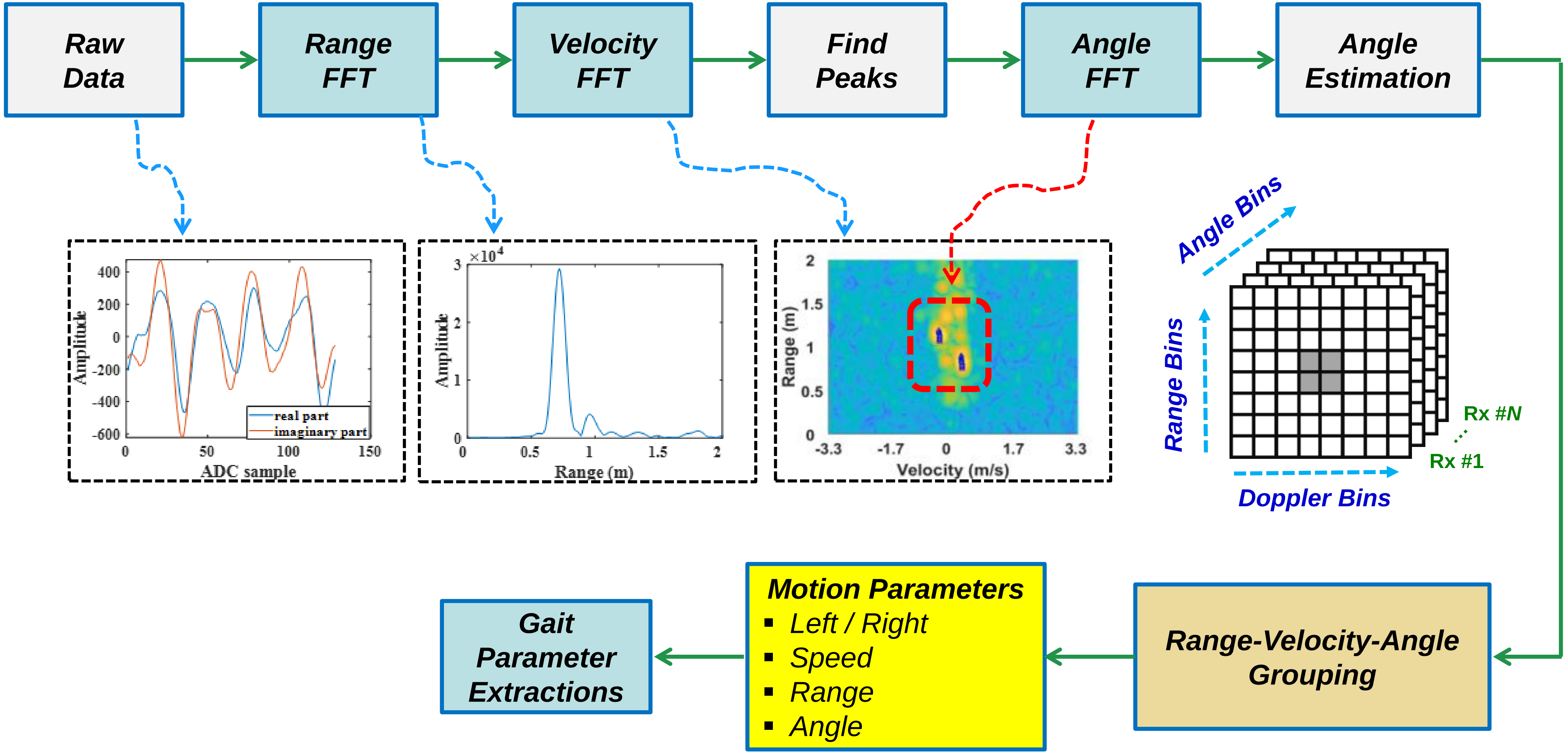
Inertial Measurement Unit (IMU) Sensor

- 3-axis Gyroscope
- 3-axis Acceleration Sensor
- 3-axis Geomagnetic Sensor

HOMETREKKING KSP-1201

Experiment #1: Extracting Gait Parameters by FMCW Radar

Nov. 07, 2024



Raw Data

Range FFT

Velocity FFT

Find Peaks

Angle FFT

Angle Estimation

Range-Velocity-Angle Grouping

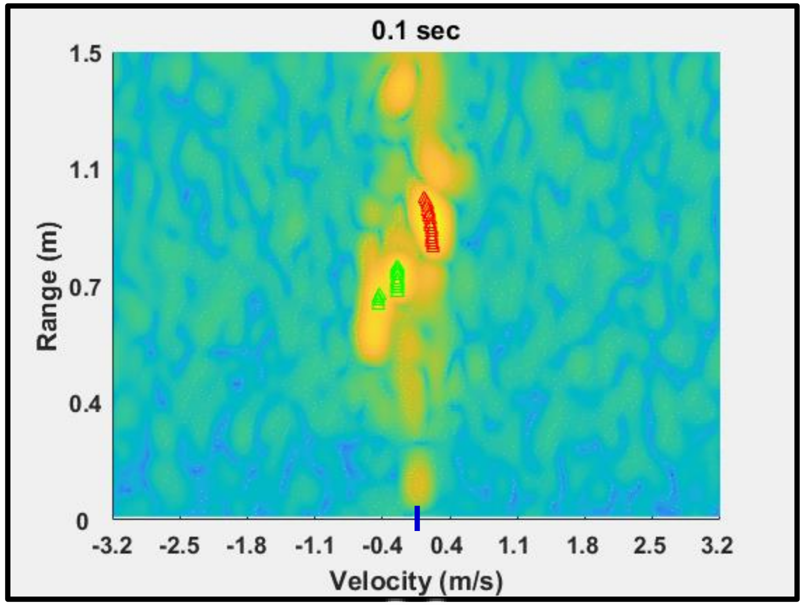
Motion Parameters

- *Left / Right*
- *Speed*
- *Range*
- *Angle*

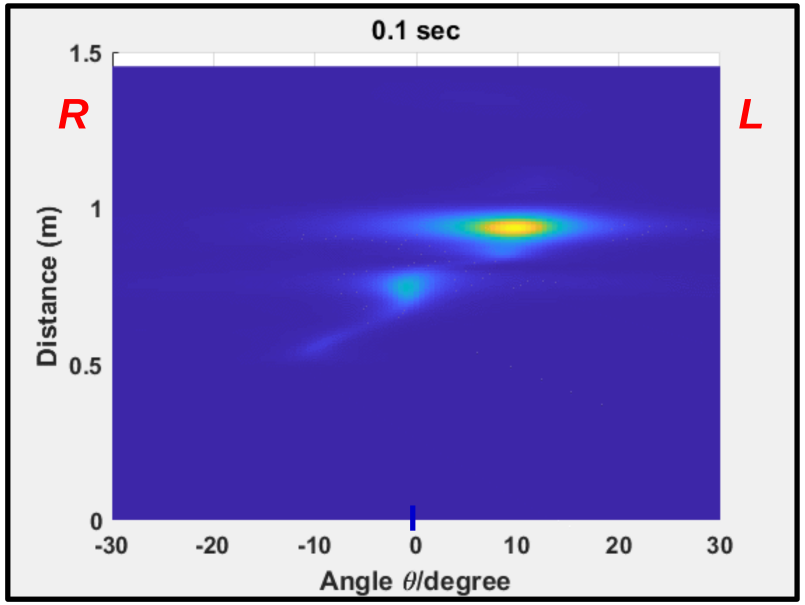
Gait Parameter Extractions

Experiment #1: Gait Cycle View

Range-Doppler Map



Range-Azimuth Map



Moving toward radar
(Negative)

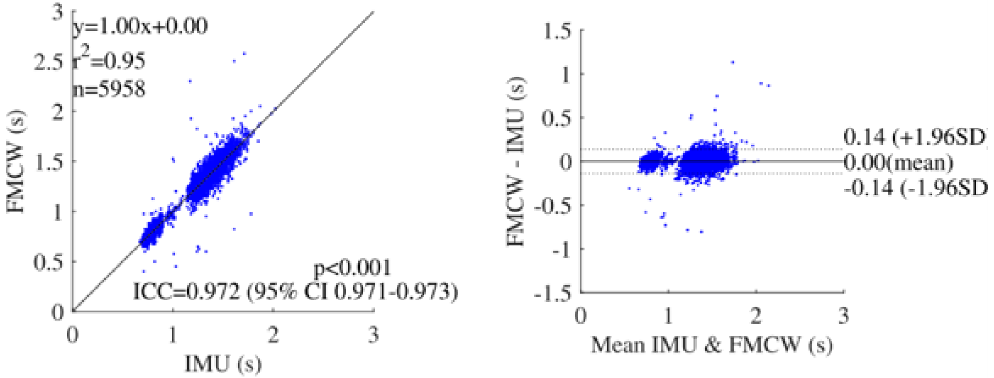
Moving away from radar
(Positive)

Experiment #1: Radar Performances (1/3)

❖ *Intraclass Correlations and Bland-Altman Plots (1/2)*

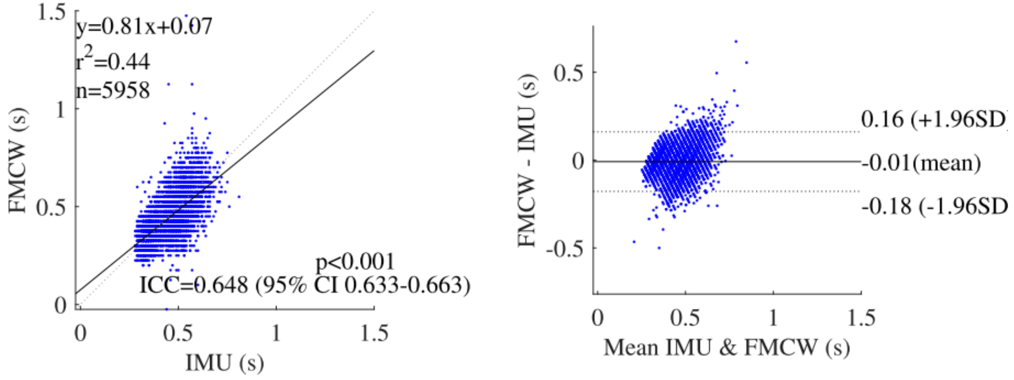
ICC = 0.972

Stride Time



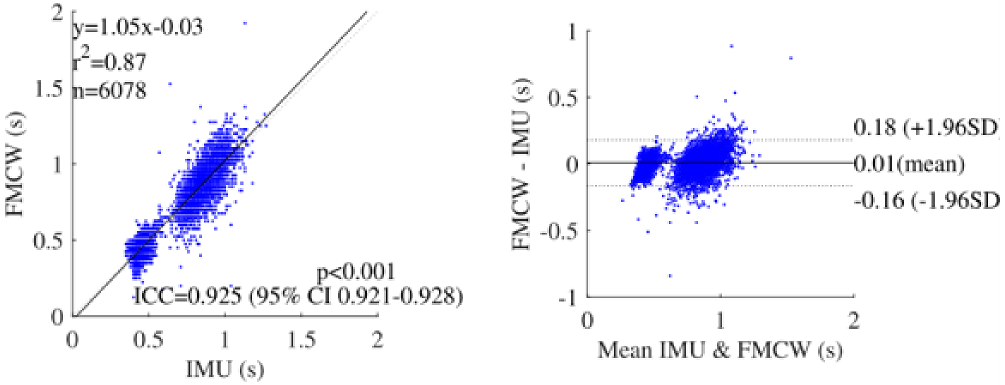
ICC = 0.648

Flight Time



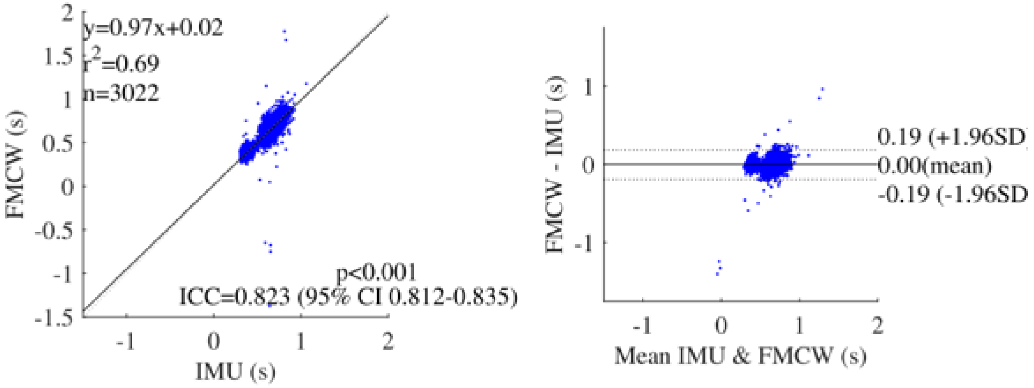
ICC = 0.925

Stance Time



ICC = 0.823

Step Time

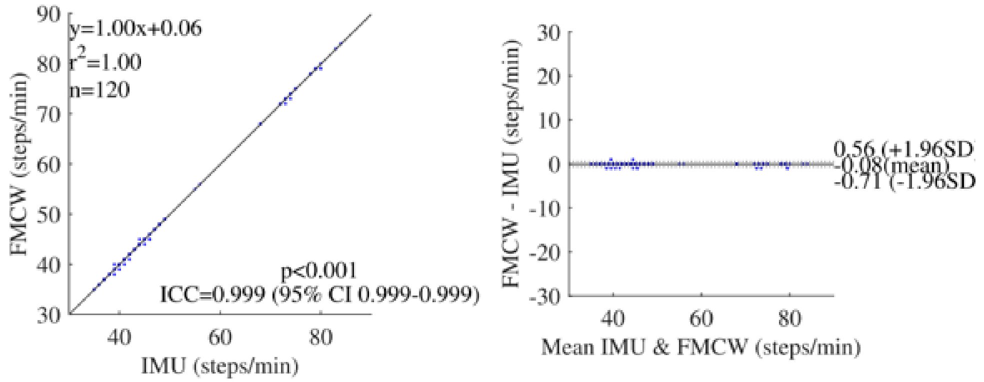


Experiment #1: Radar Performances (2/3)

❖ *Intraclass Correlations and Bland-Altman Plots (2/2)*

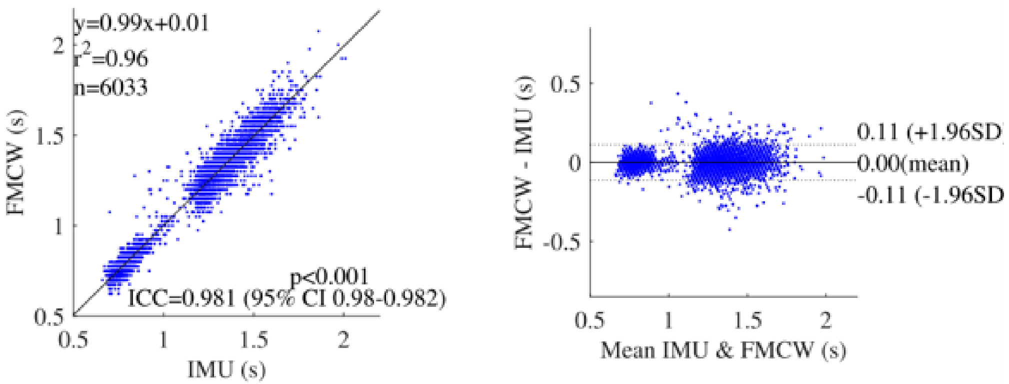
ICC = 0.999

Cadence



ICC = 0.981

Maximum Foot Velocity Interval



Experiment #1: Radar Performances (3/3)

- *Agreement between FMCW Radar and IMU Sensors*

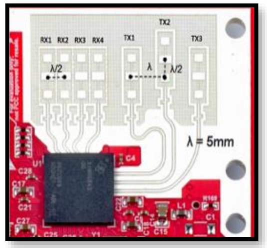
Gait Parameters	***ICC***	***Mean Bias***	***Upper LOA***	***Lower LOA***	***p-value***
Stride Time	0.972 (0.971-0.973)	0.00	0.14	-0.14	0.001
Average* Stride Time	0.999 (0.999-0.999)	0.00	0.00	0.00	0.001
Stance time	0.925 (0.921-0.928)	0.01	0.18	-0.16	0.001
Average* Stance Time	0.975 (0.964-0.982)	0.01	0.10	-0.07	0.001
Flight Time	0.648 (0.633-0.663)	-0.01	0.16	-0.18	0.001
Average* Flight Time	0.851 (0.794-0.894)	-0.01	0.07	-0.1	0.001
Step Time	0.823 (0.812-0.835)	0.00	0.19	-0.19	0.001
Average* Step Time	0.955 (0.927-0.973)	0.00	0.08	-0.08	0.001
Maximum Foot Velocity Interval	0.981 (0.980-0.982)	0.00	0.11	-0.11	0.001
Average* Maximum Foot Velocity Interval	0.999 (0.999-0.999)	0.00	0.00	0.00	0.001
Cadence	0.999 (0.999-0.999)	-0.08	0.56	-0.71	0.001

ICC: Intraclass Correlation Coefficient; *CI*: Confidence Interval; *LOA*: Limit of Agreement
*Average**: average of each gait parameter for each subject

Experiment #2: Daily Home Use

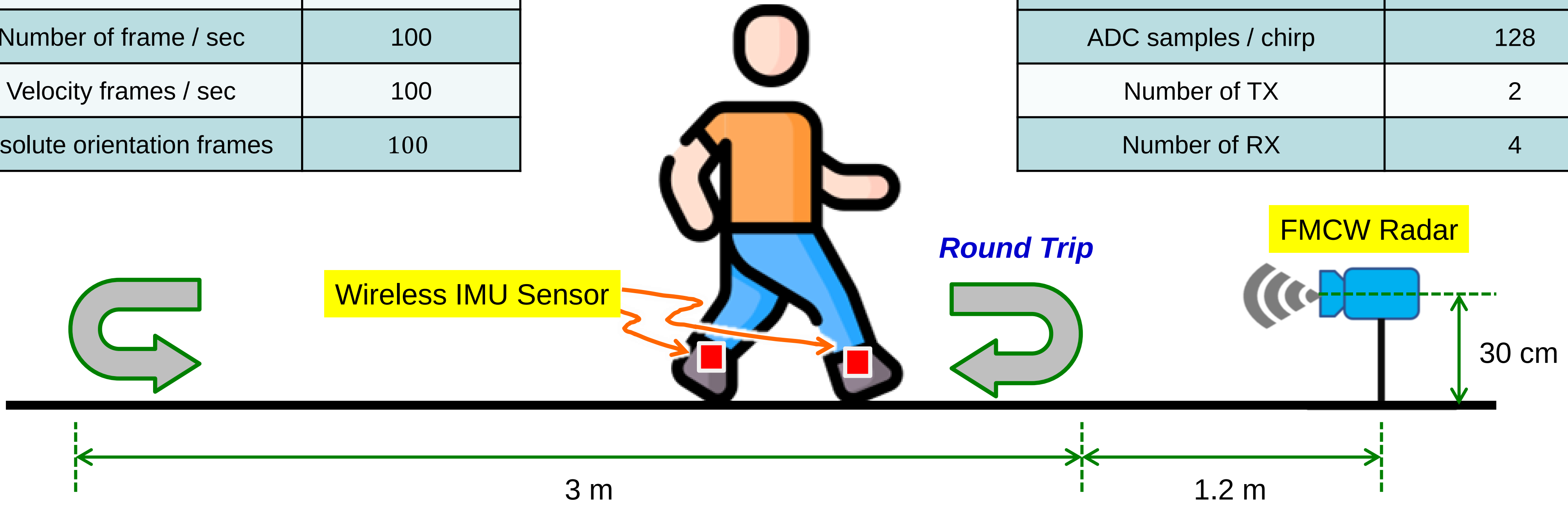
EBIMU24GV5

IMU Chip Set	*EBIMU-9DOFV5*
Frequency	2.4 GHz
Number of frame / sec	100
Velocity frames / sec	100
Absolute orientation frames	100



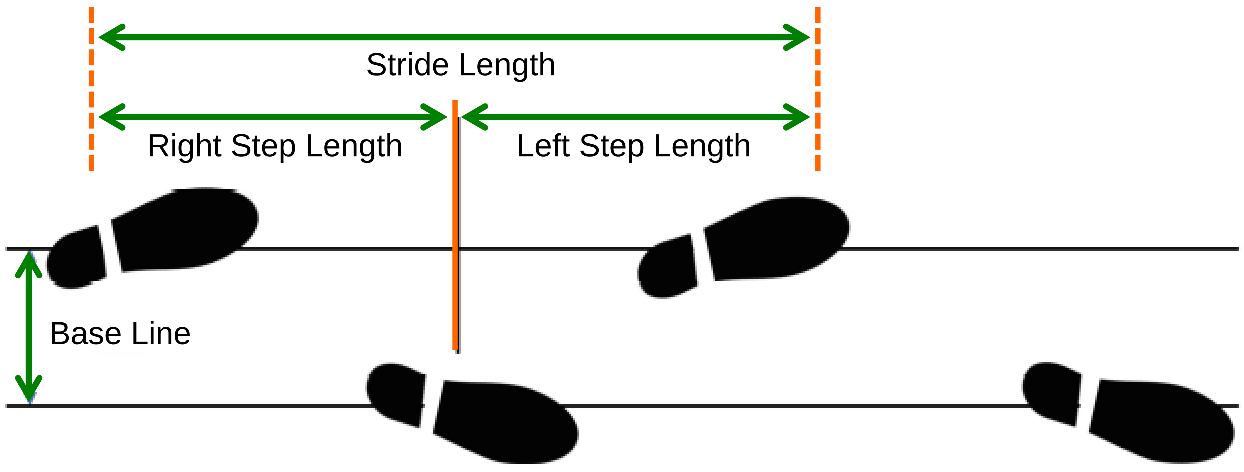
IWR6843 by TI

FMCW Chip Set	*TI IWR6843ISK*
Operating frequency	60 GHz
Sweep bandwidth	3.98 GHz
Number of frames / sec	20
Number of chirps / frame	64
ADC samples / chirp	128
Number of TX	2
Number of RX	4



Experiment #2: Gait Parameters of Interest

- *6 Gait Parameters:*
  - Step time
  - Step distance
  - Instantaneous step velocity
  - Pause time between steps
  - Step distance variations
  - Step time variations



- *Consider two walking patterns:*
  - Normal walk
  - Artificial abnormal walk

Normal Walk

Artificial Abnormal Walk

Experiment #2: Design Strategy

- *For each frame, we perform*

Raw Data → *Range FFT* → *Clutter Removal* → *Doppler FFT* → *2D Radar Array (Range-Velocity)* → *3D Radar Arrays (Range-Velocity-Time)* →

Gait Parameter Extraction

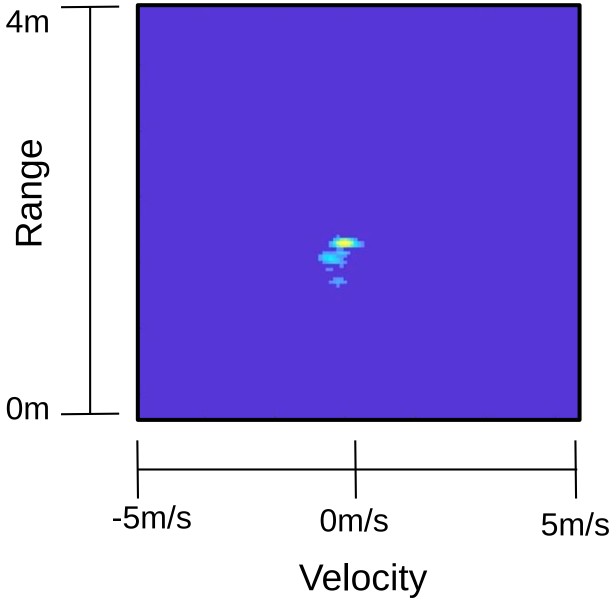
- *Step distance*
- *Step time*
- *Instantaneous step velocity*

- *Pause time between steps*
- *Step distance variations*
- *Step time variations*

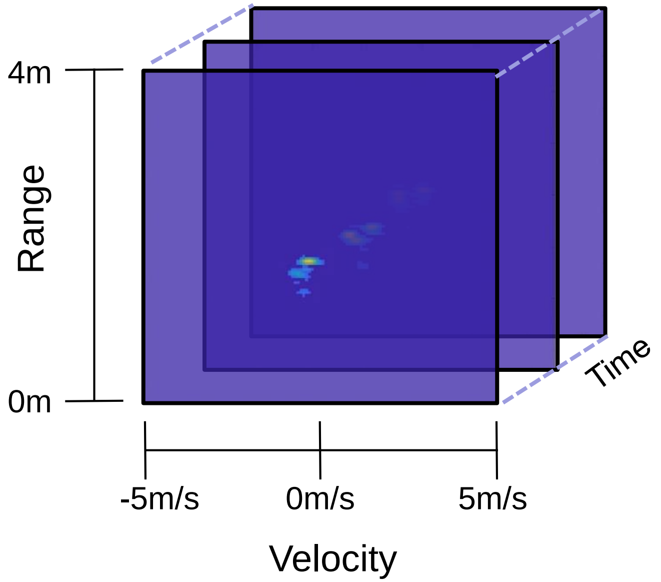
↓

- ***Gait Stability Evaluation***
- ***Gait Symmetry Evaluation***

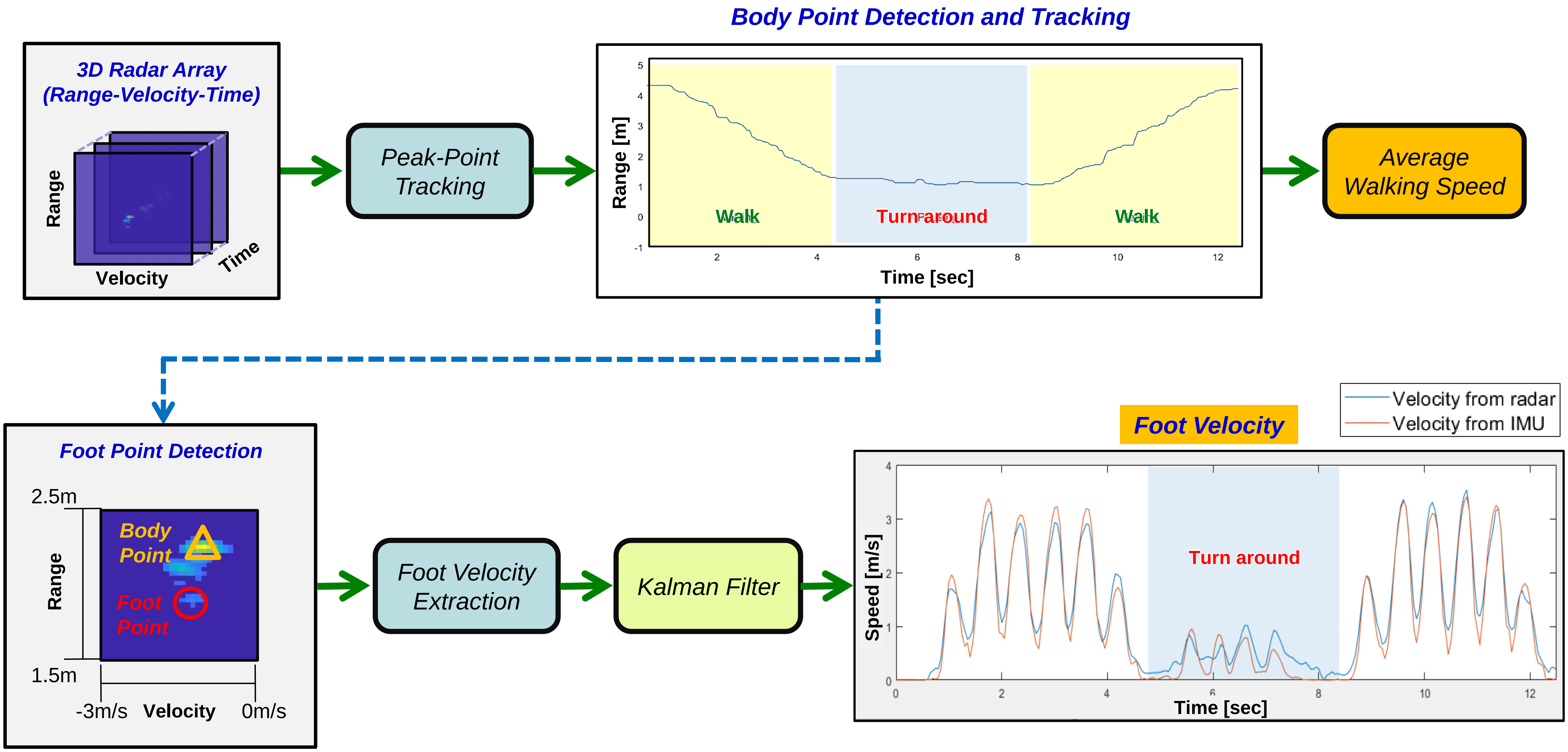
2D Radar Array (Range-Velocity)



3D Radar Arrays
(Range-Velocity-Time)



Experiment #2: Tracking the Body Point & Foot Velocity



3D Radar Array (Range-Velocity-Time)

Peak-Point Tracking

Body Point Detection and Tracking

Average Walking Speed

Foot Point Detection

Foot Velocity Extraction

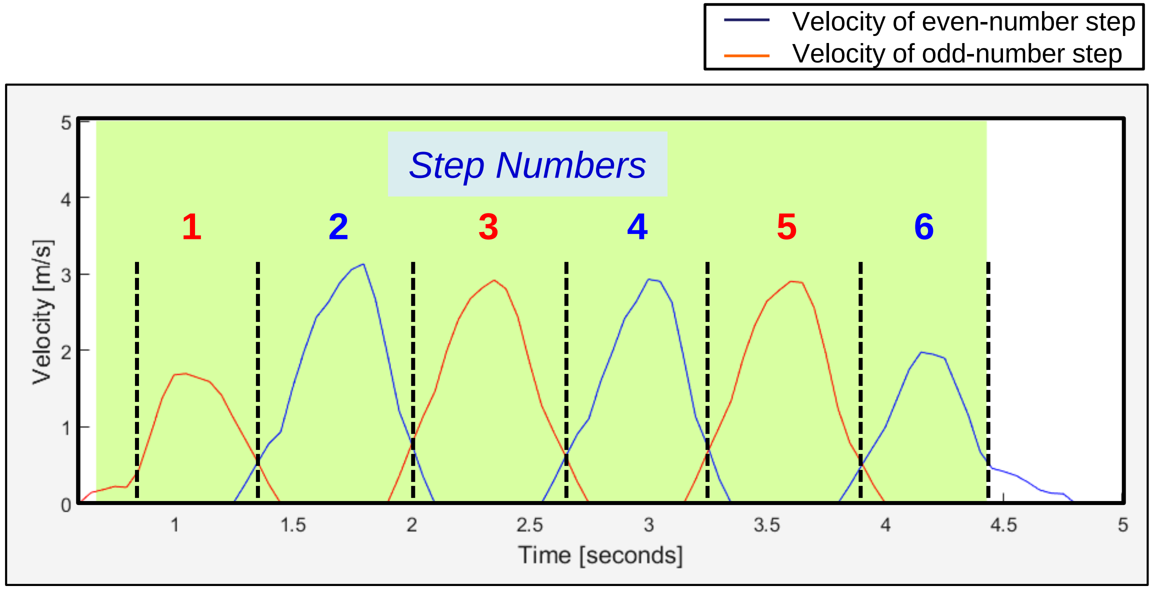
Kalman Filter

Foot Velocity

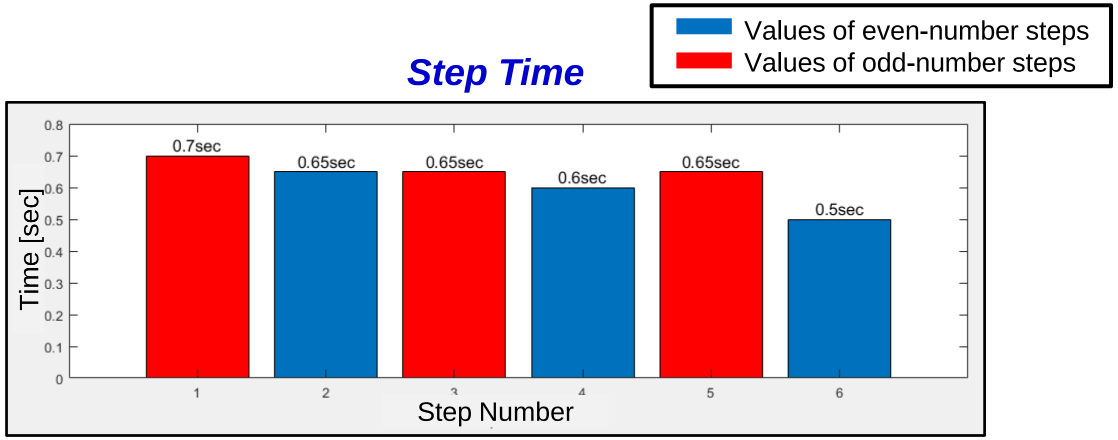
Nov. 07, 2024

Experiment #2: Gait Parameter Extraction (1/2)

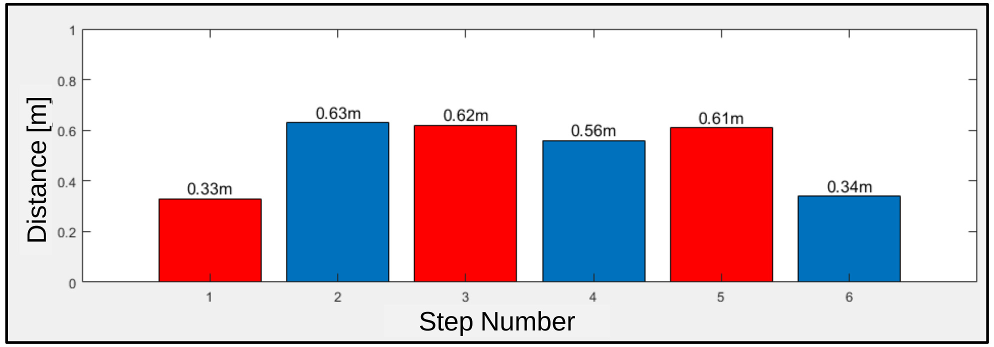
Separation of Even- and Odd-Number Steps



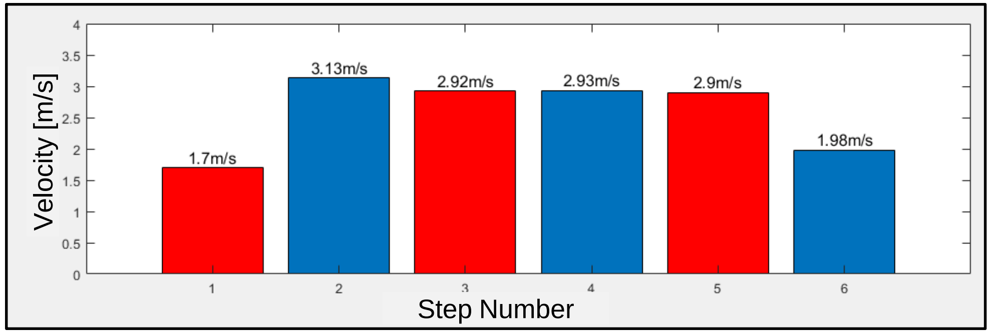
Step Time



Step Distance

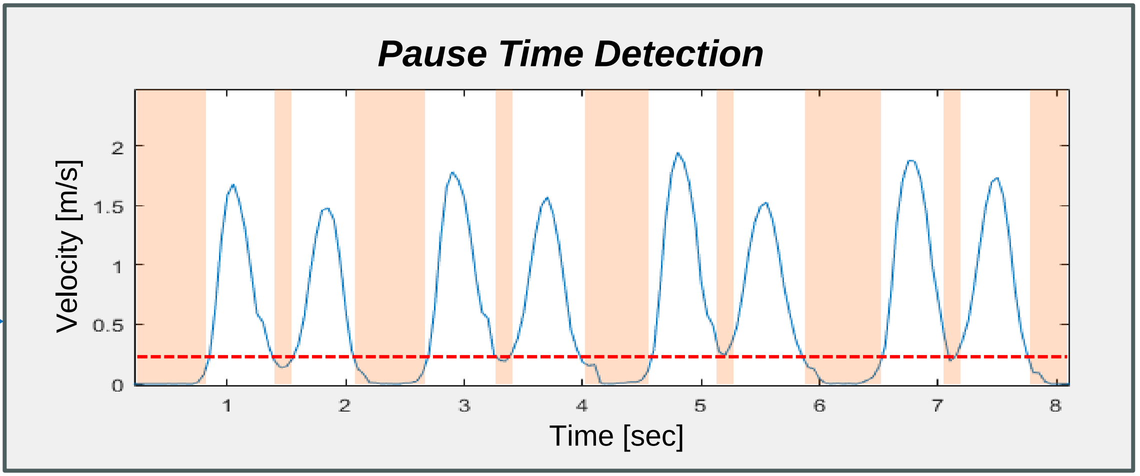


Instantaneous Step Velocity



Experiment #2: Gait Parameter Extraction (2/2)

Foot Velocity Extraction → *Thresholding* →


Pause Time Detection

Pause Time [sec]								
0.8	0.13	0.81	0.11	0.62	0.12	0.73	0.13	0.59

Step Time → *Step Time Variation* →

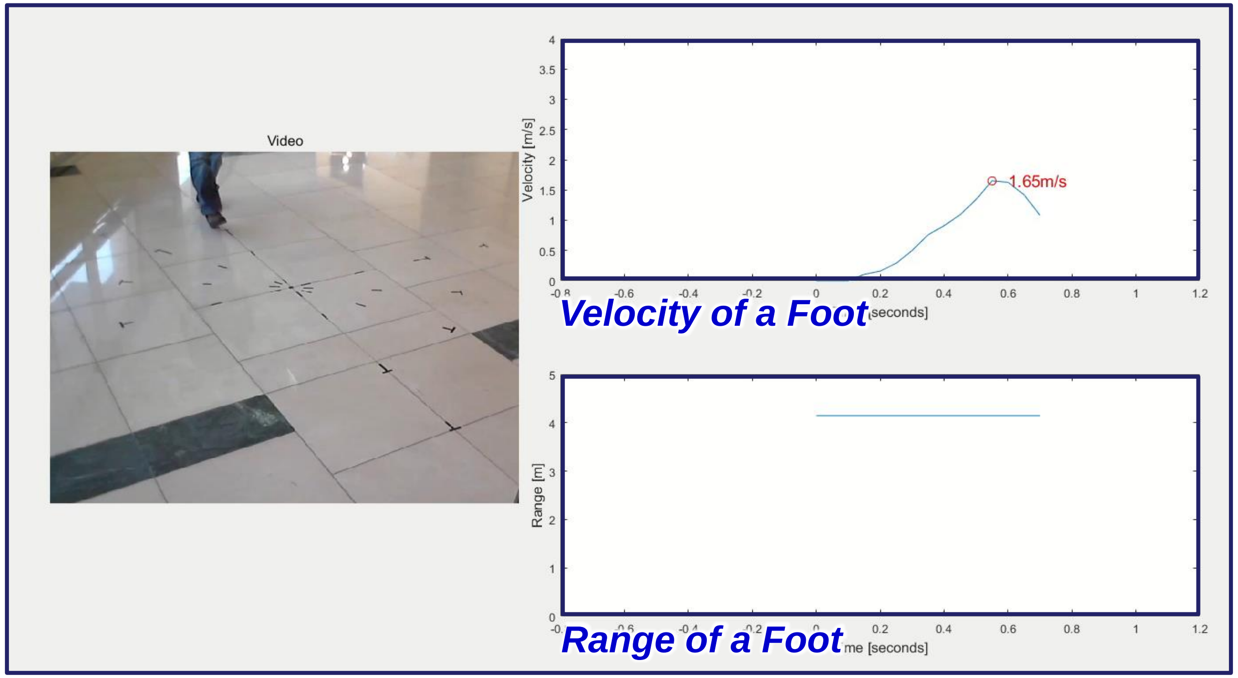
Step Times Variation [sec]						
$\mathbf{Variation}_{Time} = \lvert \mathbf{StepTime}_{current} - \mathbf{StepTime}_{previous} \rvert$						
0.08	0.06	0.05	0.13	0.12	0.09	0.07

Step Distance → *Step Distance Variation* →

Step Distance Variation [m]						
$\mathbf{Variation}_{Distance} = \lvert \mathbf{StepDistance}_{current} - \mathbf{StepDistance}_{previous} \rvert$						
0.06	0.02	0.07	0.09	0.04	0.05	0.06

Experiment #2: Walking Pattern Example

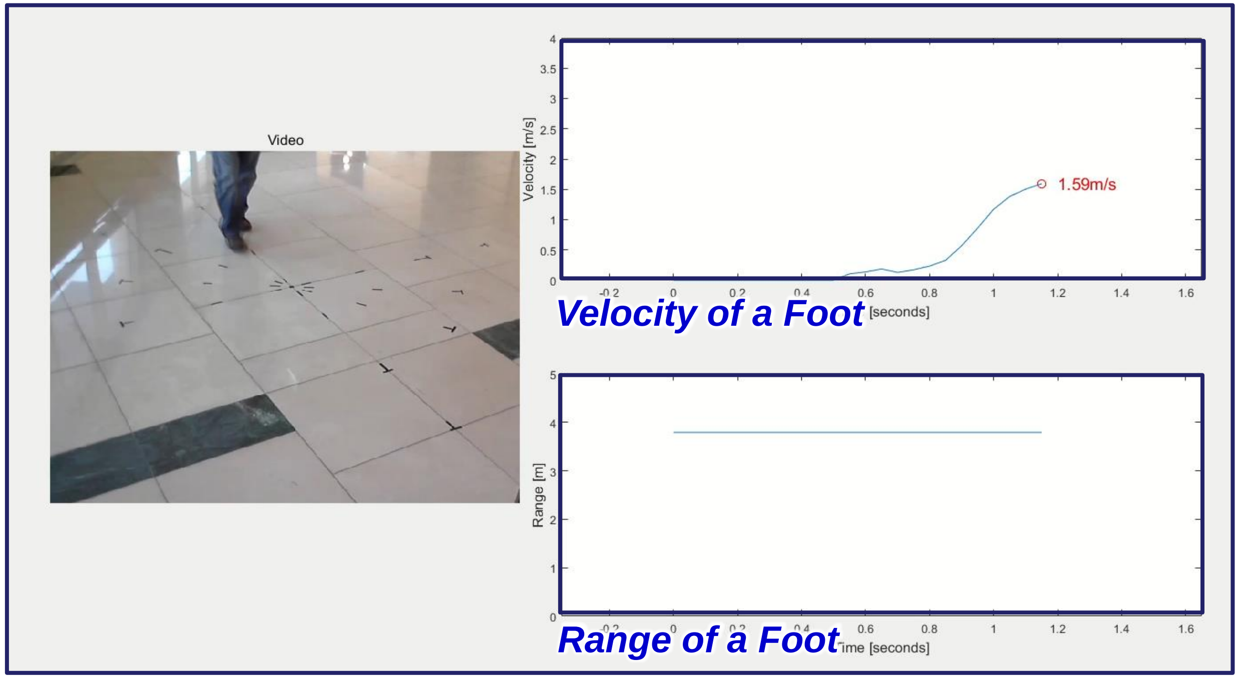
Normal Walk



Velocity of a Foot

Range of a Foot

Abnormal Walk

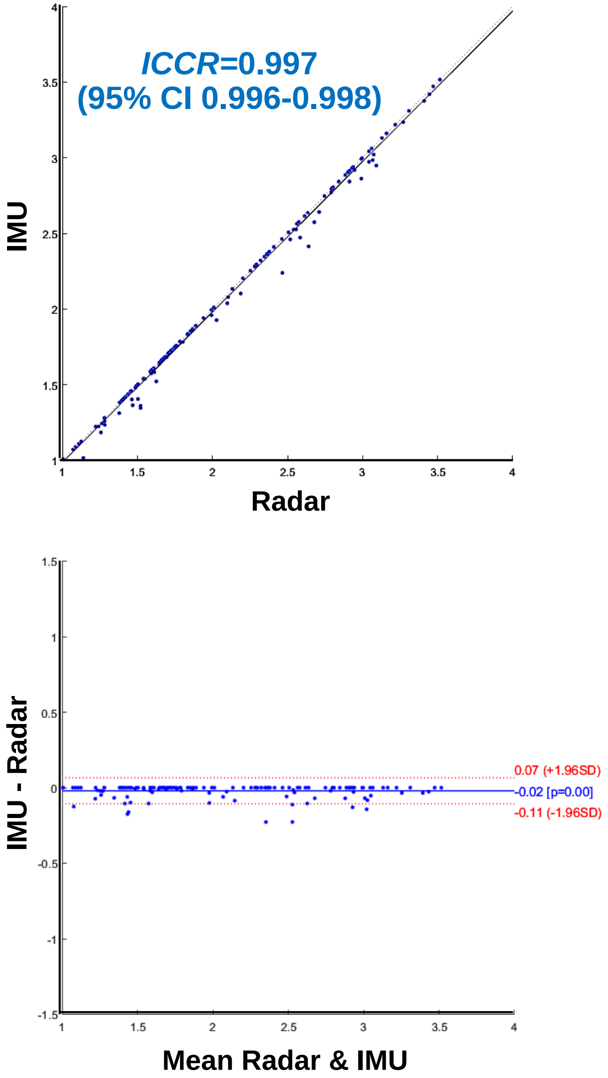


Velocity of a Foot

Range of a Foot

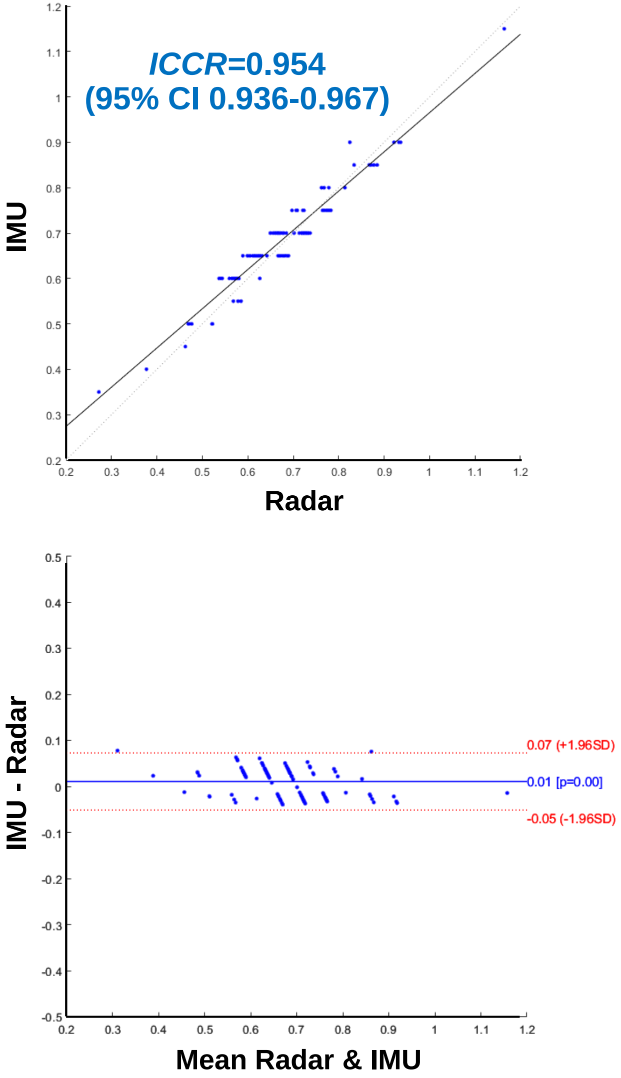
Experiment #2: Radar Performance

Instantaneous velocity



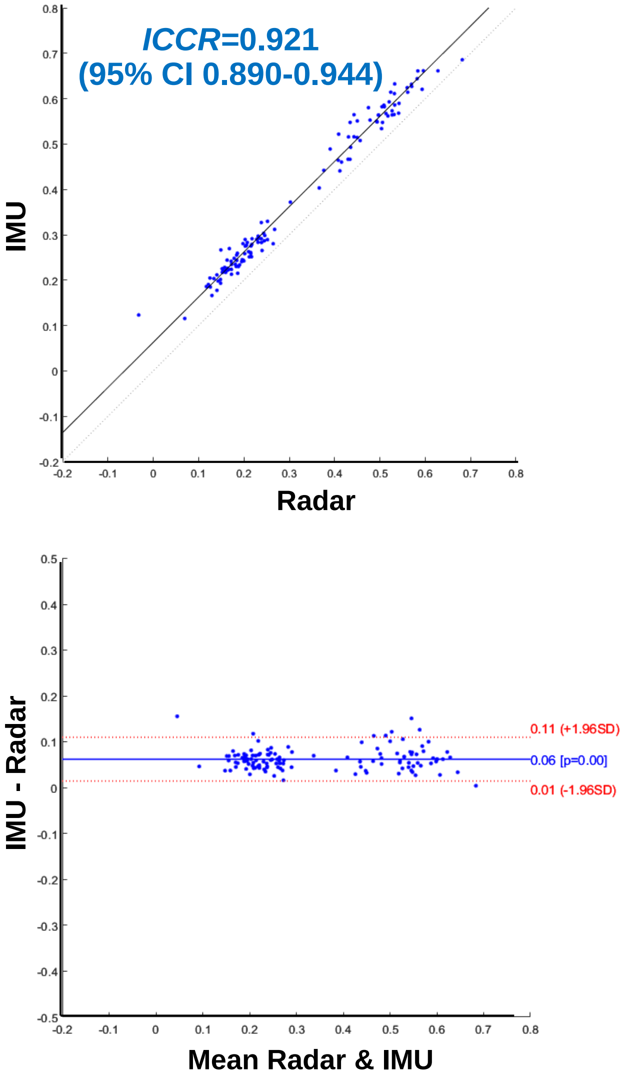
ICCR=0.997
(95% CI 0.996-0.998)

Step Time



ICCR=0.954
(95% CI 0.936-0.967)

Step Distance



ICCR=0.921
(95% CI 0.890-0.944)

Experiment #2: Evaluation of Gait Instability and Asymmetry

- *Gait Instability:*

$$\text{Gait}_{instability} = \frac{1}{N}\sum_{k=1}^{N} P_k$$

- N = *Number of steps*
- P_k = *Gait parameter values of the* k^{th} *step*

- *Gait Asymmetry:*

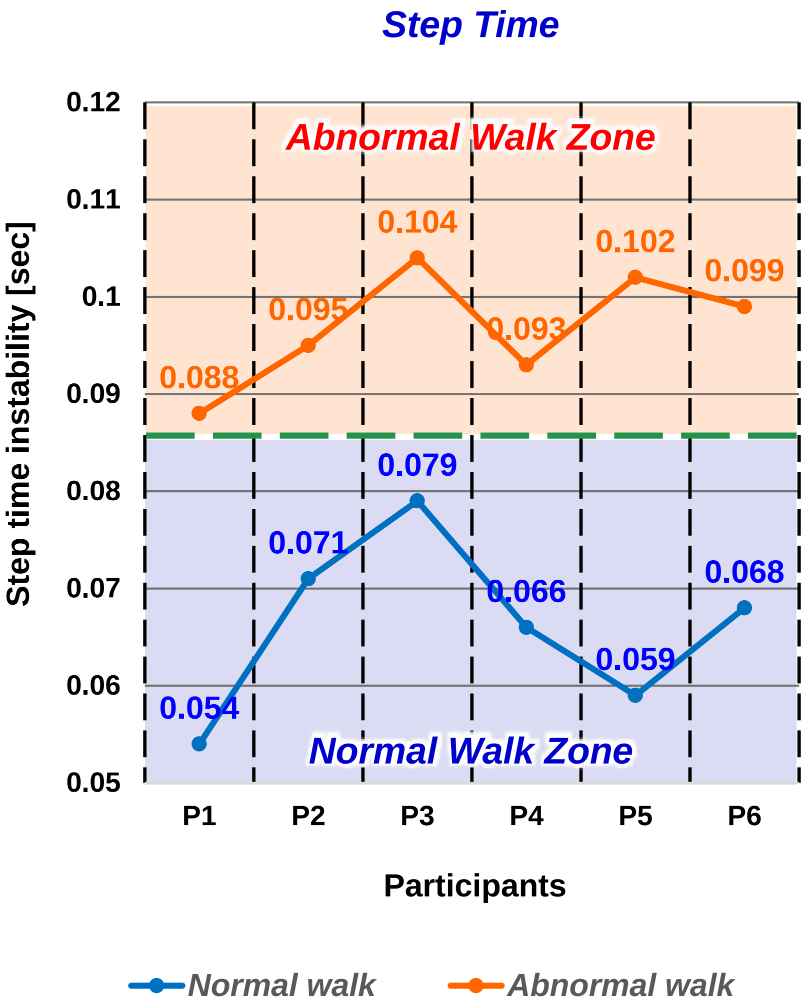
$$\text{Gait}_{asymmetry} = \frac{1}{N-1}\sum_{k=1}^{N-1} D_k$$

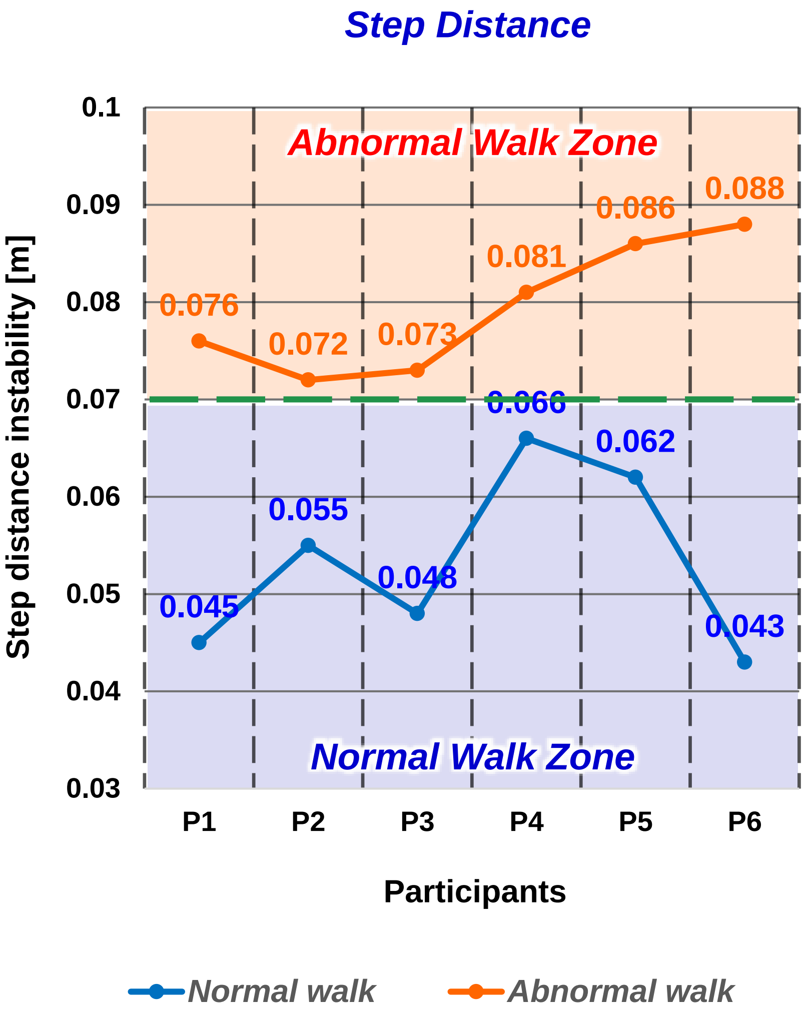
- N = *Number of steps*
- $D_k = |P_{k+1} - P_k|$ *(Difference between the* k^{th} *and* $(k+1)^{th}$ *gait parameters)*

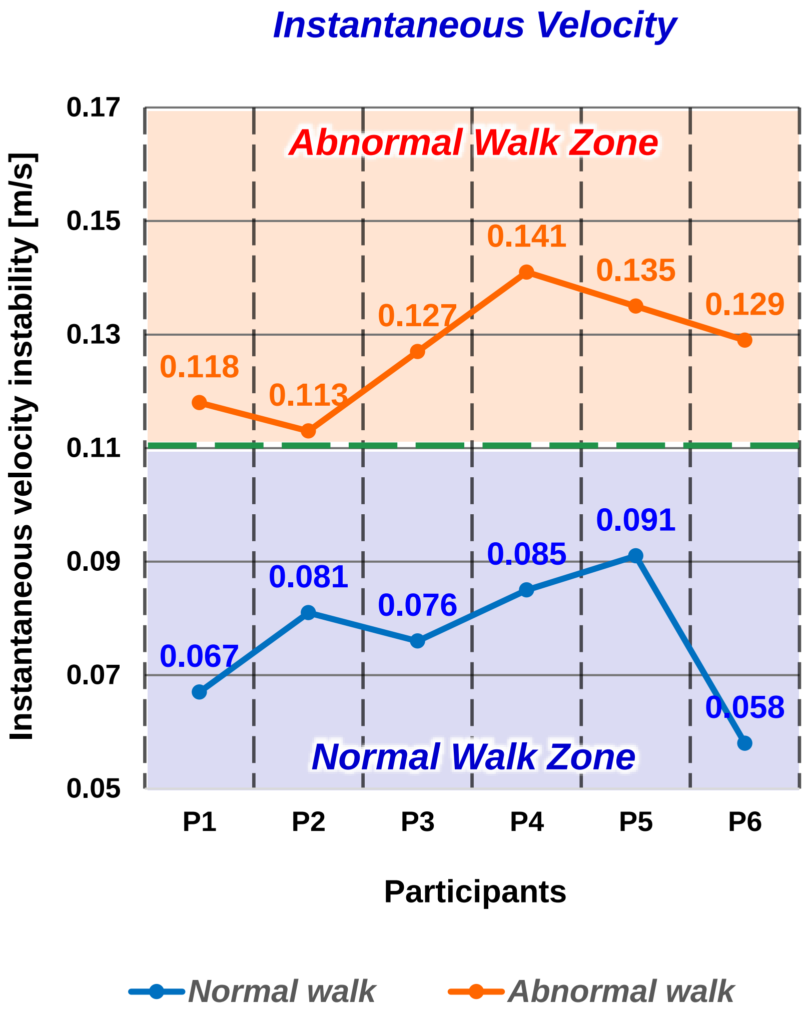
- *N = 60 (6 Steps x 10 Independent Trials) for Each Participant*

Nov. 07, 2024

Experiment #2: Gait Instability

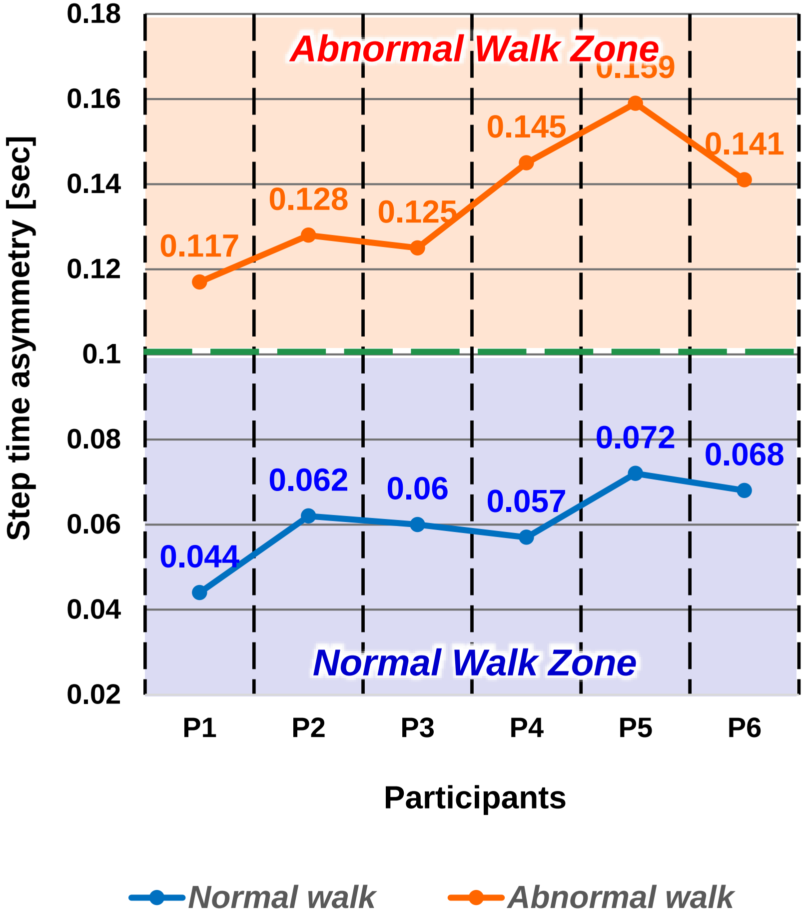

Step Time


Step Distance

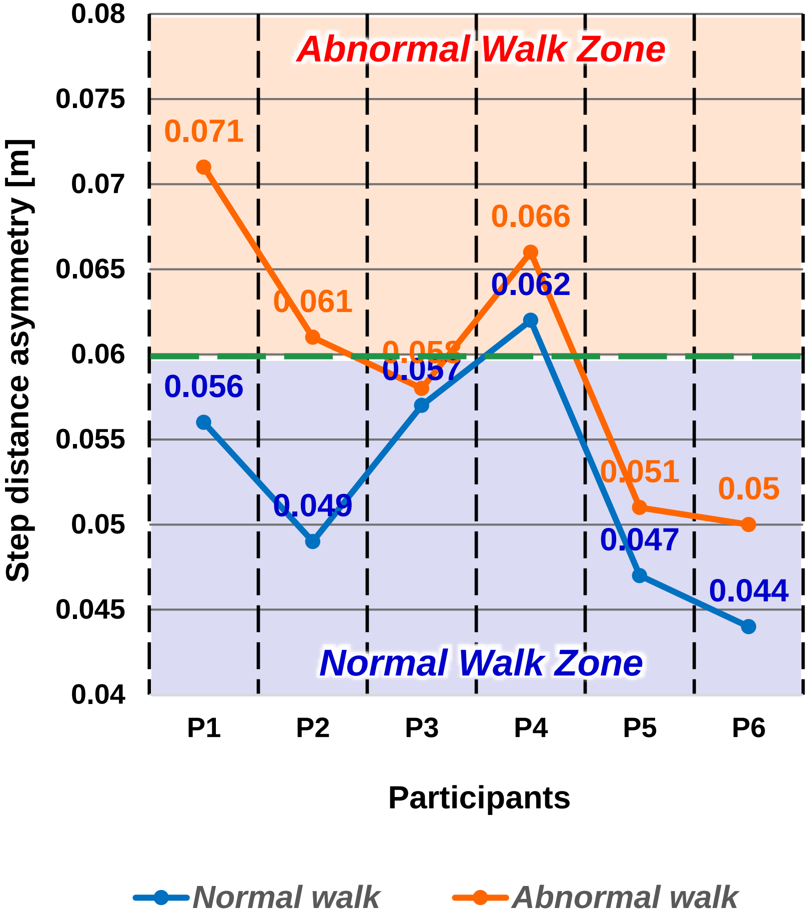

Instantaneous Velocity

Experiment #2: Gait Asymmetry

Step Time

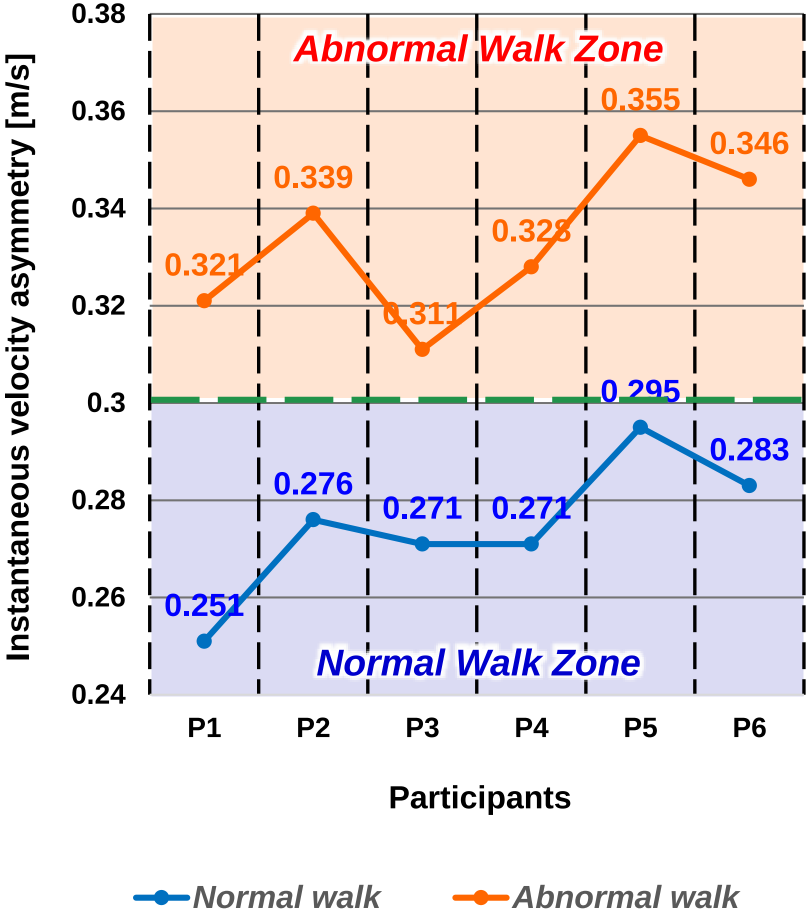


Step Distance



Not suitable for gait asymmetry evaluation.

Instantaneous Velocity



Human Posture Classification

- “Distance and Angle Insensitive Radar-Based Multi-Human Posture Recognition using Deep Learning,” *Sensors*, Oct. 2024. (Under review)
- “Advancements in Radar Point Cloud Processing for Macro Human Movements in Healthcare and Assisted Living Domains: A Review,” *IEEE Sensors Journal*, Oct. 2024.

Data Collection

Early Screening:

- Dementia
- Movement disorders
- Depression
- Stress / Anxiety
- Chronic asthma
- Chronic pain

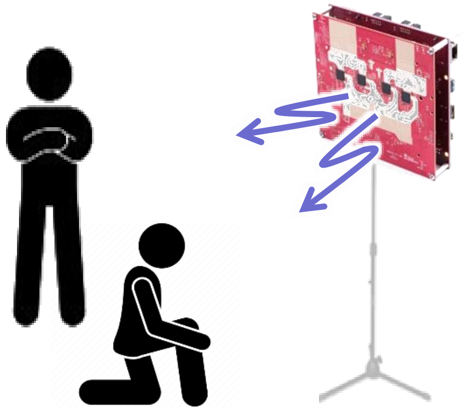
Emergency in Elderly:

- Lonely death
- Fall detection / prevention

Sleep Monitoring:

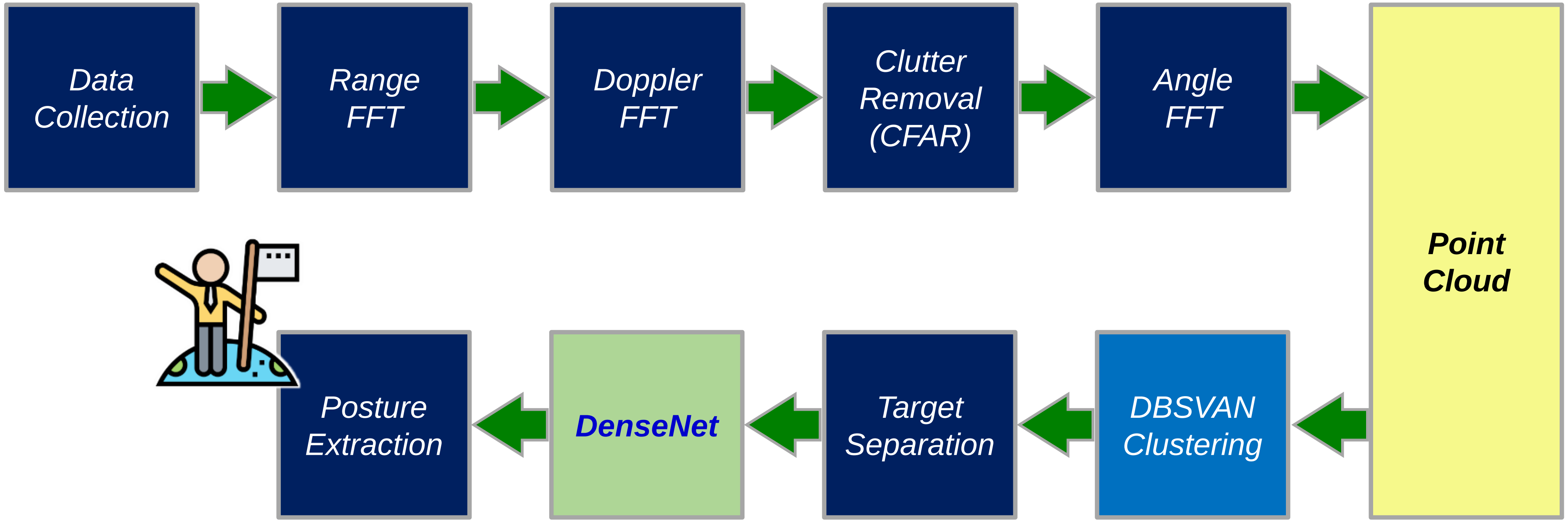
- Sleep efficiency
- Chronic insomnia

Design Strategy



MIMO FMCW Radar

Two-Person Scenario



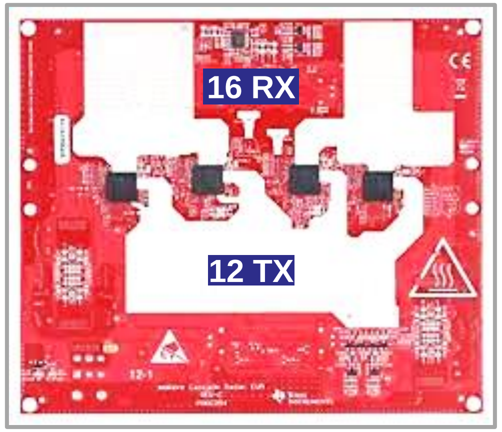
Data Collection → *Range FFT* → *Doppler FFT* → *Clutter Removal (CFAR)* → *Angle FFT* → ***Point Cloud***

Point Cloud → *DBSVAN Clustering* → *Target Separation* → ***DenseNet*** → *Posture Extraction*

Data Collection

AWR2243 Cascade Radar

- Operating Frequency: 76GHz – 81GHz
- Bandwidth: 5GHz
- No. of TX Antennas: 12
- No. of RX Antennas: 16
- Virtual Azimuth Antennas: 86
- Virtual Elevation Antennas: 4
- Field of View: ±60^{o}



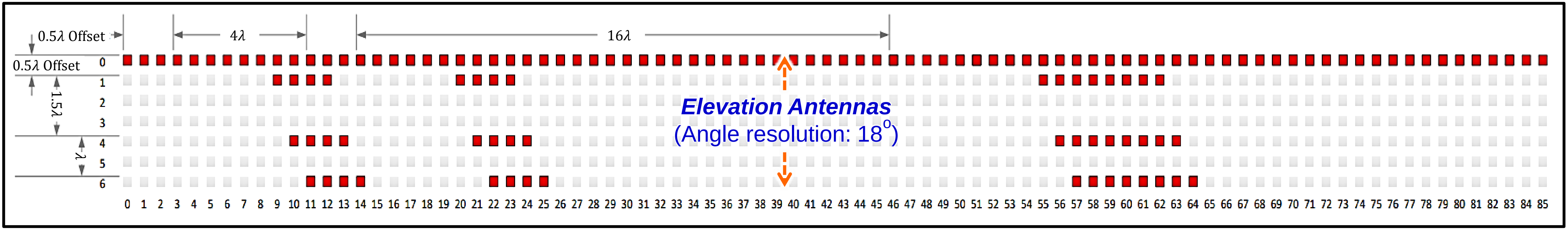
Virtual Antenna Array

86 X 4

(134 antenna elements are used.)

Azimuth Antennas

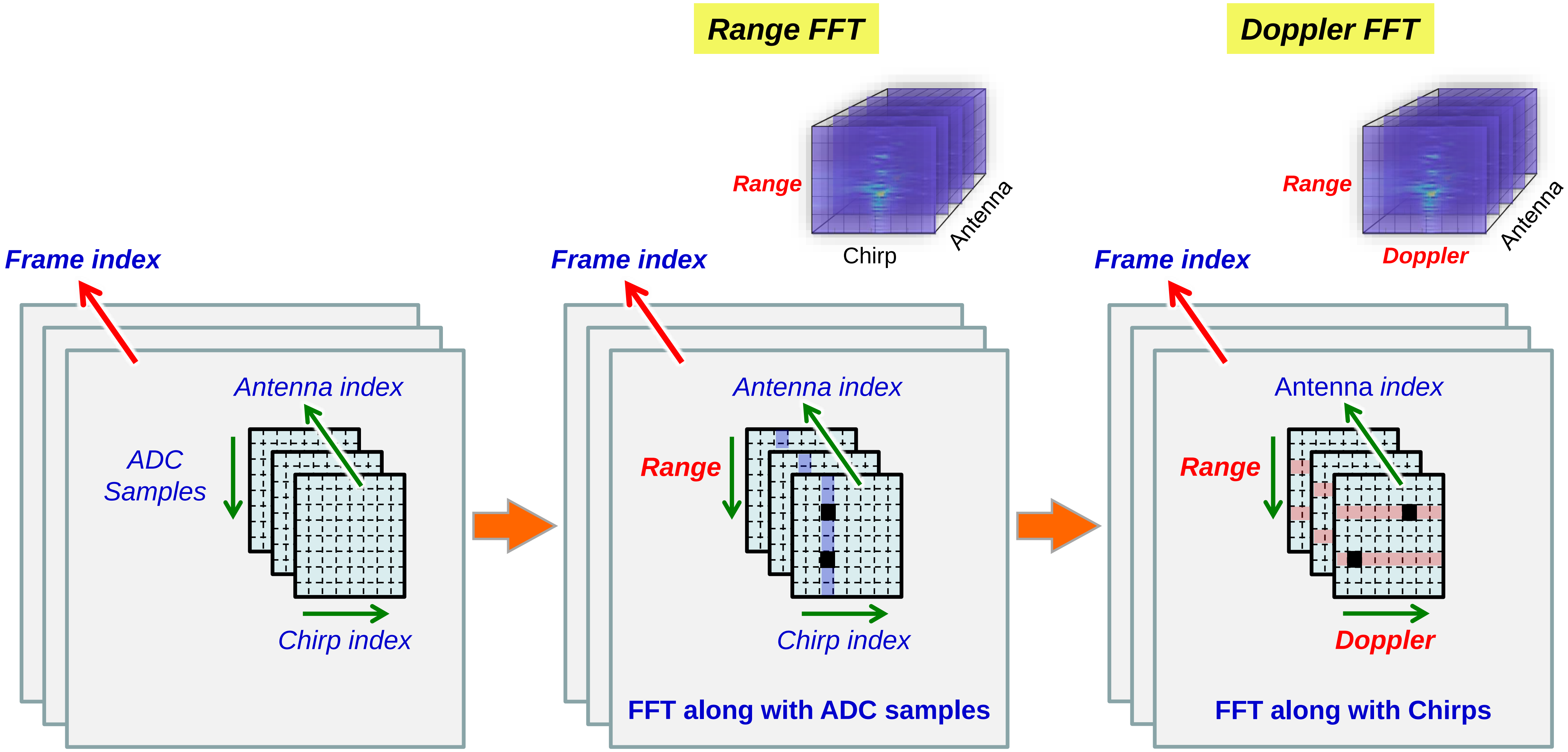
(Angle resolution: 1.4^{o})



Elevation Antennas

(Angle resolution: 18^{o})

Range and Doppler FFTs

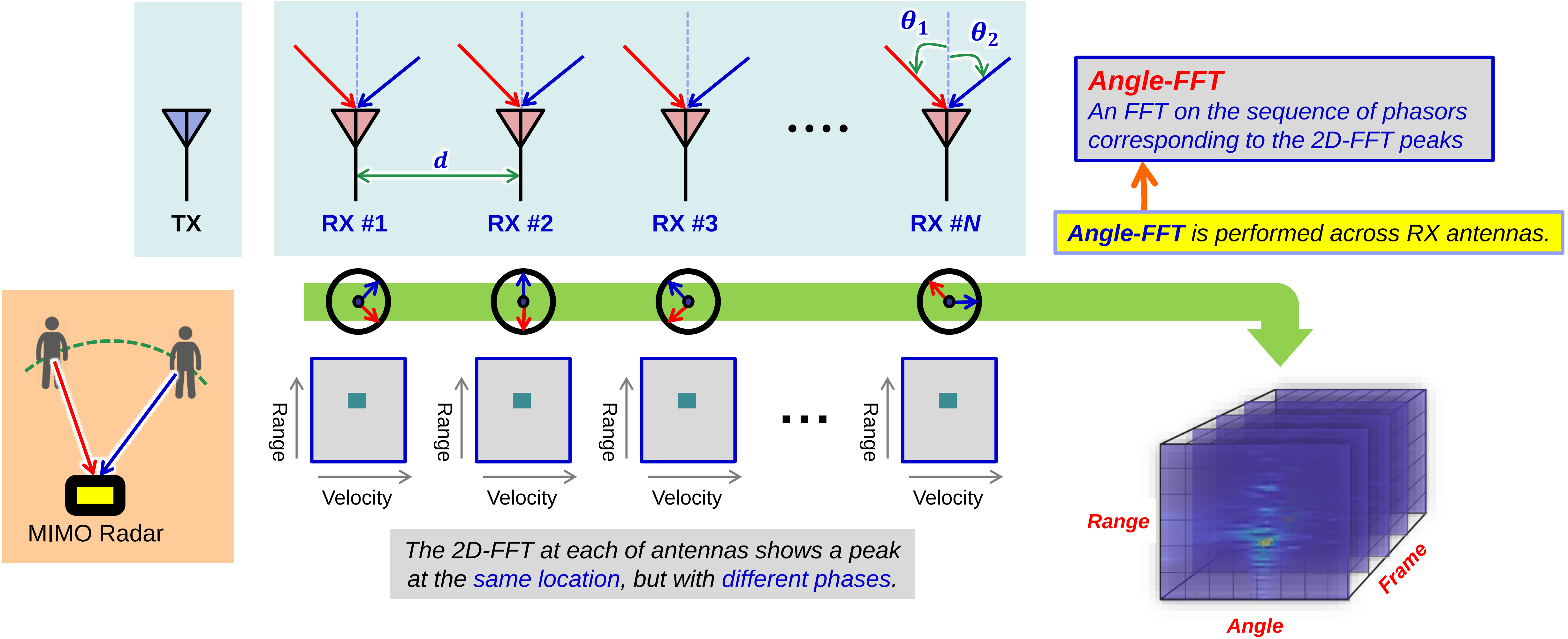


Distance to Target

Target Velocity

Angle FFT

- *Angle of Arrival (AoA) of Multiple Targets*



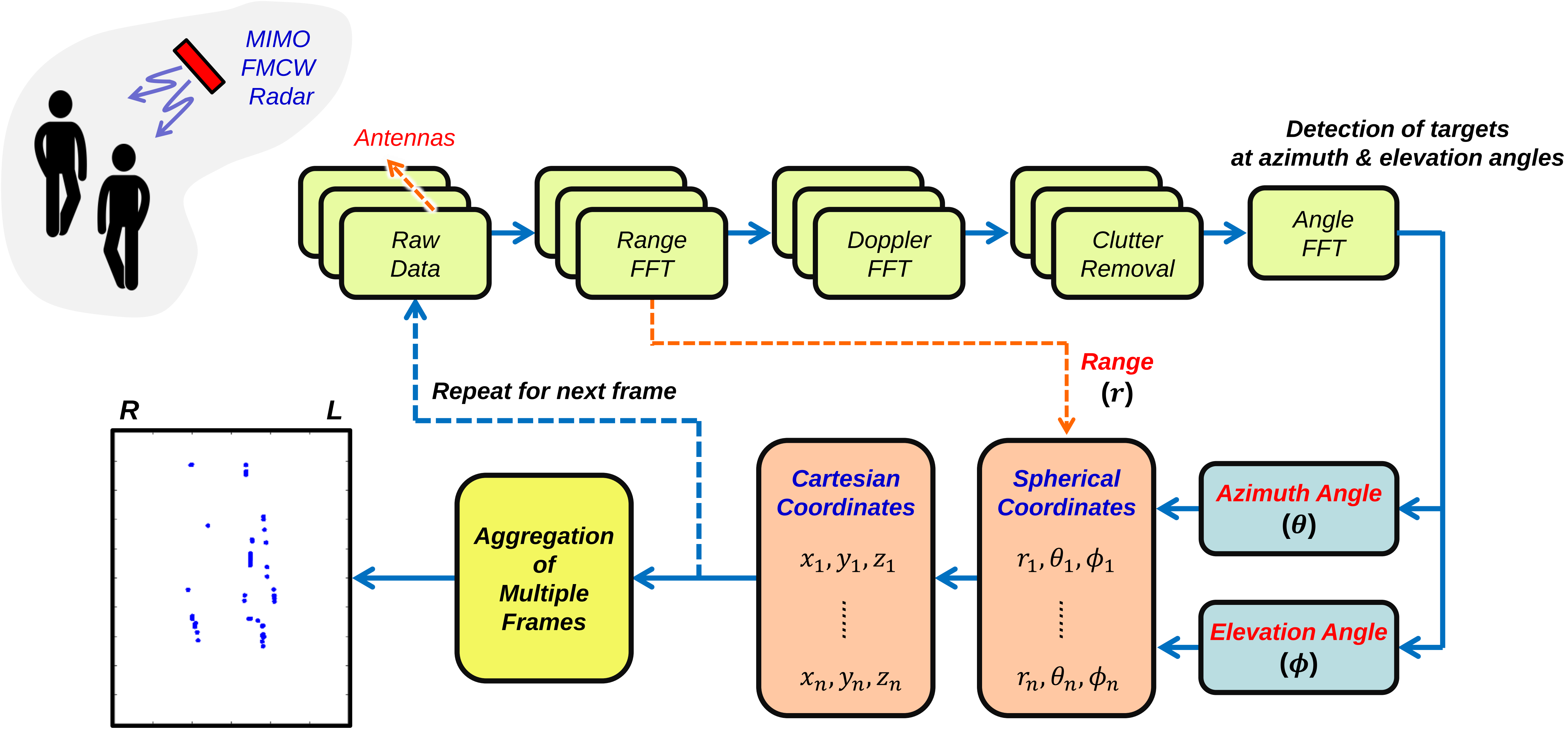
Angle-FFT
An FFT on the sequence of phasors corresponding to the 2D-FFT peaks

***Angle-FFT** is performed across RX antennas.*

The 2D-FFT at each of antennas shows a peak at the same location, but with different phases.

Point Cloud

Nov. 07, 2024



MIMO FMCW Radar

Antennas

Raw Data → Range FFT → Doppler FFT → Clutter Removal → Angle FFT

Detection of targets at azimuth & elevation angles

Range (r)

Azimuth Angle (θ)

Elevation Angle (ϕ)

Spherical Coordinates

r_1, θ_1, ϕ_1

$\vdots$

r_n, θ_n, ϕ_n

Cartesian Coordinates

x_1, y_1, z_1

$\vdots$

x_n, y_n, z_n

Aggregation of Multiple Frames

Repeat for next frame

n: number of detected target points

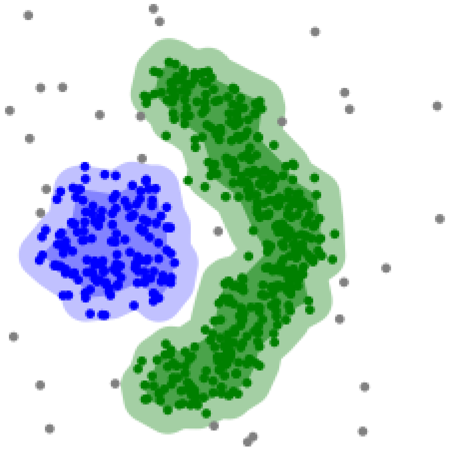
DBSCAN Clustering

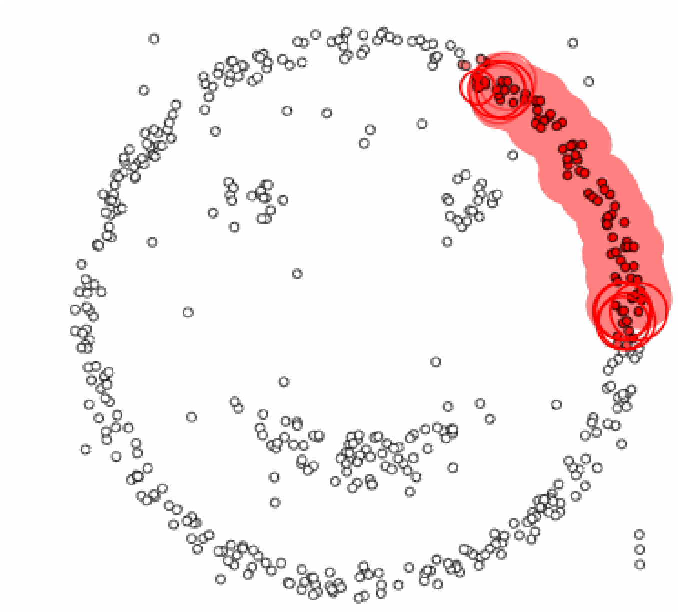
- *Density-Based Spatial Clustering of Applications with Noise (DBSCAN)*

- *DBSCAN groups points together based on density*

- *Key Parameters*
  - *Maximum radial distance between two points* (ε)
  - *Minimum number of points* (*MinPts*)

- *Key Features:*
  - *Ability to remove outliers*
  - *Ability to detect multiple targets* within one frame
  - Ability to detect noise
  - No need to specify number of clusters
  - No overlap among clusters
  - Ability to handle clusters of arbitrary shapes





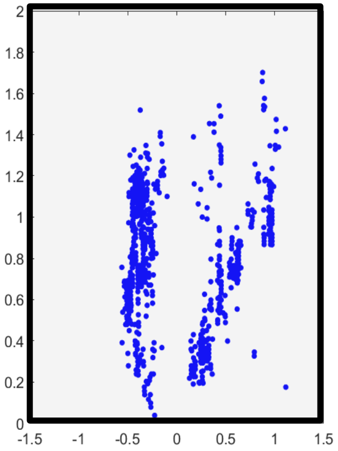
$\varepsilon = 1.00$

MinPts = 4

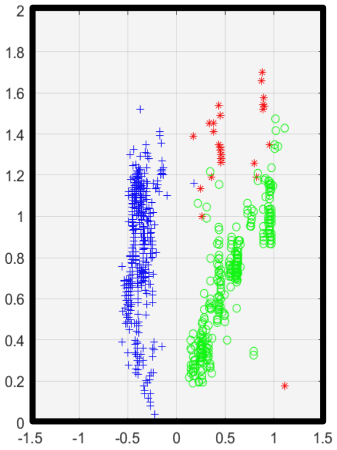
https://miro.medium.com/v2/1*tc8UF-h0nQqUfLC8-0uInQ.gif

Target Separation

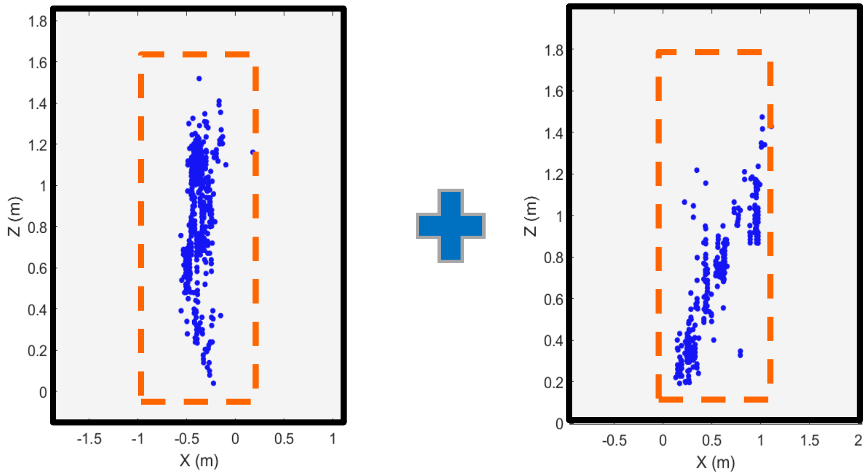
Before Clustering



After Clustering

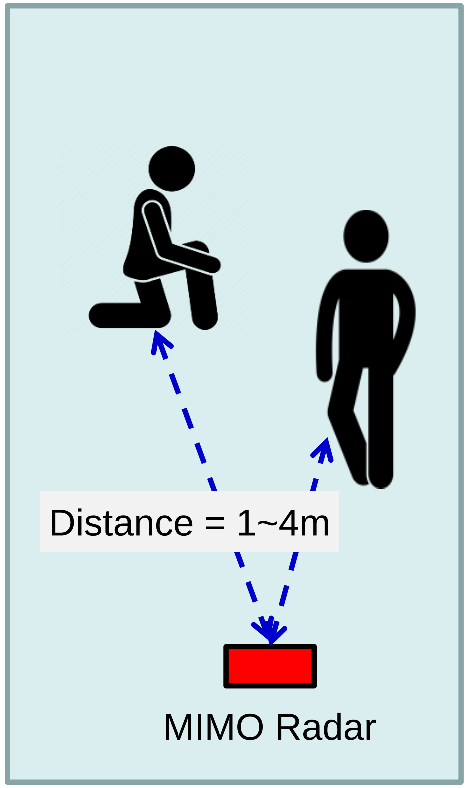


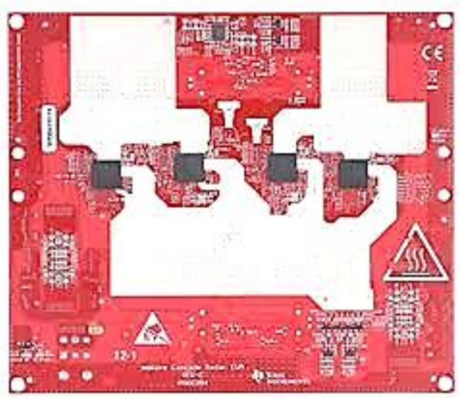
Separated and Centered Targets



Experimental Setup

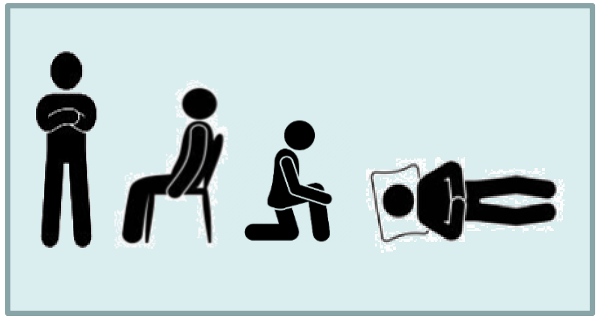
2-Human Scenario

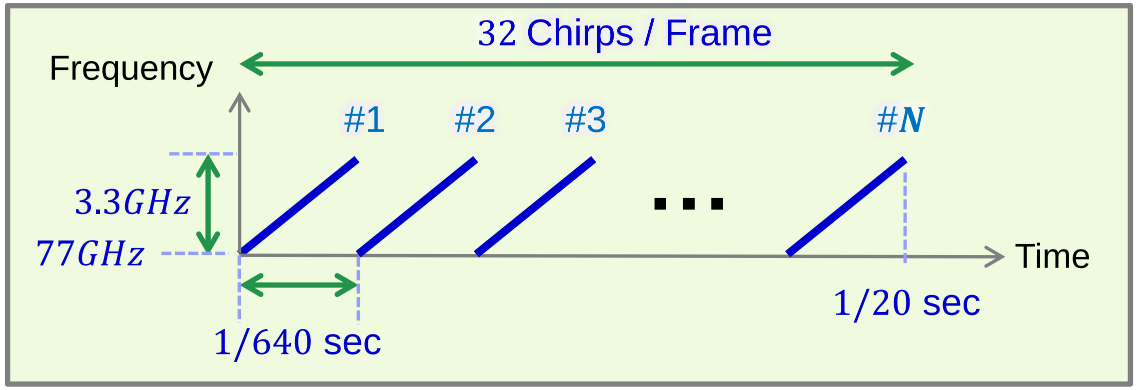




AWR2243 Cascade Radar

4 Postures





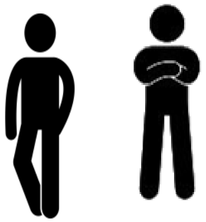
Radar Parameter	Value
Starting frequency	77 GHz
Bandwidth	3.3 GHz
Number of frames per second	20
Number of chirps per frame	32
ADC samples per chirp	256
Number of Tx antennas	12
Number of Rx antennas	16
Field of View (FOV)	$\pm 60^{o}$

Experiment #1: Non-Overlapping Posture Combinations (1/3)

- *10 Non-Overlapping Combinations*

C#1

Both Standing

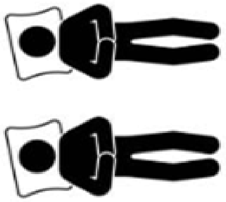


C#2

Both
Sitting on chair

C#3

Both
Lying on Bed
(Top View)

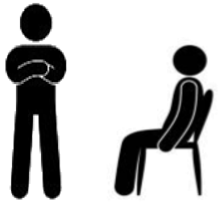


C#4

Both
Picking up

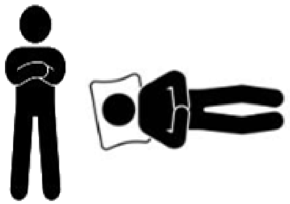
C#5

Standing
&
Sitting on chair



C#6

Standing
&
Lying on bed

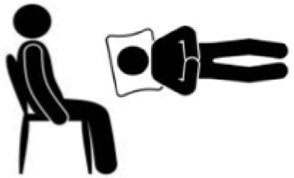


C#7

Standing
&
Picking up

C#8

Sitting on chair
&
Lying on bed

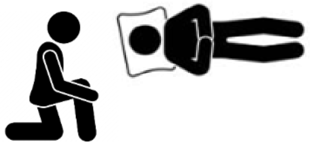


C#9

Sitting on chair
&
Picking up

C#10

Picking up
&
Lying on bed

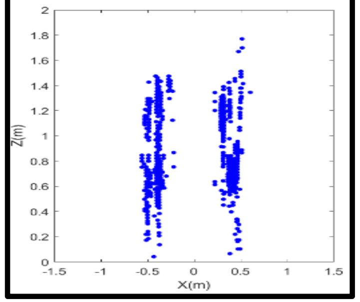


Experiment #1: Non-Overlapping Posture Combinations (2/3)

- *Results of Point Cloud*

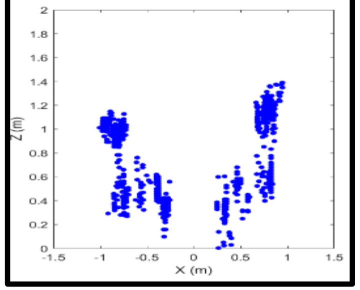
C#1

Both Standing



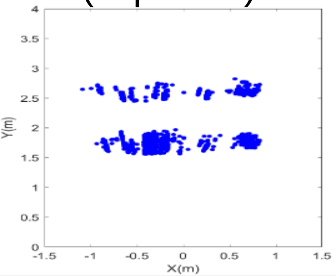
C#2

Both
Sitting on chair



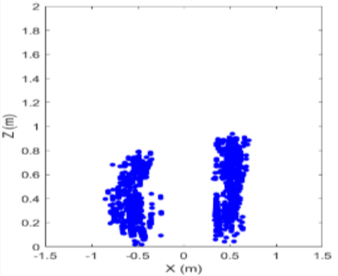
C#3

Both
Lying on Bed
(Top View)



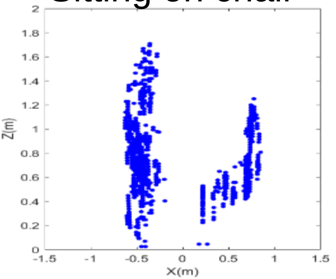
C#4

Both
Picking up



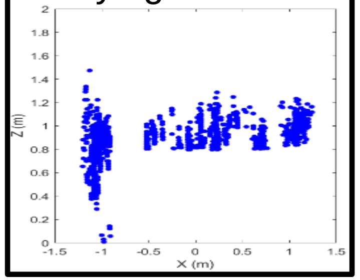
C#5

Standing
&
Sitting on chair



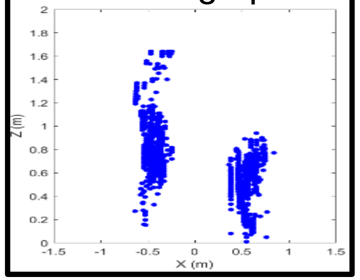
C#6

Standing
&
Lying on bed



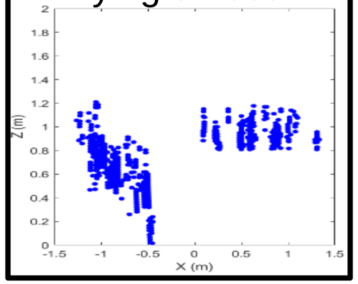
C#7

Standing
&
Picking up



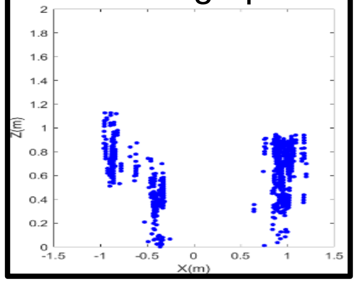
C#8

Sitting on chair
&
Lying on bed



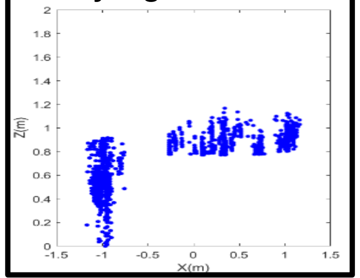
C#9

Sitting on chair
&
Picking up



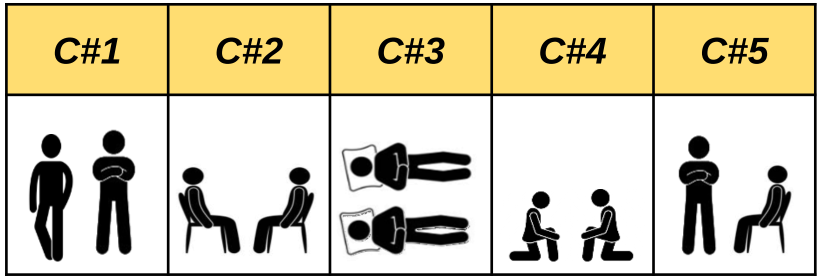
C#10

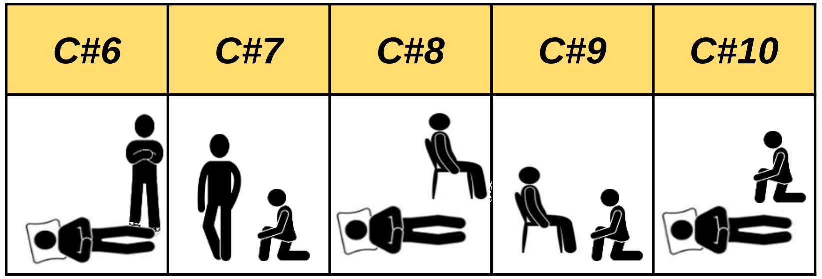
Picking up
&
Lying on bed



Experiment #1: Non-Overlapping Posture Combinations (3/3)

- *Results of DenseNet*





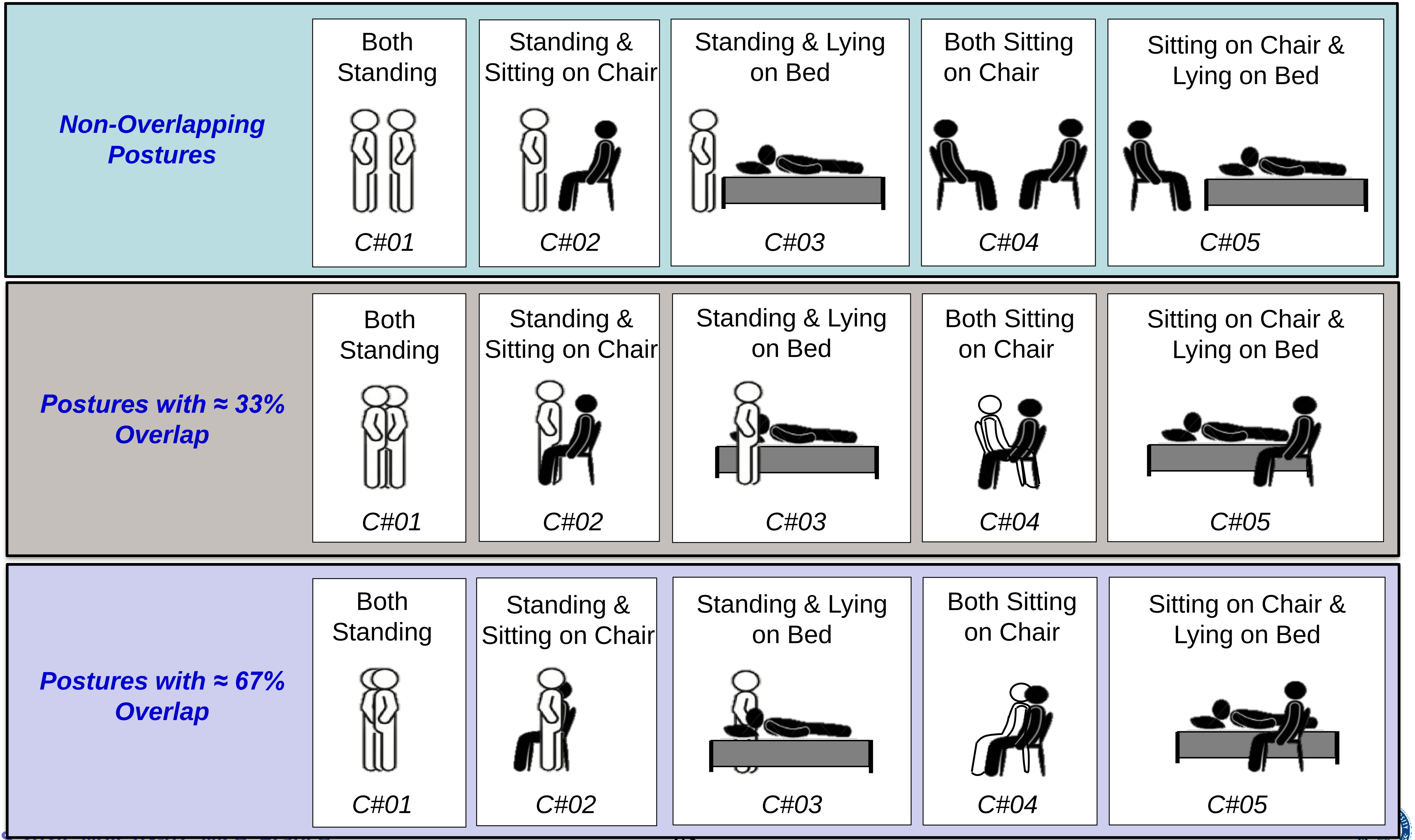
Predicted Label

True Label

	C#1	**C#2**	**C#3**	**C#4**	**C#5**	**C#6**	**C#7**	**C#8**	**C#9**	**C#10**
C#1	100%	11.1%					11.1%			
C#2		88.8%								
C#3			100%							
C#4				100%			5.5%		5.5%	
C#5					100%					
C#6						100%				
C#7							83.3%			
C#8								100%		5.5%
C#9									94.4%	
C#10										94.4%
***Overall Prediction Accuracy* 96.0%**										

18 trials per each combination (180 trials in total)

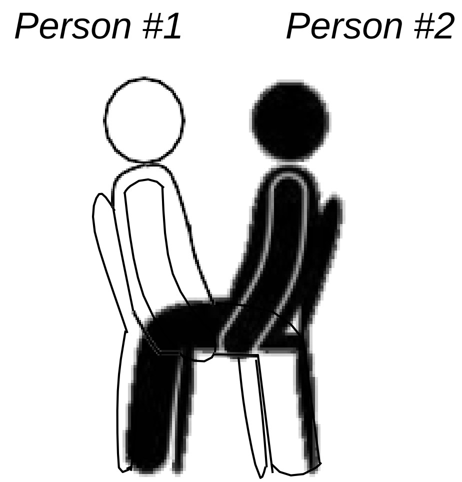
Experiment #2: Overlapping & Non-Overlapping Posture Combinations (1/3)



Non-Overlapping Postures	Both Standing *C#01*	Standing & Sitting on Chair *C#02*	Standing & Lying on Bed *C#03*	Both Sitting on Chair *C#04*	Sitting on Chair & Lying on Bed *C#05*
Postures with ≈ 33% Overlap	Both Standing *C#01*	Standing & Sitting on Chair *C#02*	Standing & Lying on Bed *C#03*	Both Sitting on Chair *C#04*	Sitting on Chair & Lying on Bed *C#05*
Postures with ≈ 67% Overlap	Both Standing *C#01*	Standing & Sitting on Chair *C#02*	Standing & Lying on Bed *C#03*	Both Sitting on Chair *C#04*	Sitting on Chair & Lying on Bed *C#05*

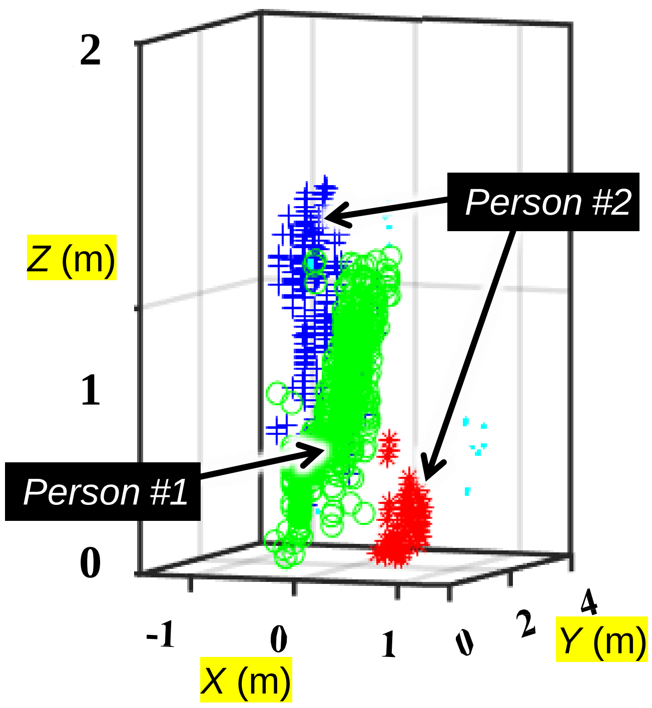
Experiment #2: Overlapping & Non-Overlapping Posture Combinations (2/3)

Overlapping Postures

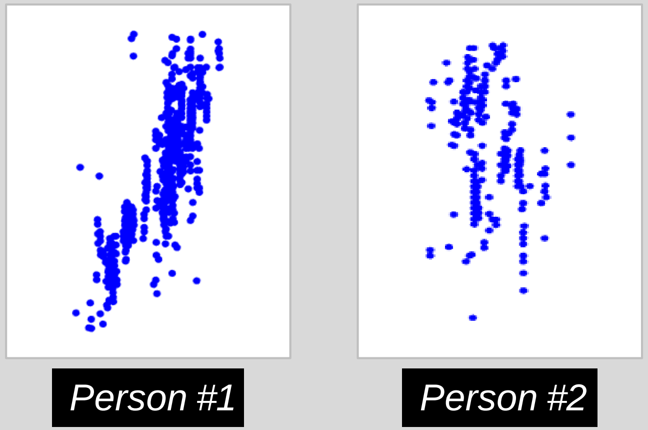


DBSCAN

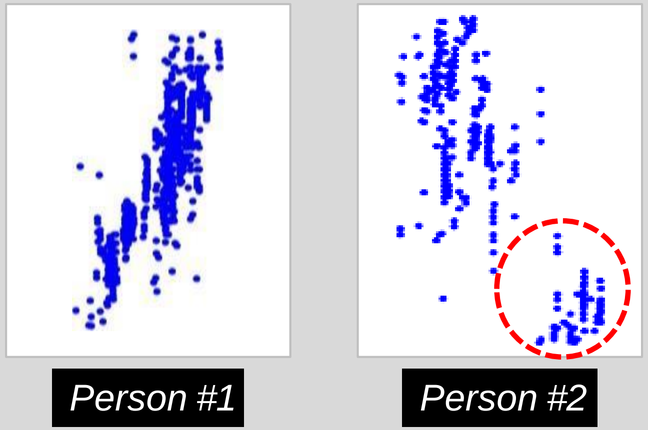
Person #1: Cluster Blue & Cluster Red
Person #2: Cluster Green



Without Combination of Clusters



With Combination of Clusters

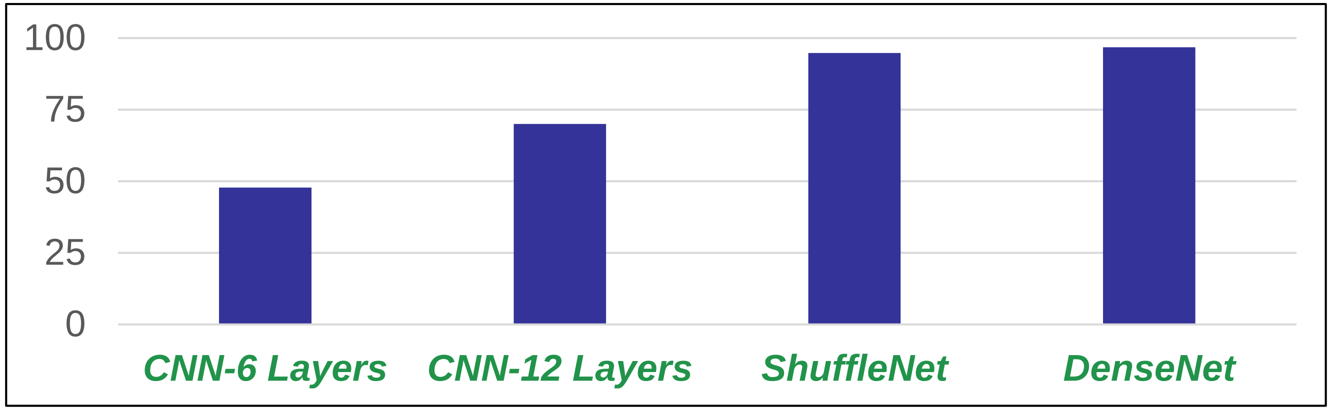


Experiment #2: Overlapping & Non-Overlapping Posture Combinations (3/3)

- Results

Scenario	Both Standing (C#01)	Standing & Sitting (C#02)	Standing & Lying (C#03)	Both Sitting (C#04)	Sitting & Lying (C#05)	Overall
Non-Overlap	100%	100%	100%	94.4%	100%	**98.8%**
≈ 33% Overlap	100%	94.4%	100%	94%	94%	**96%**
≈ 66% Overlap	94%	94%	100%	83%	83%	**91%**

- Comparison with Other CNNs



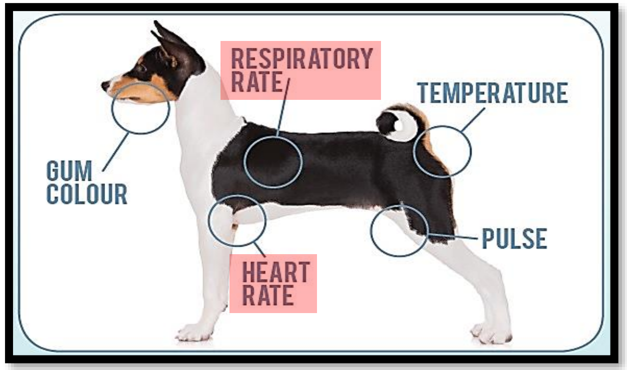
WORK IN PROGRESS

Radar for Pets

- "A Public Dataset of Dogs Vital Signs Recoded with Ultra Wideband Radar and Reference Sensors," *Scientific Data*, Jan. 2024.
- "UWB Radar-Based Pet Monitoring on Daily Basis in an Unconstrained Living Environment." *Int. Radar Symp. (IRS 2023)*, May 2023.

Motivations and Objectives

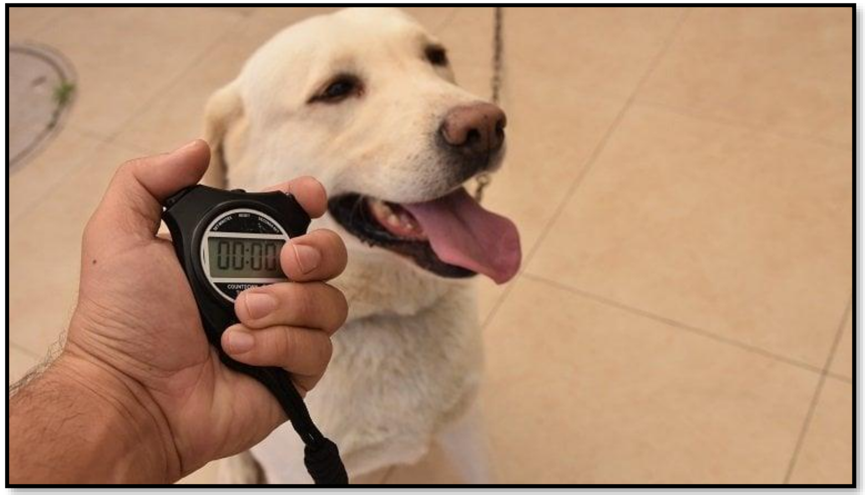
- *Want to construct a non-contact method to monitor the basic health condition of dogs raised at home on a daily basis using radar.*
  - Vital sign measurements
  - Movement quantification
  - *Early detection of potential illness*



- *Validation of radar-based vital sign measurements of dogs in controlled environments.*
  - Resting respiratory and heart rates
  - Validation by gold standard references

- *Radar-based daily vital sign measurements of dogs in semi-constraint and unconstrained environments.*
  - Respiratory and heart rates of dogs
  - Movement quantification
  - Validation by video record references

Respiratory Rate (RR) of Dogs



❖ *Normal RR of a Dog at Rest*

- 10~35 breaths per minute.

❖ *Panting Mode*

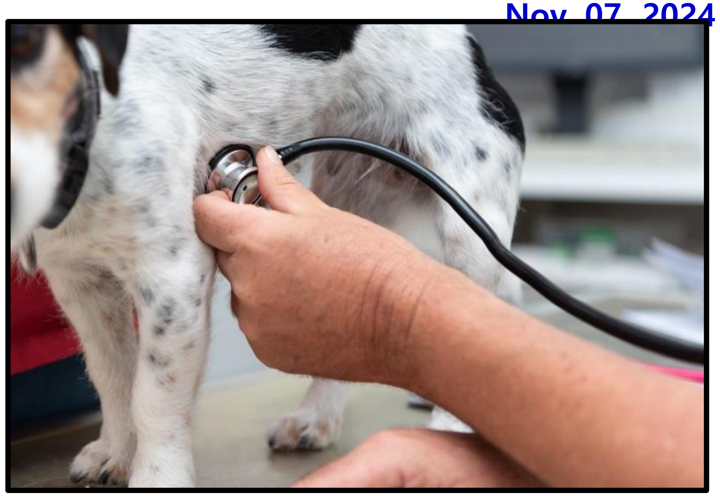
- Up to 200 pants per minute
  (Due to heat, excitement, stress, pain, medicine, heatstroke)

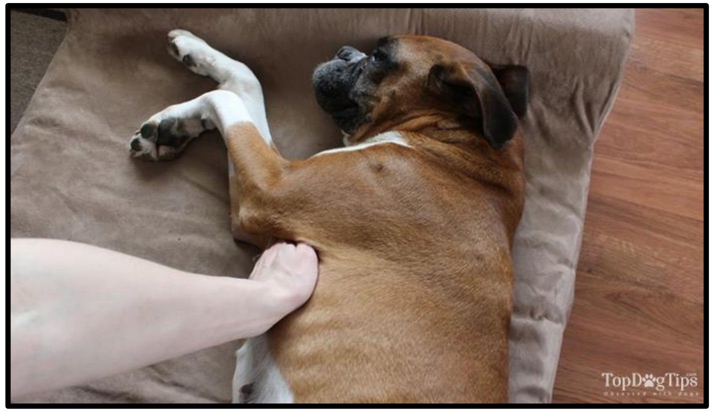
❖ *Vet's Access to Dog's RR*

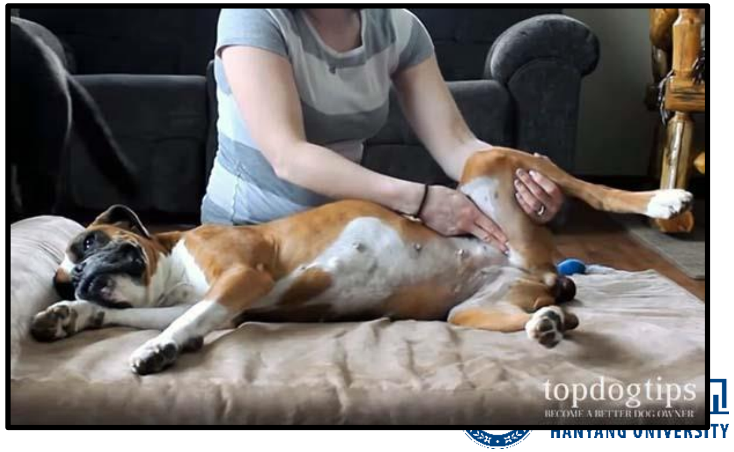
- The easiest way to gather your dog's respiratory rate is to count the number of breaths per 30 seconds and then multiply by two.

Panting Dog

Heart Rate (HR) of Dogs







Normal HR for a Dog at Rest

- Small Breed: 90~150 beats per minute
- Medium Breed: 70~120 beats per minute
- Large Breed: 60~90 beats per minute

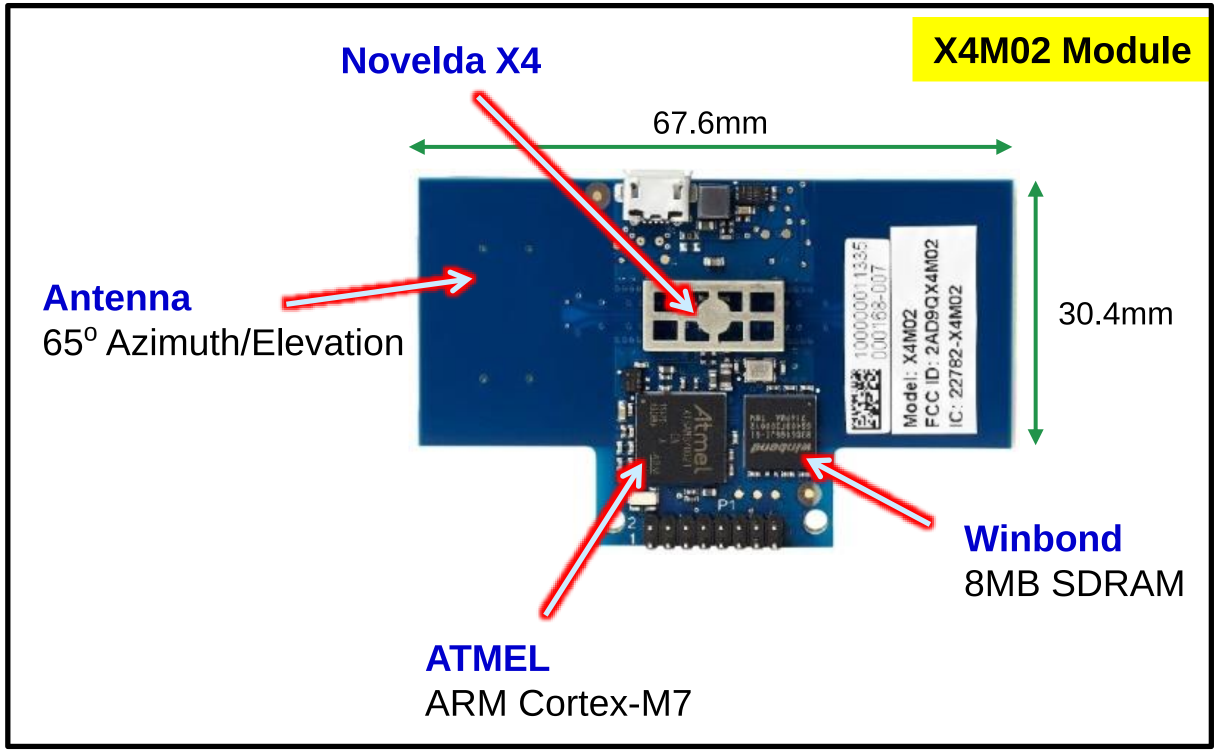
Vet's Access to Dog's HR

- The best spot to find the dog's heart rate is the left side of the chest, right behind the dog's elbow.
- Use stethoscope to count the beats, or put the flat palm of your hand on the dog's chest wall.
- If the dog prefers to lie down, have the dog lie on the right side.
- The easiest way to gather your dog's heart rate is to count the number of beats per 15 seconds and then multiply by four.

Experiment #1: Controlled Environment

Novelda X4M02 Module

- Single-chip ultra-wideband (UWB) impulse radar transceiver
- Frequency: 7.25~10.2 GHz
- Bandwidth: 1.5 GHz
- FOV(Field of View) : about 65° (azimuth/elevation)
- Detection Speed : 50 frames per second (FPS)
- Power consumption: typically < 120 mW
- Operating temperature range: -40 / +85 °C
- Master/Slave Serial Peripheral Interface (SPI)



X4M02 Module

Novelda X4

67.6mm

30.4mm

Antenna
65^{o} Azimuth/Elevation

Winbond
8MB SDRAM

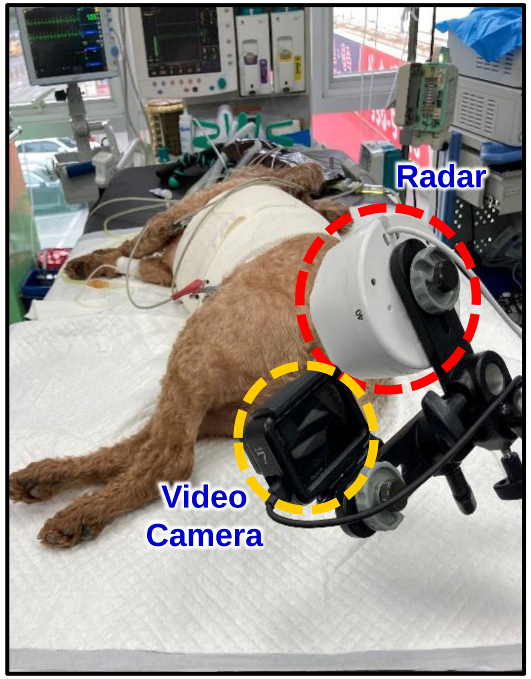
ATMEL
ARM Cortex-M7

Experiment #1: Experimental Setup

- *The experiment was performed in the operation room at **N Animal Medical Center**, Seoul, South Korea.*
- *Radar is positioned approximately 30cm above the operating bed.*
- *Data collection was made for 3 minutes under sleep anesthesia immediately after surgery.*
- *10 dogs participated in the experiment.*

Veterinary Multi-Parameter Vital Sign Monitor

Bionet
BM7Vet Pro



Experiment #1: Demography

#1

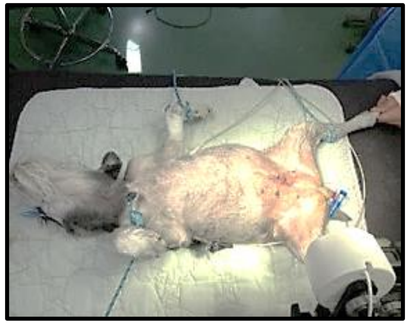
#2

#3

#4

#5

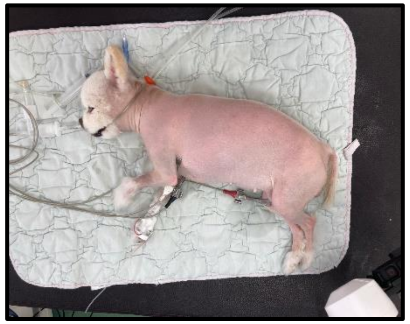
#6



Number	*Breed*	*Gender*	*Age*	*Weight (Kg)*	*Neutering*	*Surgery*
1	Dachshund	M	7	11.3	O	Disc
2	Shiva Dog	F	4	12	X	Chylothorax
3	Poodles	F	8	8.7	X	MGT(Mammary Gland Tumor)
4	Poodles	F	5	2.9	X	Left Cruciate Ligament Rupture
5	Poodles	F	8	8.3	O	Cholecystectomy
6	Schnauzer	F	4	5.5	O	Neutering
7	Maltese	F	7	3.8	O	Cruciate Ligament Rupture
8	Pomeranian	F	12	3.2	X	Canine Pyometra
9	Poodles	F	8	6	O	Tooth Extraction, Neutering
10	Pompitz	F	4	5.1	X	Right Cruciate Ligament Rupture

#7

#8

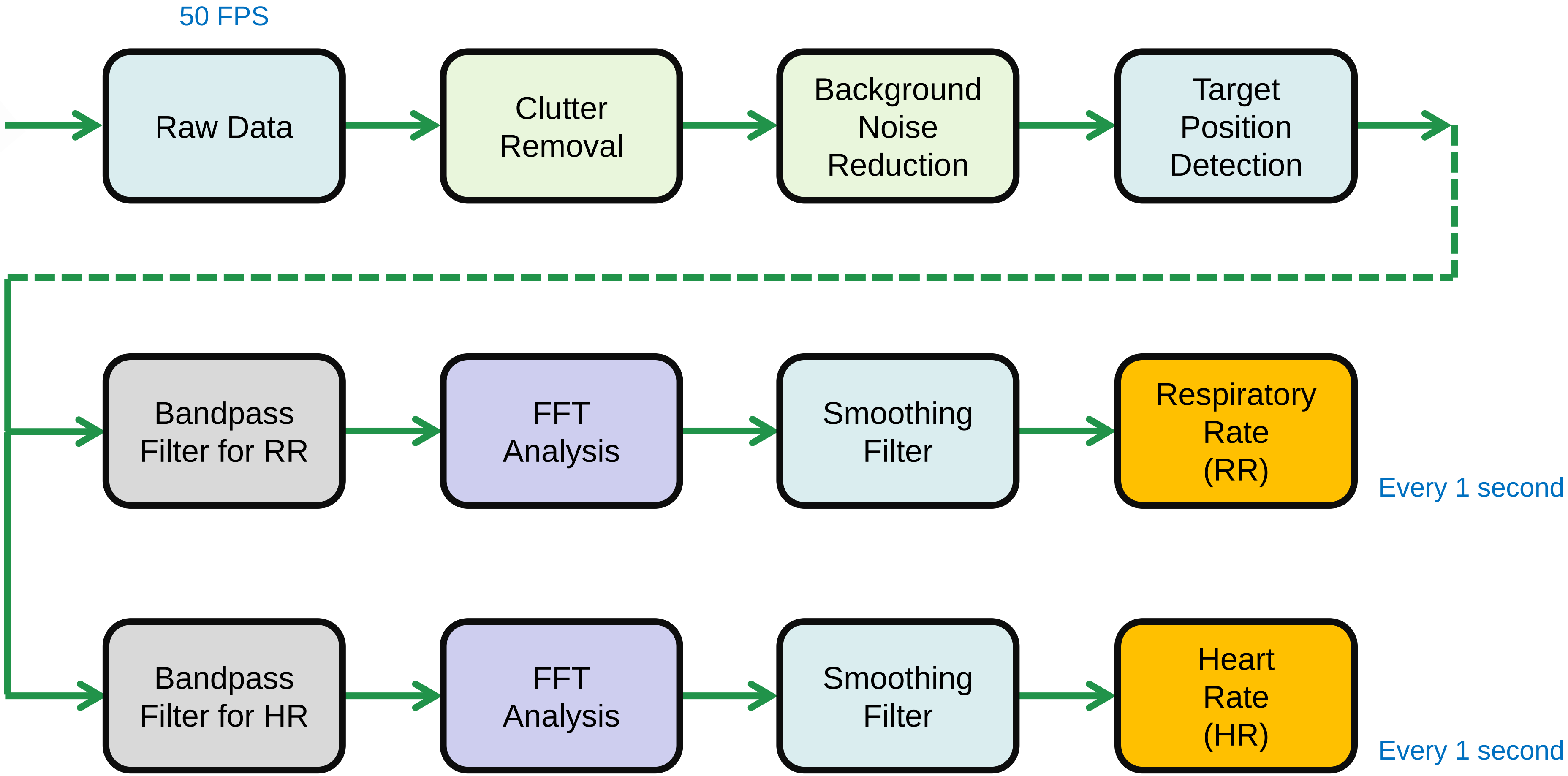


#9

#10

Experiment #1: Method

❖ *Extraction of RR and HR*



50 FPS

Raw Data → Clutter Removal → Background Noise Reduction → Target Position Detection

Bandpass Filter for RR → FFT Analysis → Smoothing Filter → Respiratory Rate (RR)

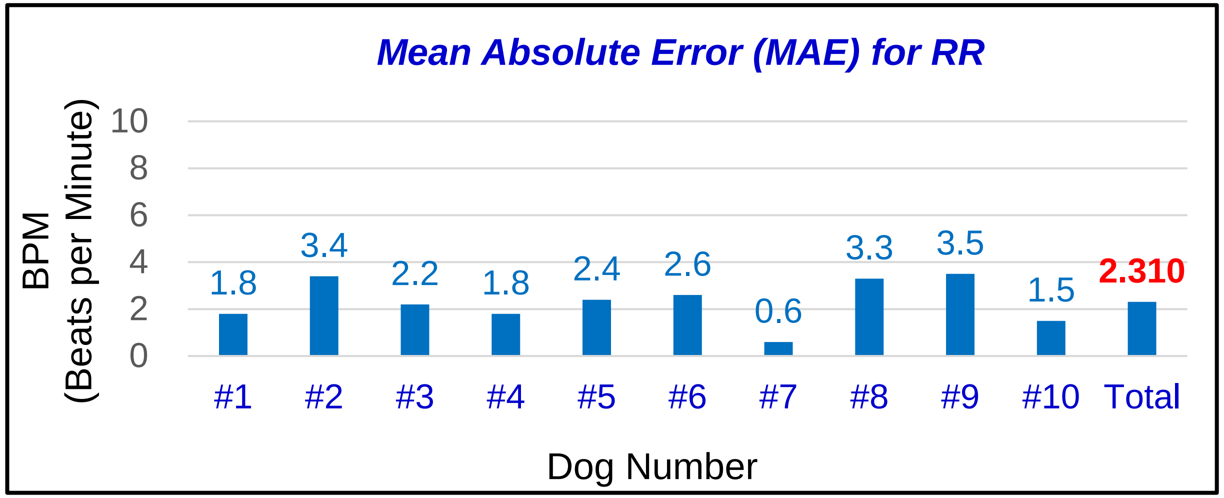
Every 1 second

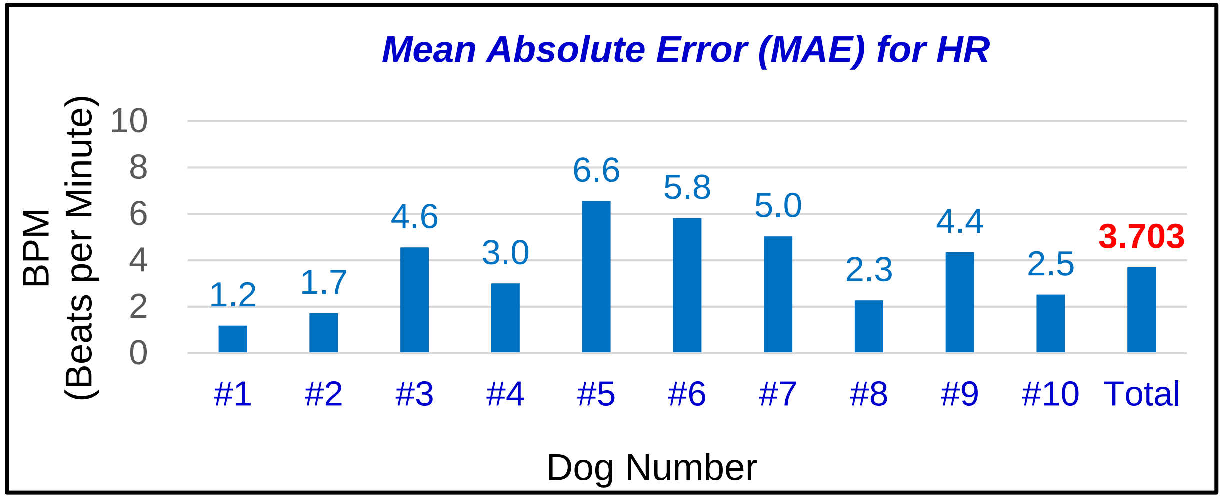
Bandpass Filter for HR → FFT Analysis → Smoothing Filter → Heart Rate (HR)

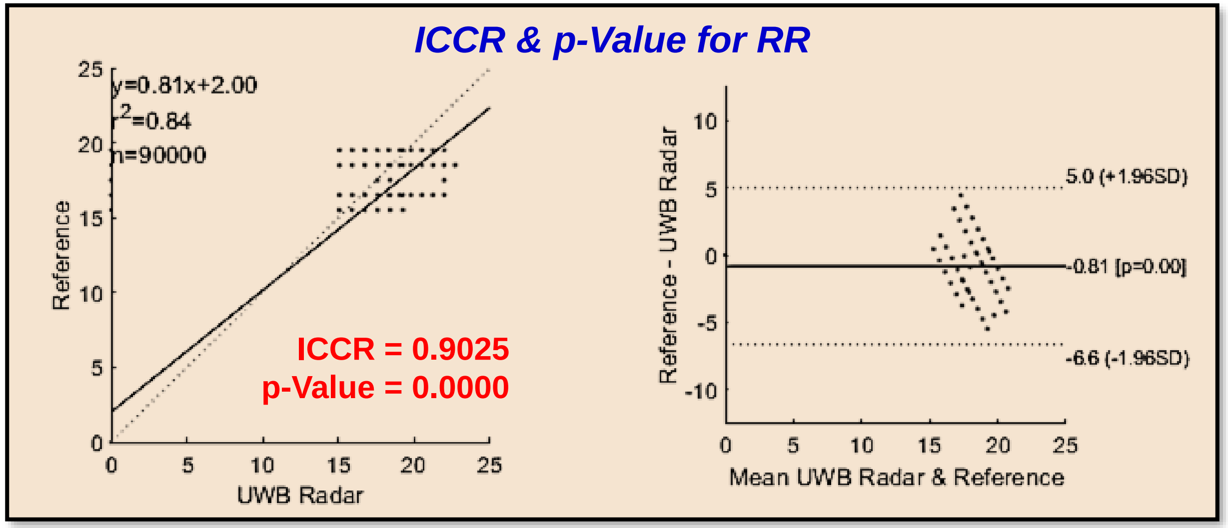
Every 1 second

Experiment #1: Preclinical Validation

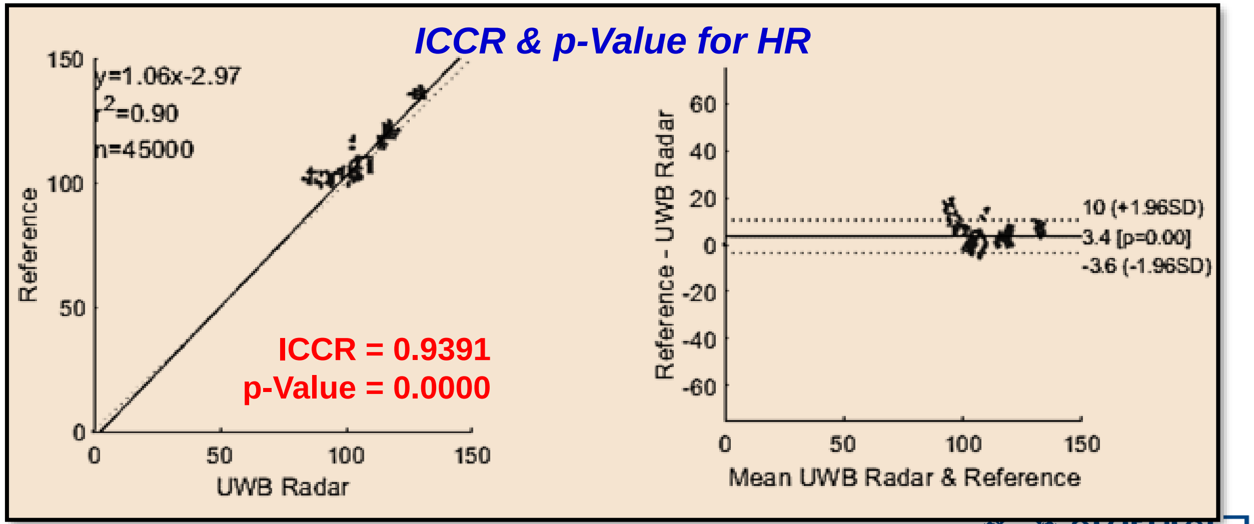
- *Comparisons between Radar and Gold Standard*


Mean Absolute Error (MAE) for RR


Mean Absolute Error (MAE) for HR


ICCR & p-Value for RR

ICCR = 0.9025
p-Value = 0.0000


ICCR & p-Value for HR

ICCR = 0.9391
p-Value = 0.0000

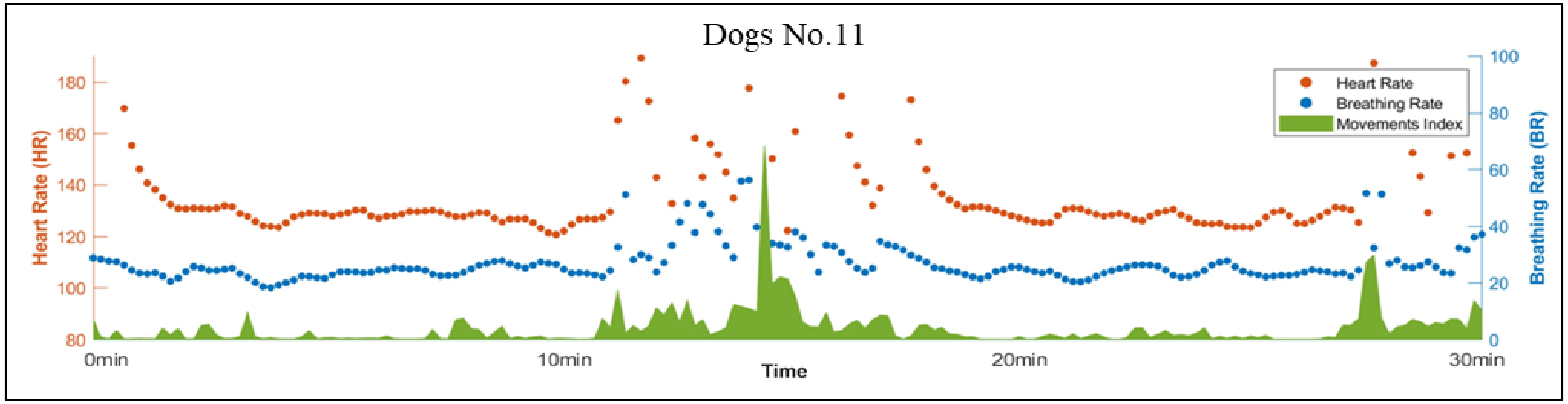
Experiment #2: Semi-Constrained Environment

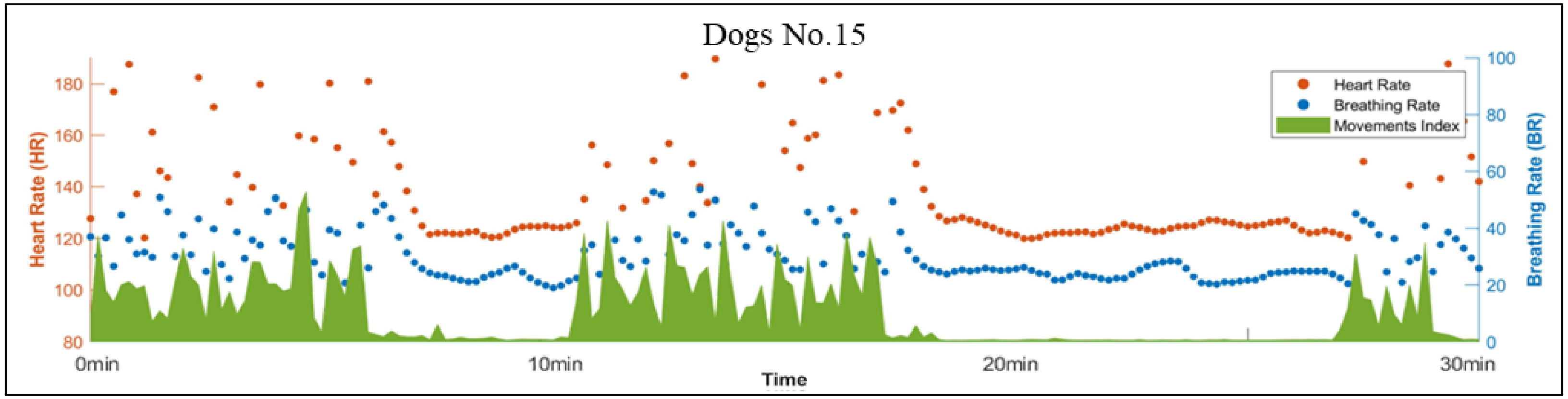
- *The experiment was performed at the intensive care unit (ICU) chamber.*
- *Radar is positioned on the glass outside the chamber.*
- *Data collection was made for 24 hours.*
- *20 dogs participated in the experiment.*

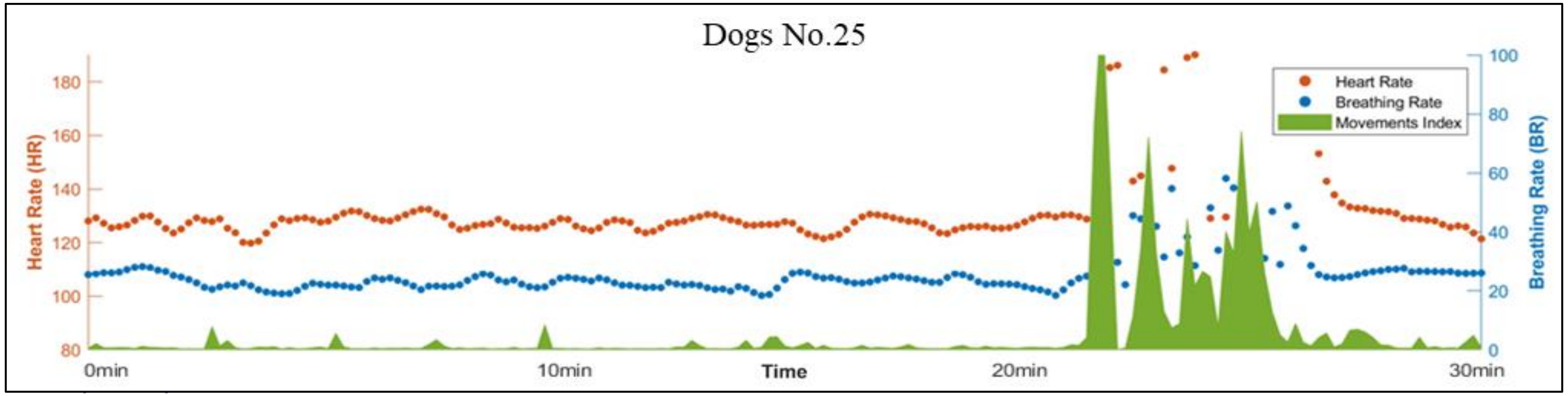
Experiment #2: Demographic Data

Num	Age	Breed	Gender	Weight (Kg)	Environments	Neutering	Surgery	Chamber No.
1	9	Shih Tzu	F	7.4	ICU	O	Hospitalization for surgery	Big No.1 ICU
2	4	Maltese	M	10.7	ICU	O	Hospitalization for surgery	Small No.2 ICU
3	10	Mixed Breed	F	8.2	ICU	O	Hospitalization for surgery	Small No.1 ICU
4	10	Pomeranian	F	8.1	ICU	O	Hospitalization for surgery	Big No.1 ICU
5	12	Mixed Breed	F	11.3	ICU	O	Hospitalization for surgery	Small No.2 ICU
6	8	Maltese	M	7.6	ICU	O	Hospitalization for surgery	Big No.1 ICU
7	5	Mixed Breed	M	5	ICU	O	Hospitalization for surgery	Big No.1 ICU
8	7	Mixed Breed	F	7.7	ICU	O	Hospitalization for surgery	Big No.1 ICU
9	6	Hound	F	12.2	ICU	X	Hospitalization for surgery	Small No.2 ICU
10	10	Maltese	F	9.9	ICU	X	Hospitalization for surgery	Small No.2 ICU
11	9	Maltese	F	7.2	ICU	O	Hospitalization for surgery	Big No.1 ICU
12	10	Mixed Breed	F	13.7	ICU	X	Hospitalization for surgery	Small No.2 ICU
13	4	Shiva dog	F	12	ICU	X	Hospitalization for surgery	Small No.2 ICU
14	5	Maltese	M	6.1	ICU	O	Hospitalization for surgery	Small No.2 ICU
15	5	Welsh Corgi	F	8.5	ICU	O	Hospitalization for surgery	Big No.1 ICU
16	11	Poodle	M	11.5	ICU	X	Hospitalization for surgery	Small No.2 ICU
17	10	Maltese	M	7.6	ICU	O	Hospitalization for surgery	Small No.2 ICU
18	6	Dachshund	M	13.5	ICU	X	Hospitalization for surgery	Big No.1 ICU
19	8	Pomeranian	M	7.4	ICU	O	Hospitalization for surgery	Small No.2 ICU
20	7	Maltese	F	6.6	ICU	O	Hospitalization for surgery	Small No.2 ICU

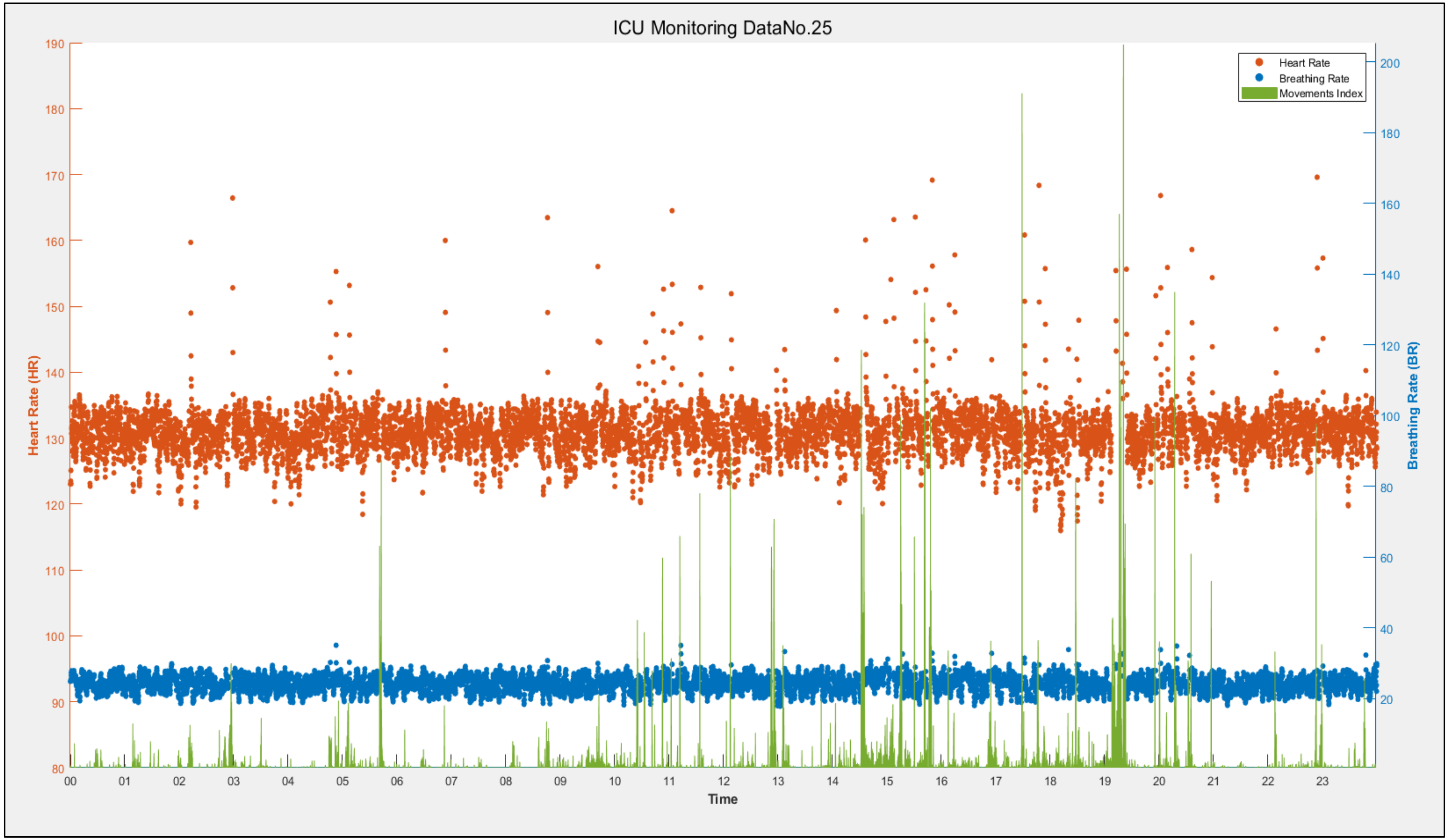
Experiment #2: 30 Minute Dashboard







Experiment #2: 24 Hour Dashboard



Experiment #3: Unconstrained Living Environment

- *Want to realize radar-based daily vital sign measurements of dogs in an unconstrained living environment (i.e., Home).*
  - RR and HR of dogs
  - Movement quantification
  - Validation by video record references (No gold standard)

- *Want to provide a 24/7 dashboard that shows*
  - Changes in vital signs
  - Quantified body movements

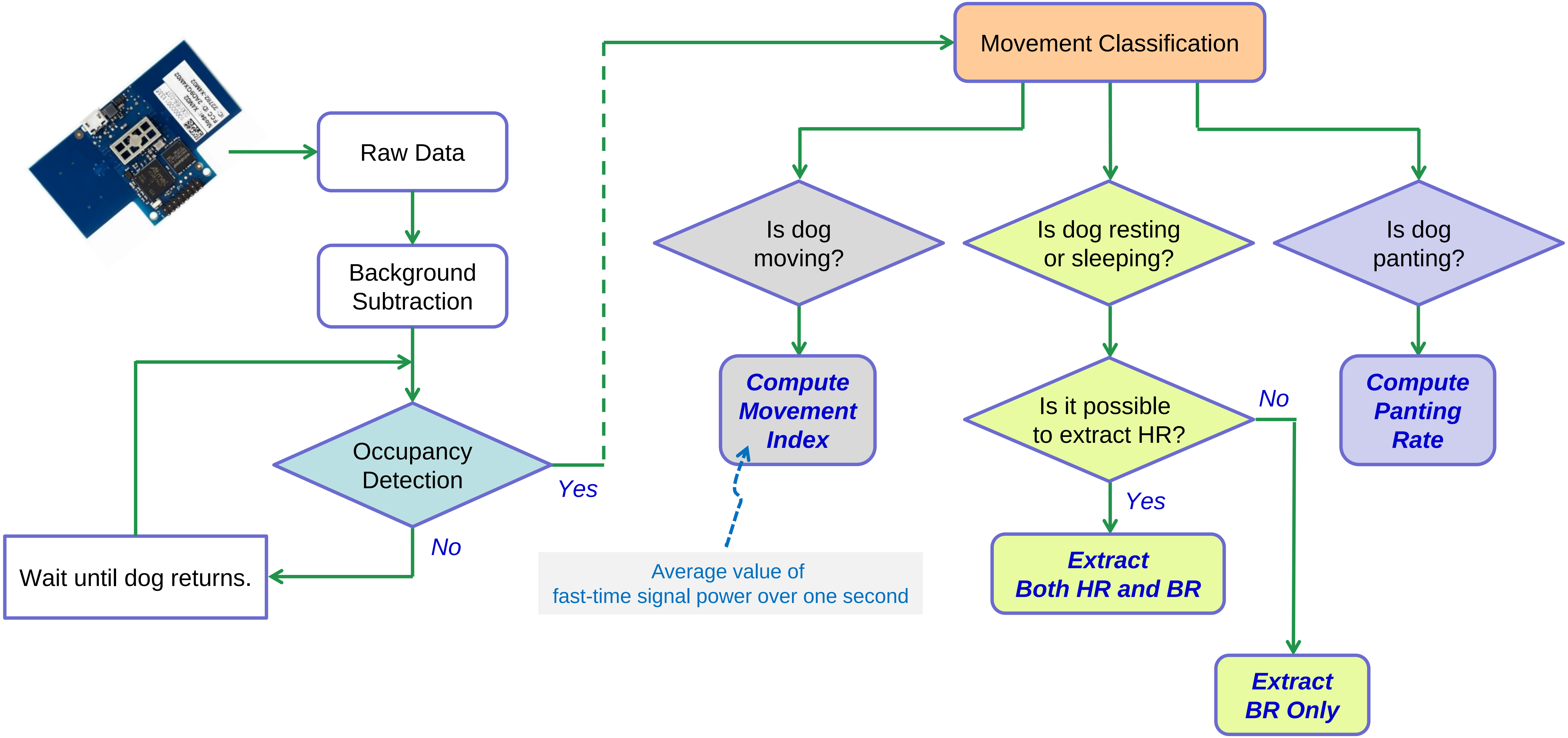
- *Recruiting dogs was the most difficult part.*

Number	*Breed*	*Gender*	*Age*	*Weight (Kg)*	*Neutering*	*Health Issues*
1	Mix-Breed	M	11	8.1	O	Nothing Special
2	Mix-Breed	M	12	10.5	O	Aging

#1

#2

Experiment #3: Design Strategy



Raw Data

Background Subtraction

Occupancy Detection

Yes

No

Wait until dog returns.

Movement Classification

Is dog moving?

Is dog resting or sleeping?

Is dog panting?

Compute Movement Index

Is it possible to extract HR?

No

Yes

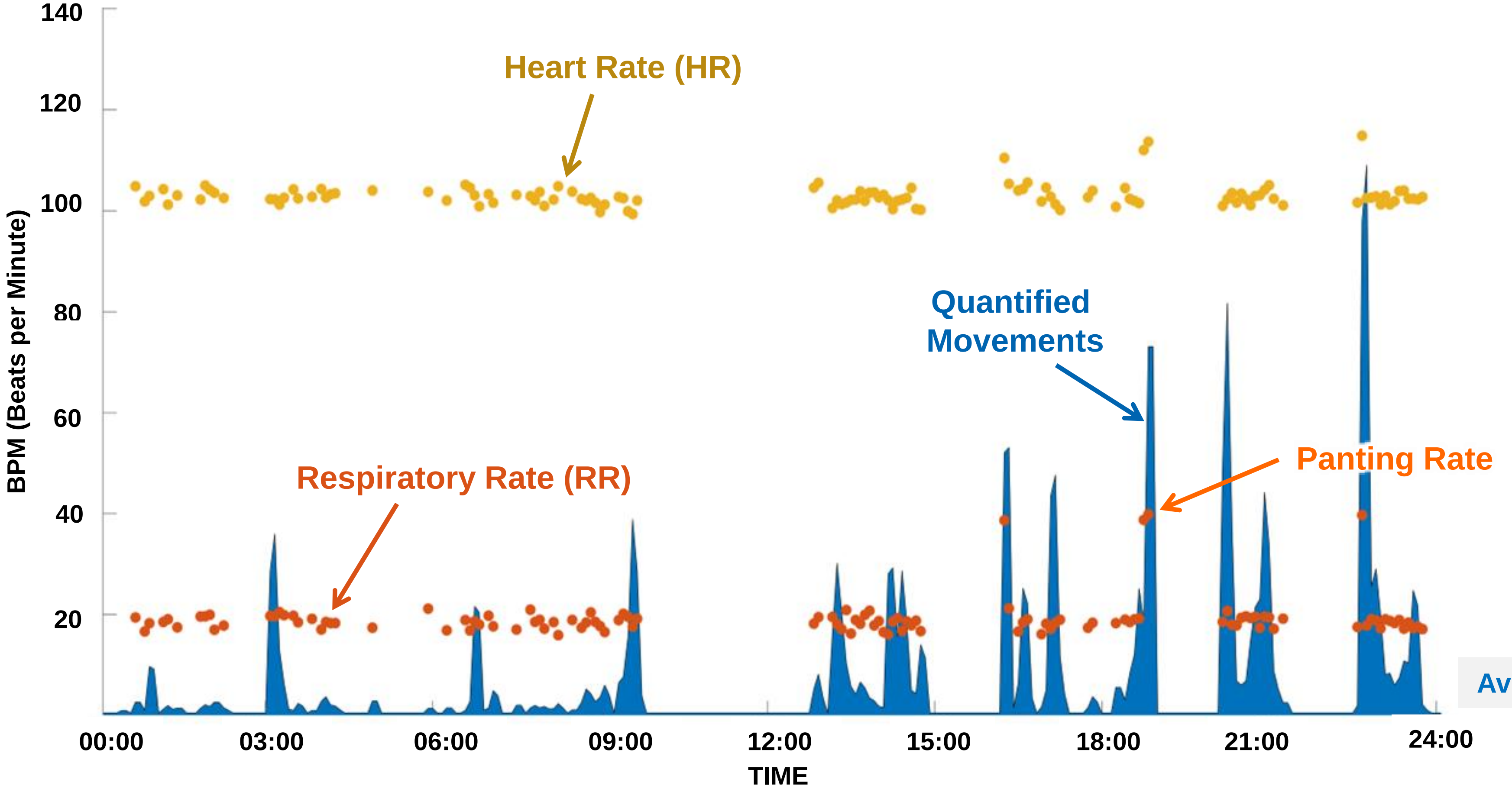
Compute Panting Rate

Extract Both HR and BR

Extract BR Only

Average value of fast-time signal power over one second

Experiment #3: 24 Hour Dashboard (1/2)



Heart Rate (HR)

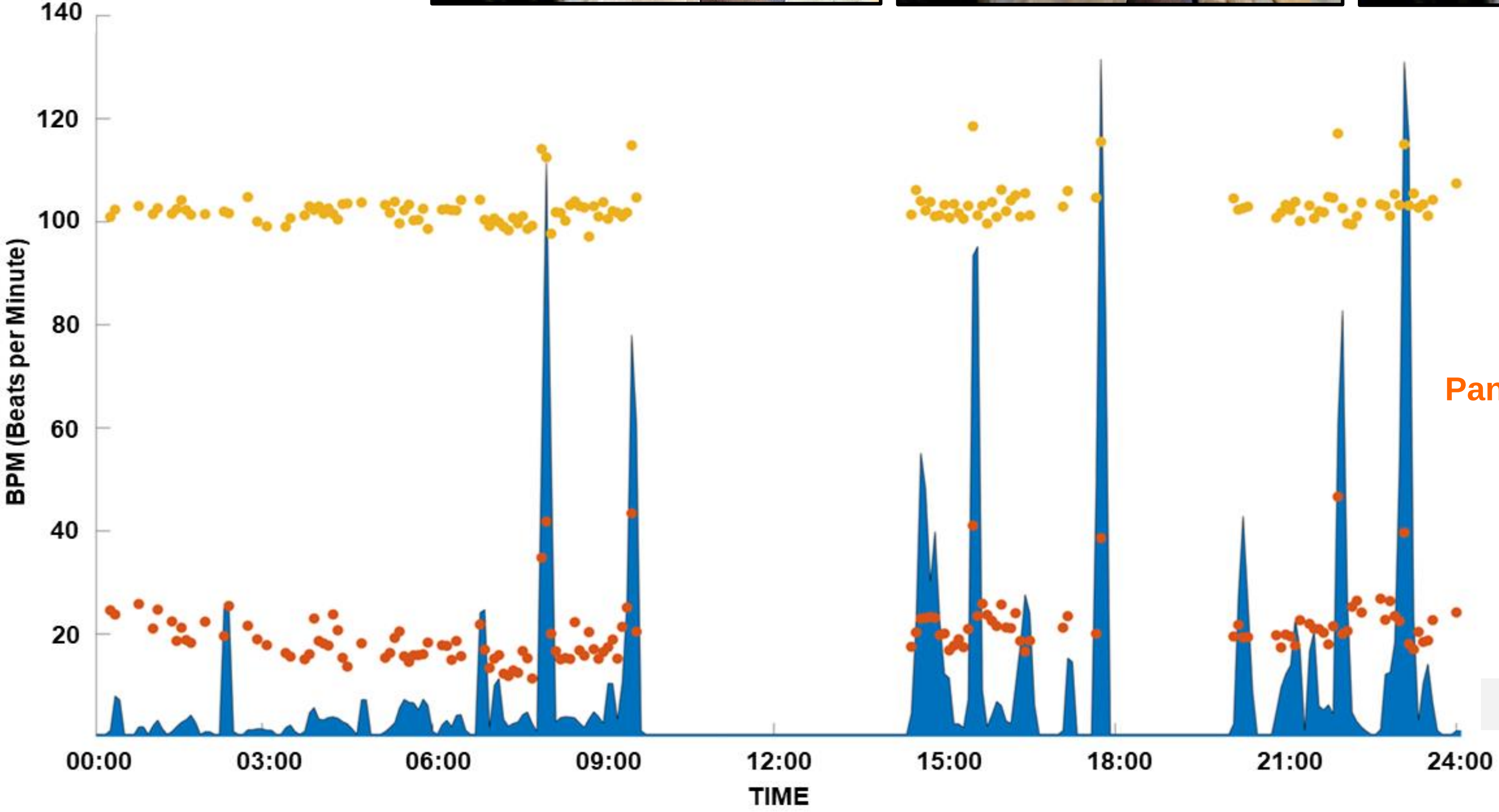
Quantified Movements

Panting Rate

Respiratory Rate (RR)

Averaged over 5 minutes

Experiment #3: 24 Hour Dashboard (2/2)



Panting Rate

Averaged over 5 minutes

Radar in Neonates

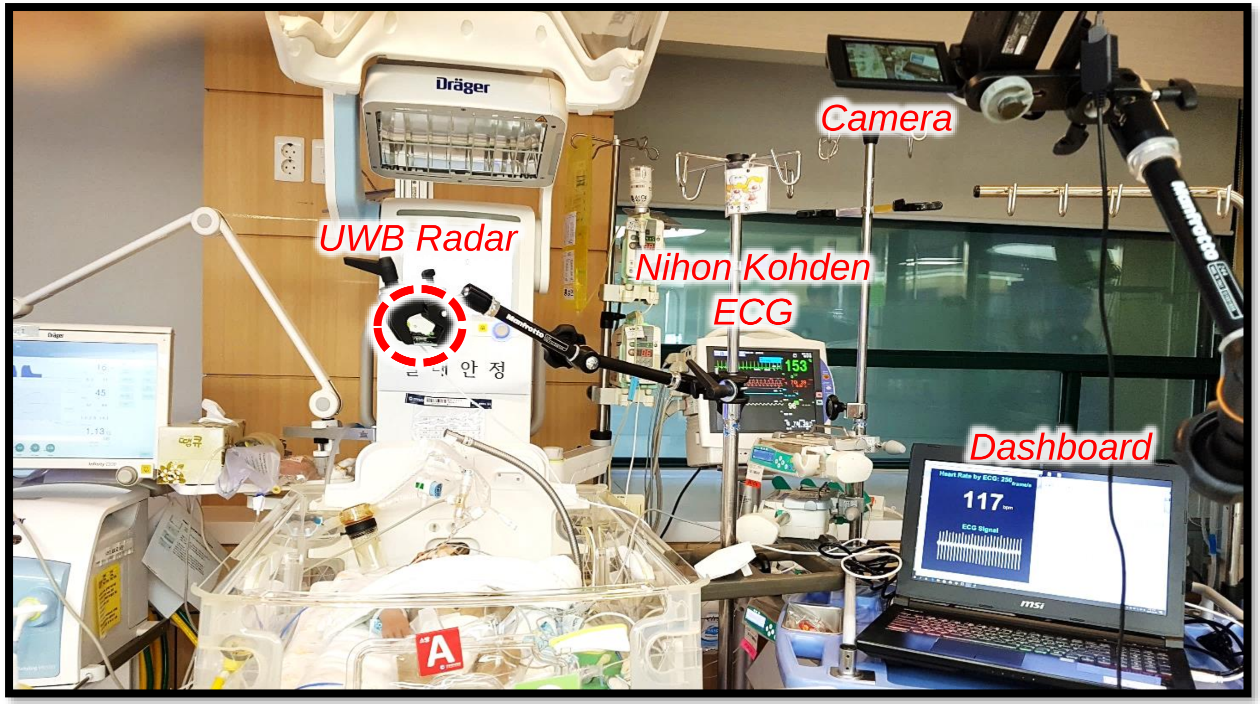
- “Radar Recorded Child Vital Sign Public Dataset and Deep Learning-Based Age Group Classification Framework for Vehicular Application,” *Sensors*, Mar. 2021.
- “Feasibility of Non-Contact Cardiorespiratory Monitoring Using Impulse-Radio Ultra-Wideband Radar in the Neonatal Intensive Care Unit,” *PLOS ONE*, Dec. 2020.
- “Non-Contact Respiration Monitoring Using Impulse Radio Ultrawideband Radar in Neonates,” *Royal Society Open Science*, Jun. 2019.

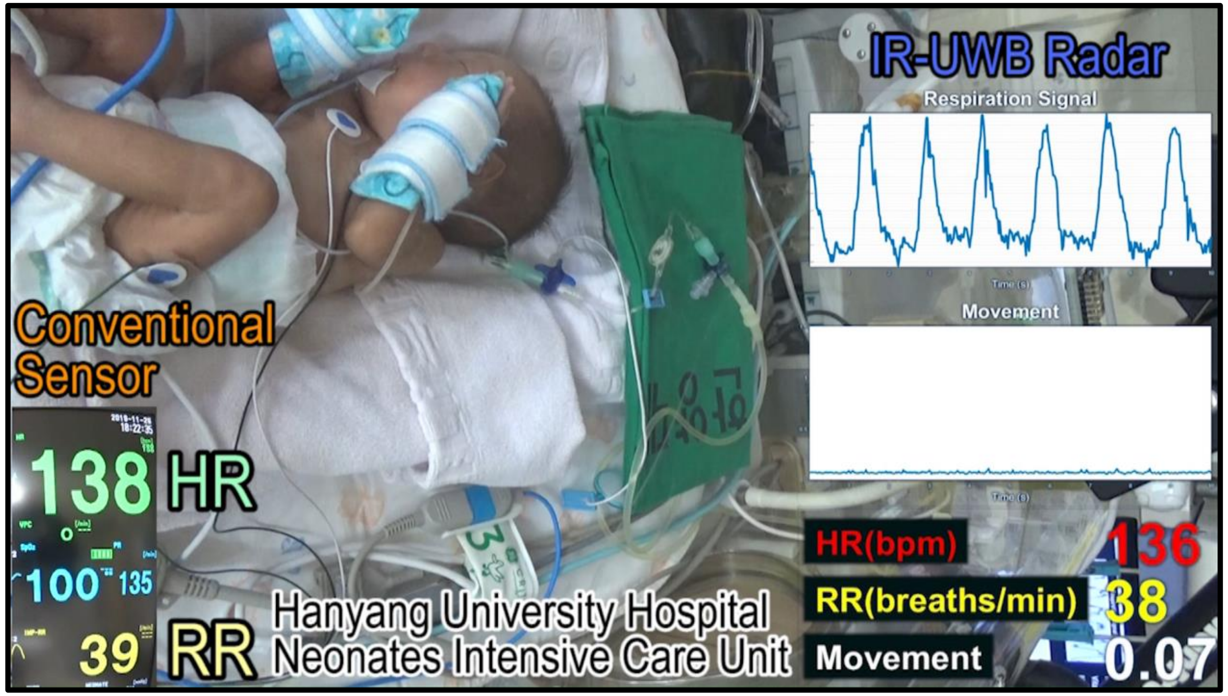
Vital Sign Monitoring (1/5)

- *Need a safe way of monitoring premature / newborn babies.*
  - Non-Contact Vital Sign Monitoring
  - Non-Contact Movement Monitoring

Vital Sign Monitoring (2/5)

- *Neonatal Intensive Care Unit (NICU)*

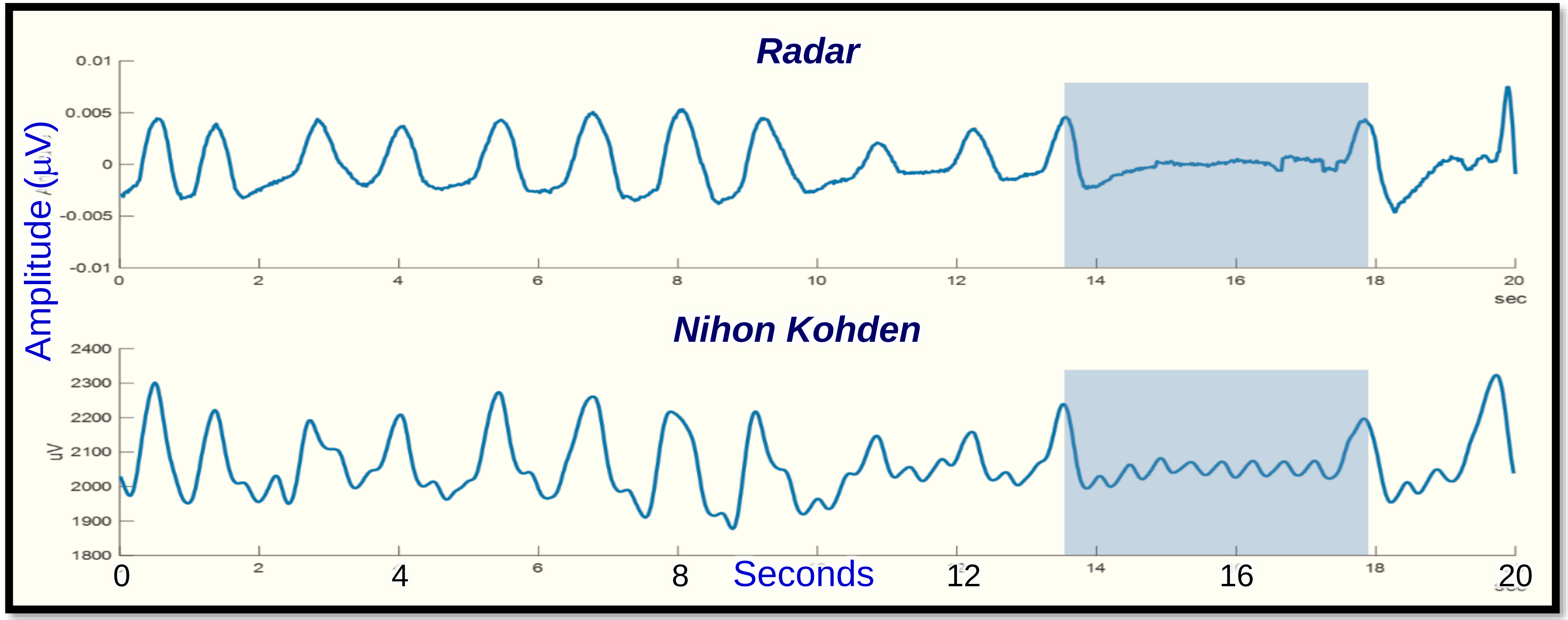




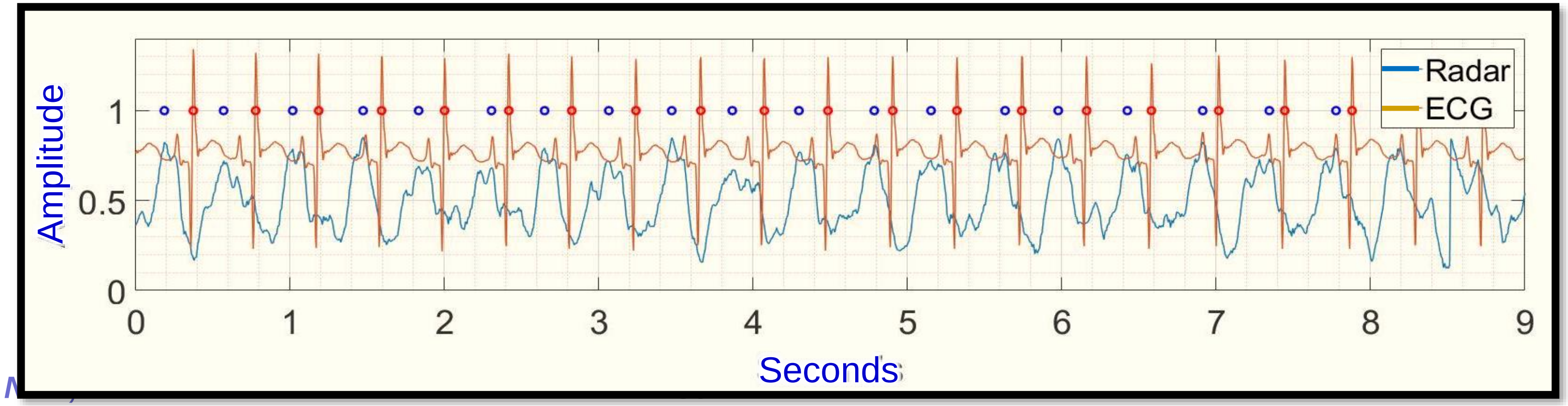
Vital Sign Monitoring (3/5)

❖ *Respiration and Heartbeat Waves*

Respiration Wave

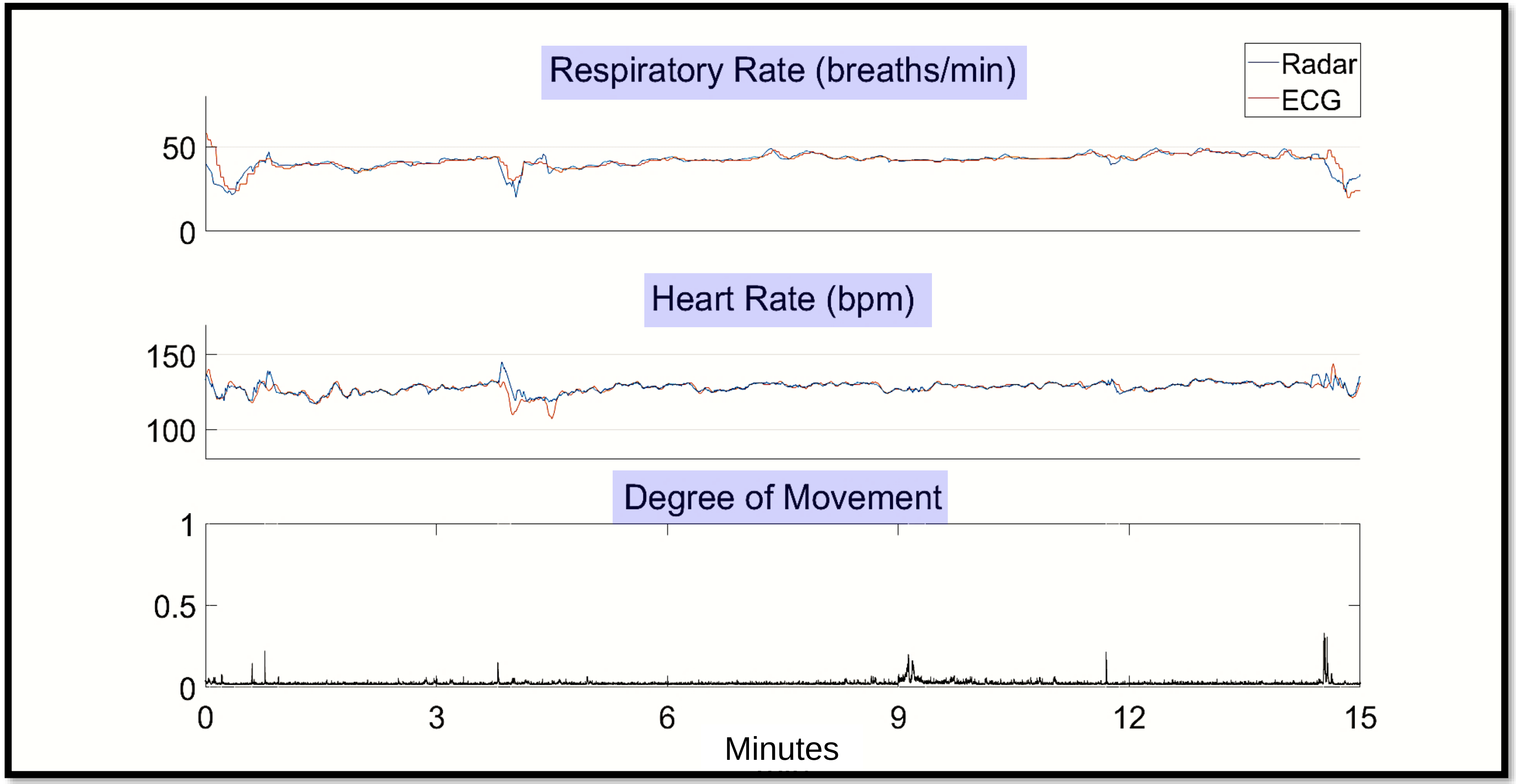


Heartbeat Wave



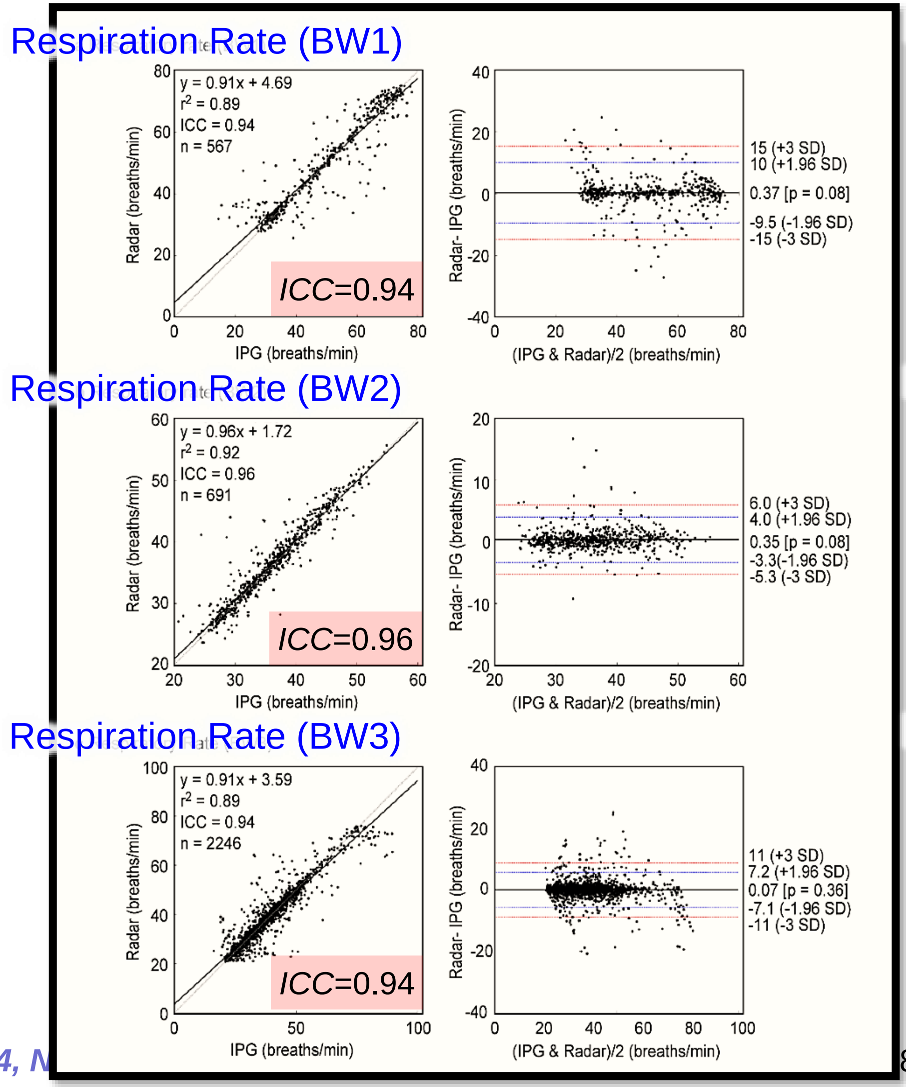
Vital Sign Monitoring (4/5)

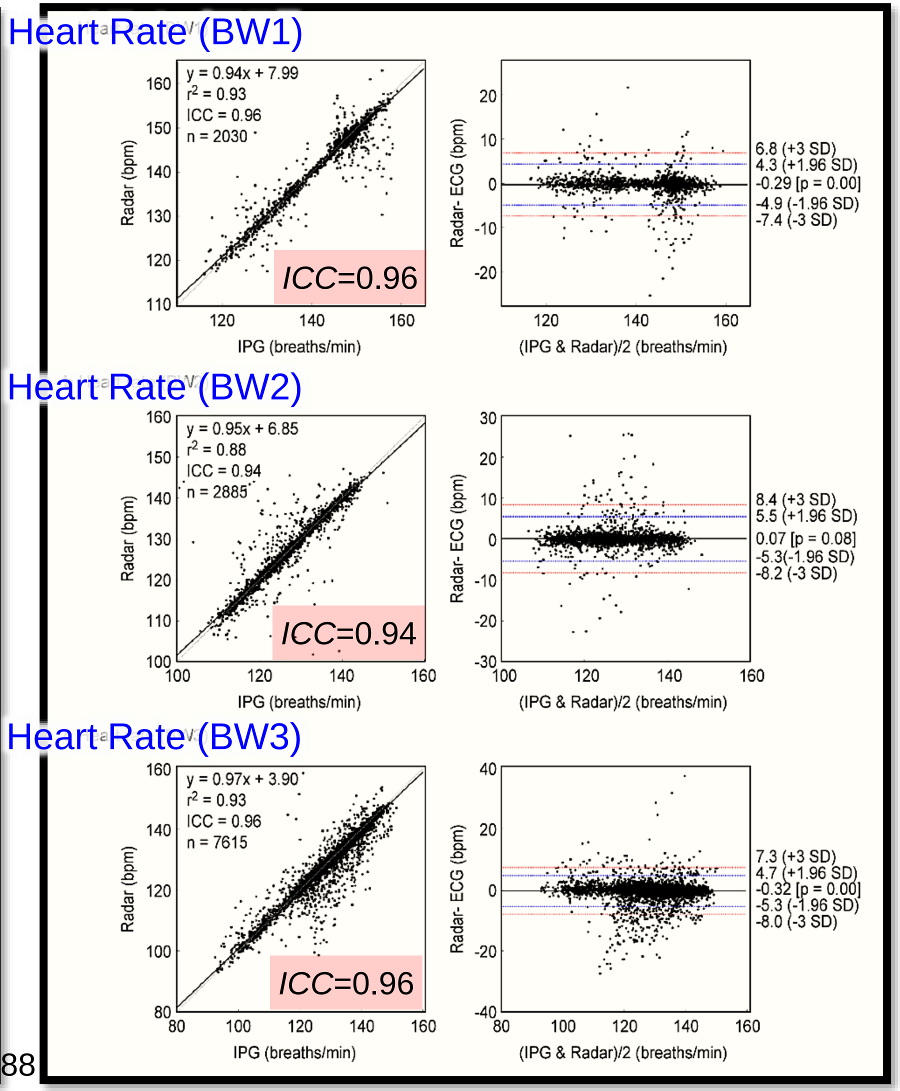
- *Respiration Rate (RR) and Heart Rate (HR) Trend*



Vital Sign Monitoring (5/5)

❖ *Statistics (BW1, BW2, and BW3 Separately)*





Body Weights

- BW1 (< 2Kg)
- BW2 (2~3Kg)
- BW3 (> 3Kg)

Anthropometric Measurement in Neonates

- "Machine Learning Assisted Noncontact Neonatal Anthropometry Using FMCW Radar," *Scientific Reports*, Sep. 2024. (Under review)
- "Preclinical Trial of Noncontact Anthropometric Measurement Using IR-UWB Radar," *Scientific Reports*, May 2022.

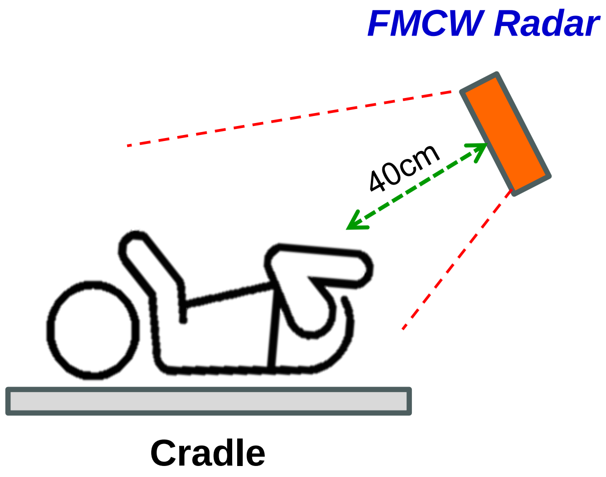
Height and Weight Measurements of Newborns

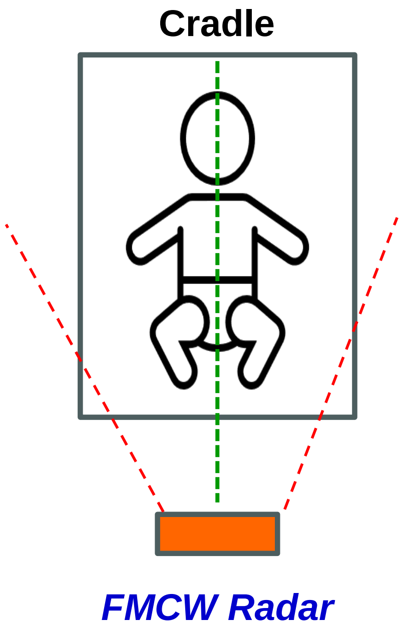
- *Periodic measurement of height and weight of newborns*
  - A criterion for evaluating growth status
  - The most basic indicator for determining whether nutrition is adequately supplied and whether there is any edema.

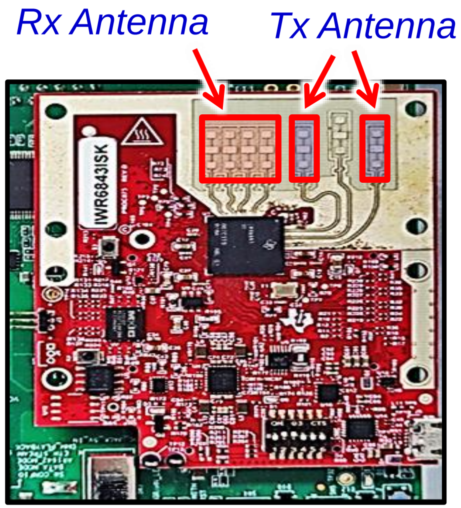
- *However, there is always a risk of having to move the child to measure height and weight.*
  - This often requires a lot of caution and effort to ensure a certain level of safety and accuracy.

- *A non-contact method of measuring the height and weight of a newborn baby is necessary.*
  - Radar based machine learning technique

Experimental Setup







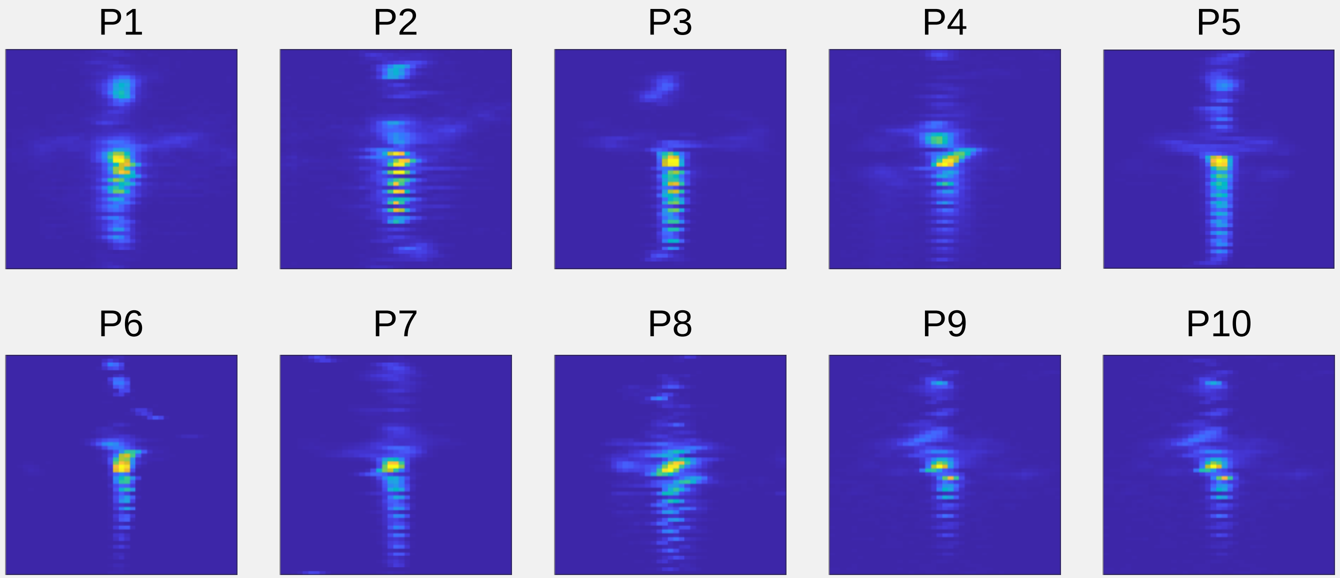
IWR6843 by TI

Radar Parameter	***Value/Description***
Starting frequency	60 GHz
Bandwidth	3.98 GHz
Frame rate	20 frames per second
Number of chirps	16 chirps per frame
ADC samples rate	520 samples per chirp
Number of Tx antenna used	2 Tx Antenna
Number of Rx antenna used	4 Rx Antenna

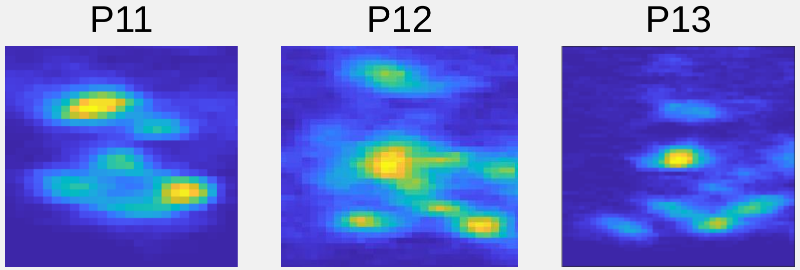
8 Virtual Antennas

Generation of Radar Signature Images

Raw Data → *Range FFT* → *Clutter Removal* → *Capon Algorithm* → *CFAR Algorithm* → *Radar Signature Image*



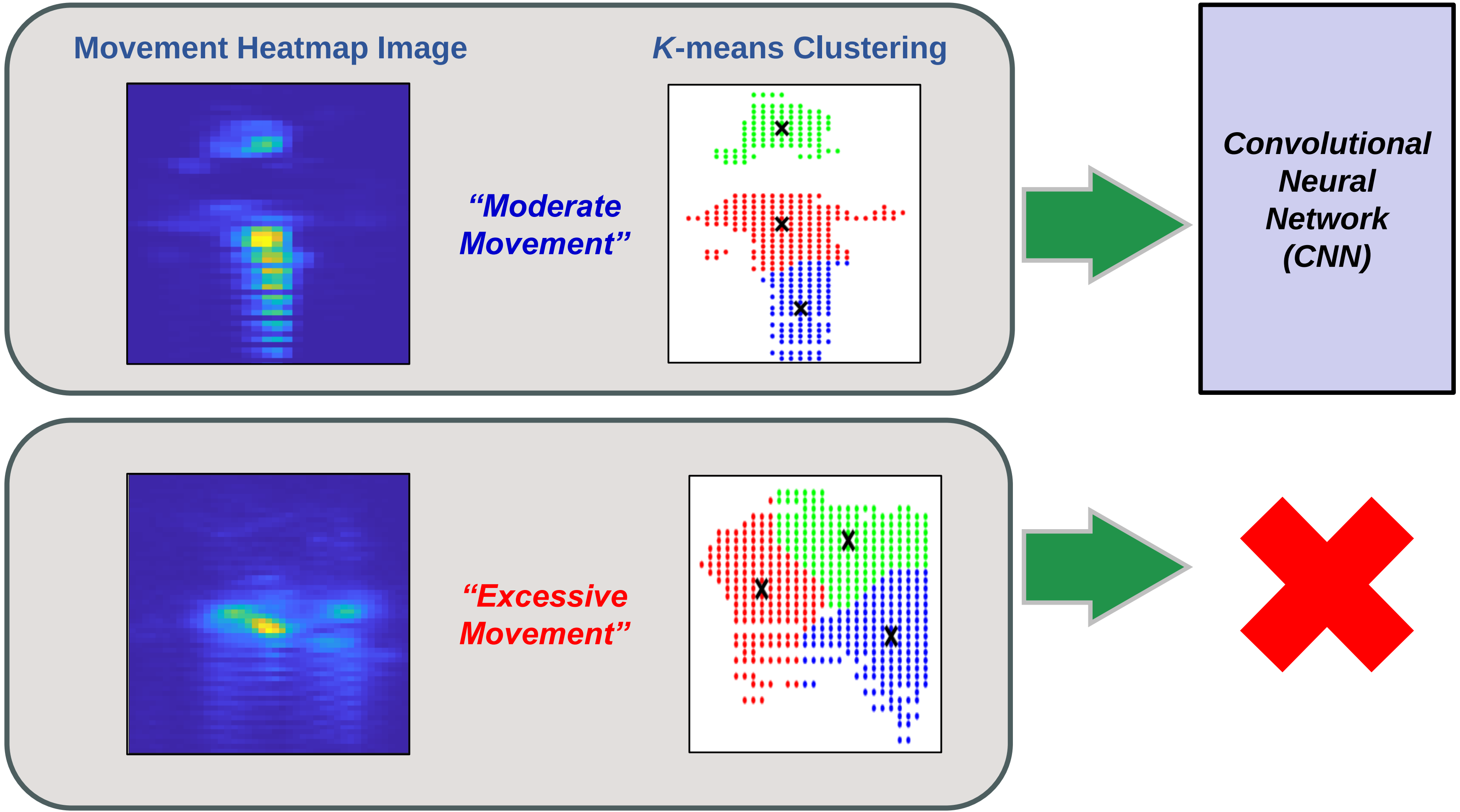
NICU / NB



Outpatient Clinic

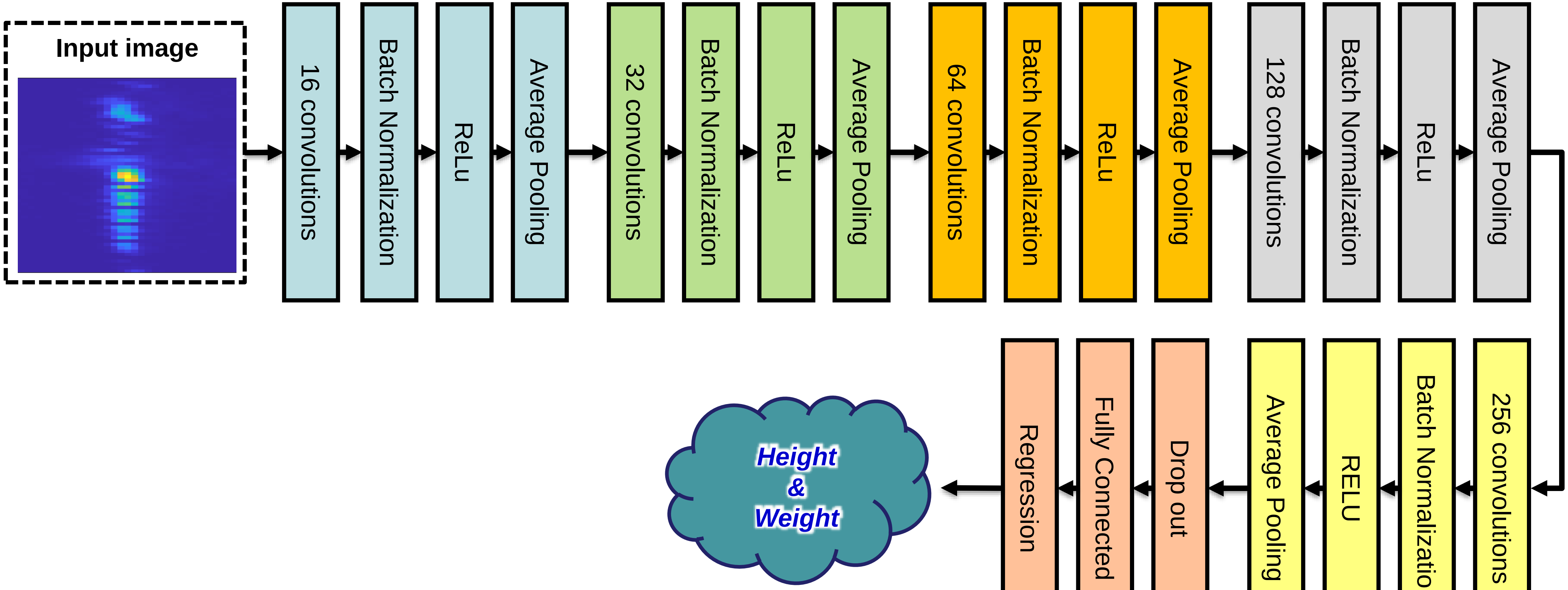
Selection of Heatmap Images

- *Images that show excessive movements of the neonates were eliminated for machine learning*
- *The K-means clustering technique is applied.*



Machine Learning Structure

- *Convolution Neural Network (CNN)*



Input image

16 convolutions

Batch Normalization

ReLu

Average Pooling

32 convolutions

Batch Normalization

ReLu

Average Pooling

64 convolutions

Batch Normalization

ReLu

Average Pooling

128 convolutions

Batch Normalization

ReLu

Average Pooling

256 convolutions

Batch Normalization

RELU

Average Pooling

Drop out

Fully Connected

Regression

Height & Weight

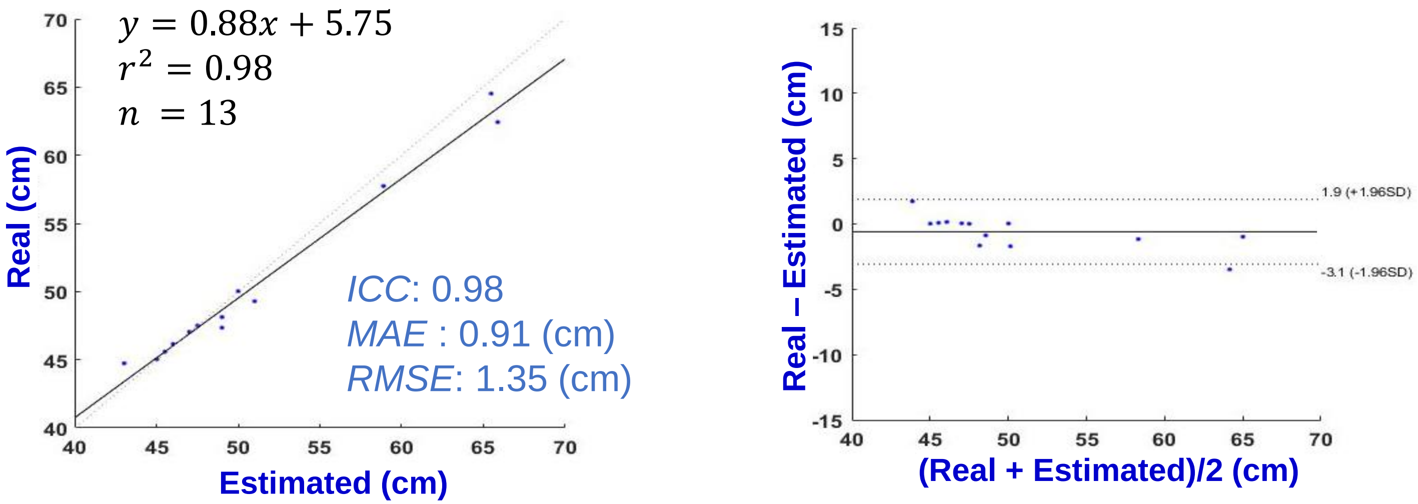
Results

Subjects	***Height Measurements (cm)***				***Weight Measurements (gram)***				***Locations of Data Acquisition***
	Radar	Real	Error (cm)	Error (%)	Radar	Real	Error (gram)	Error (%)	
P1	46.2	46	-0.2	0 %	2393	2210	-183.5	-8 %	NICU
P2	47.1	47	-0.1	0 %	3166	3200	33.8	1 %	NICU
P3	47.5	47.5	0.0	0 %	3287	3410	122.7	4 %	NICU
P4	47.3	49	1.7	3 %	3267	3560	292.9	8 %	NICU
P5	45.6	45.5	-0.1	0 %	2342	2180	-162.3	-7 %	NICU
P6	44.7	43	-1.7	-4 %	3172	3160	-11.6	0 %	NB
P7	48.1	49	0.9	2 %	2820	2640	-179.5	-7 %	NICU
P8	49.3	51	1.7	3 %	3491	3540	49.0	1 %	NICU
P9	45.0	45	0.0	0 %	2739	2640	-99.5	-4 %	NB
P10	50.0	50	0.0	0 %	3312	3450	137.5	4 %	NB
P11	57.7	58.9	1.2	2 %	6480	7200	719.7	10 %	Outpatient Clinic
P12	64.5	65.5	1.0	1 %	7434	7500	66.1	1 %	Outpatient Clinic
P13	62.4	65.9	3.5	5 %	6391	7000	609.0	9 %	Outpatient Clinic

Statistics

- *Intra-class correlation coefficient (ICC)*
- *Mean absolute error (MAE)*
- *Root mean square error (RMSE)*

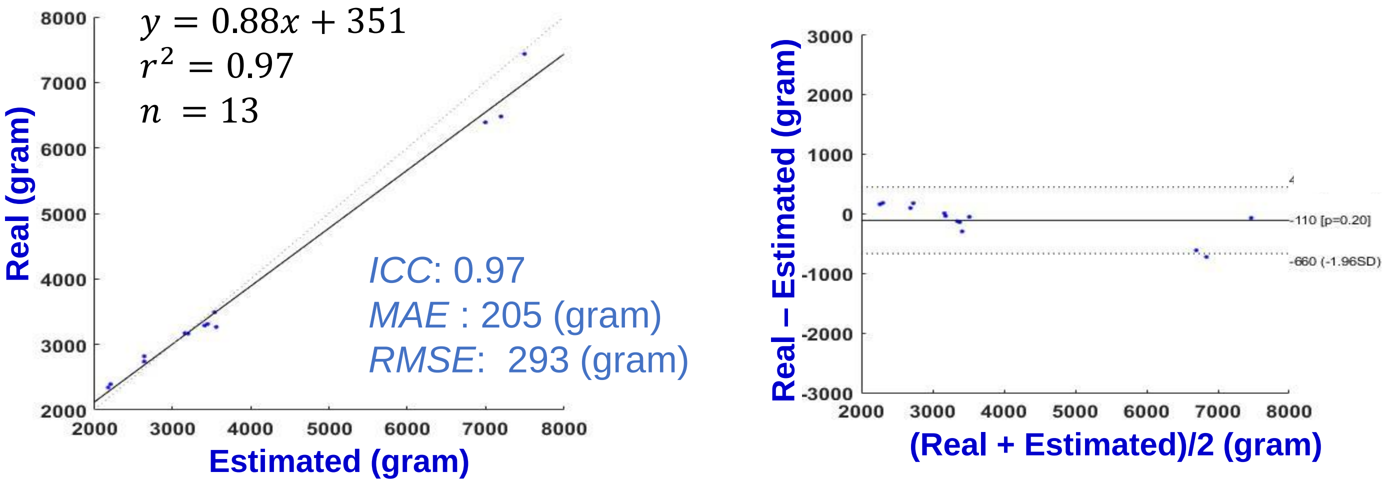
Height Measurement



$y = 0.88x + 5.75$
$r^2 = 0.98$
$n = 13$

ICC: 0.98
MAE : 0.91 (cm)
RMSE: 1.35 (cm)

Weight Measurement



$y = 0.88x + 351$
$r^2 = 0.97$
$n = 13$

ICC: 0.97
MAE : 205 (gram)
RMSE: 293 (gram)

Autonomous Screening of Neurodevelopmental High-Risk Infants

- "Autonomous Screening of Infants at High Risk for Neurodevelopmental Impairments using a Radar-based Machine Learning Method," *Scientific Reports*. Sep. 2024. (Under review)
- "Early Screening Tool for Developmental Delay in Infancy: Quantified Assessment of Movement Asymmetry Using IR-UWB Radar," *Frontiers in Pediatrics*, Oct. 2022.
- "Quantified Assessment of Hyperactivity in ADHD Youth Using IR-UWB Radar," *Scientific Reports*, May 2021.
- "Quantified Activity Measurement for Medical Use in Movement Disorders through IR-UWB Radar Sensor," *Sensors*, Feb. 2019.
- "Human–Computer Interaction Using Radio Sensor for People with Severe Disability," *Sensors and Actuators A: Physical*, Oct. 2018.

Importance of General Movements (GMs) Monitoring

❖ *General Movements (GMs)*

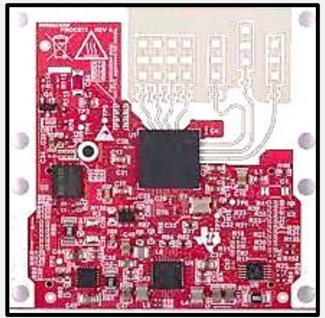
- An approach for early identification of infants at high risk of *neuro-developmental impairments (NDIs)*
- *C. Einspieler and H.F.R. Prechtl, "Prechtl's assessment of general movements: A diagnostic tool for the functional assessment of the young nervous system," Mental Retardation and Developmental Disabilities, Research Review, 11(1):61-67 (2005), doi: 10.1002/mrdd.20051.*
    - GMs involve the whole body in a variable sequence of arm, leg, neck, and trunk movements.
    - GMs wax and wane in intensity, force and speed, and have a gradual beginning and end.
    - If the nervous system is impaired, GMs loose their complex and variable character and become monotonous and poor.

❖ *Two specific abnormal GM patterns reliably predict later cerebral palsy:*

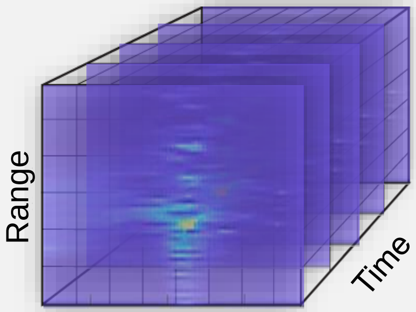
- A persistent pattern of ***Cramped Synchronized GMs (CSGMs)***.
    - The movements appear rigid and lack the normal smooth and fluent character.
    - Limb and trunk muscles contract and relax almost simultaneously.
- The absence of GMs with *Fidgety Character*.
    - So-called fidgety movements are small movements of moderate speed with variable acceleration of neck, trunk, and limbs in all directions.

Design Strategy

Data Collection

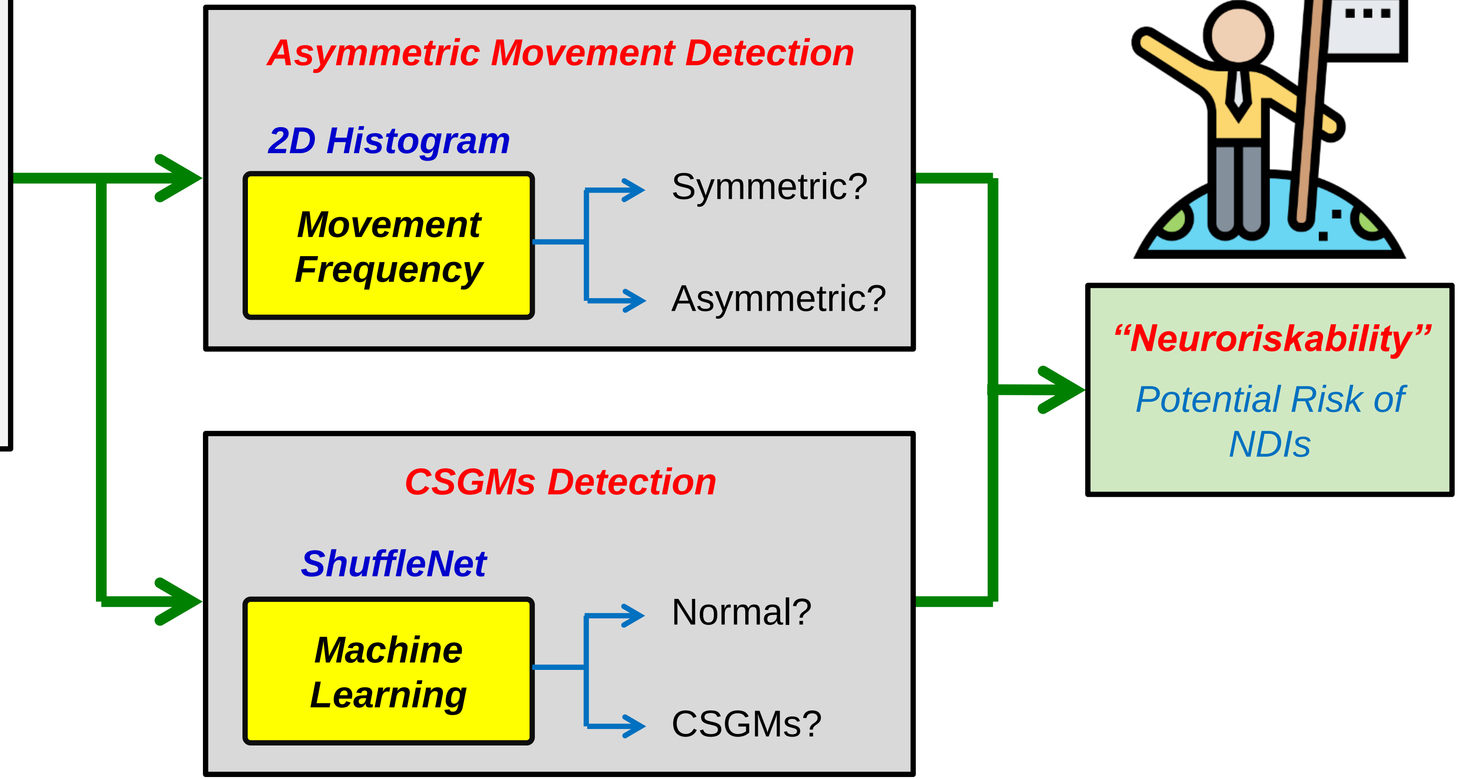


3D Radar Array (Range-Angle-Time)



Radar Parameters	***Description***
Starting frequency	60 GHz
Bandwidth	4 GHz
Frame rate	20 frames per second
Number of chirps	16 chirps per frame
ADC sample per chirp	520 samples
Number of Tx antennas	2
Number of Rx antennas	4
Field of view (FOV)	±60°

8 Virtual Antennas



Asymmetric Movement Detection

2D Histogram

Movement Frequency

- Symmetric?
- Asymmetric?

CSGMs Detection

ShuffleNet

Machine Learning

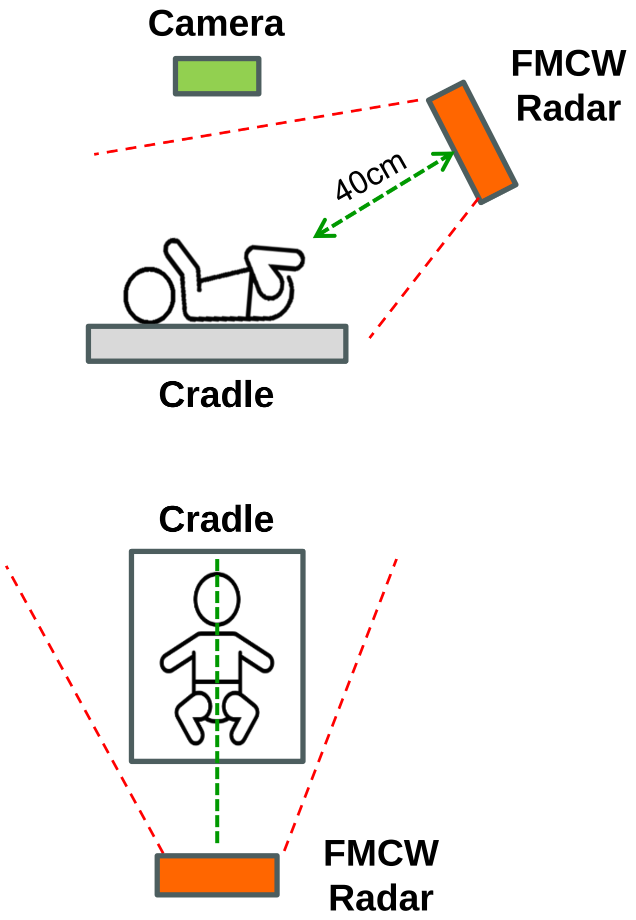
- Normal?
- CSGMs?

"Neuroriskability"

Potential Risk of NDIs

Data Collection

❖ *Experimental Setup*



NICU
Hanyang University Hospital

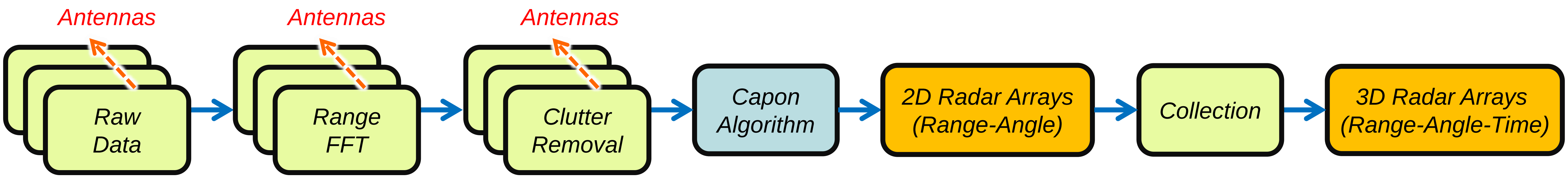
Baseline Characteristics of Infants Enrolled in This Study

Participants	*Gestational age (weeks)*	*Birth weight (grams)*	*Corrected age at experiment (weeks)*	*Weight at experiment (grams)*	*Diagnosis*
Control 1 (C1)	38^{+1}	3,320	38^{+4}	3,160	Normal Full-Term
Control 2 (C2)	38^{+0}	2,700	38^{+2}	2,640	Normal Full-Term
Control 3 (C3)	38^{+4}	3,450	38^{+5}	3,450	Normal Full-Term
Patient 1 (P1)	24^{+2}	710	37^{+6}	2,210	Suspicious HIE (both)
Patient 2 (P2)	25^{+0}	820	41^{+4}	3,410	Both IVH (GIII, both), PVL (left-G2, right-G4)

NICU: Neonatal Intensive Care Unit
HIE: Hypoxic Ischemic Encephalopathy (저산소 허혈성 뇌병증)
IVH: Intraventricular Hemorrhage (뇌실내 출혈)
PVL: Periventricular Leukomalacia (뇌실주변 백질연화증)
G: Grade

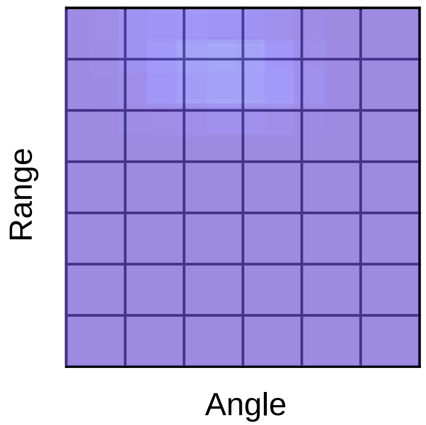
Generation of 3D Radar Arrays

- *For each frame, we perform*



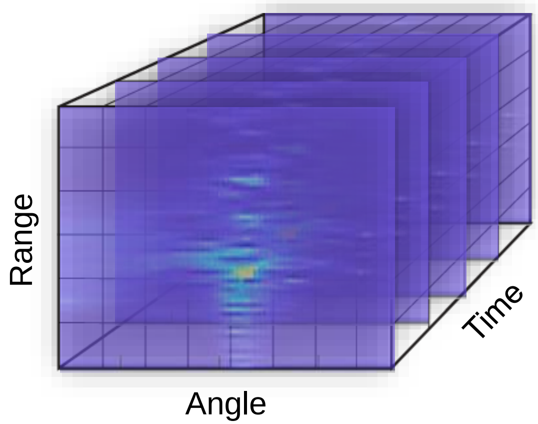
Radar Parameters	***Description***
Starting frequency	60 GHz
Bandwidth	4 GHz
Frame rate	20 frames per second
Number of chirps	16 chirps per frame
ADC sample per chirp	520 samples
Number of Tx antennas	2
Number of Rx antennas	4
Field of view (FOV)	±60°

2D Radar Arrays
(Range-Angle)



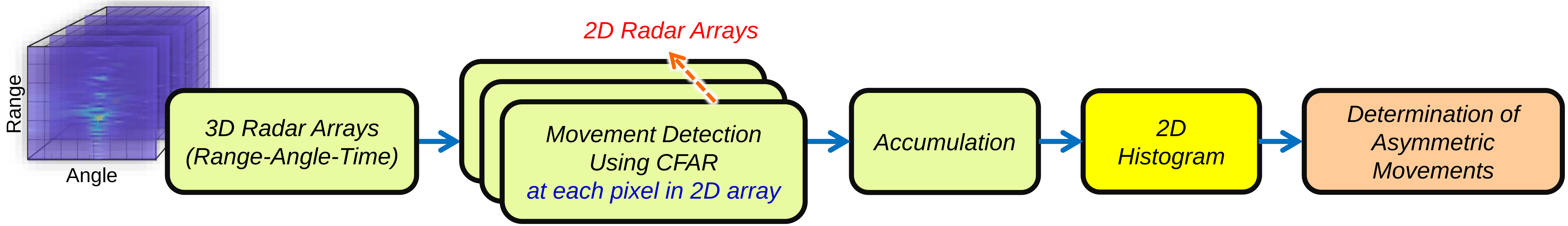
*Generate **20** 2D arrays / sec.*

3D Radar Arrays
(Range-Angle-Time)



Generate a 3D array by collecting 2D arrays for 10 seconds.
*(i.e., **200** 2D arrays for 10 sec)*

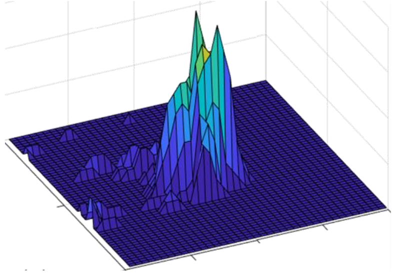
Asymmetric Movement Detection



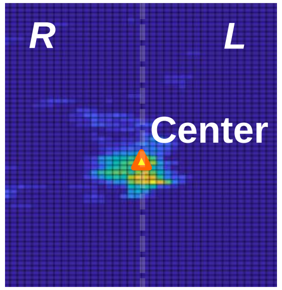
3D Radar Arrays (Range-Angle-Time) → *Movement Detection Using CFAR at each pixel in 2D array* → *Accumulation* → *2D Histogram* → *Determination of Asymmetric Movements*

Tolerance rage of difference in the R and L movements for being symmetric: **±10%**

Example:

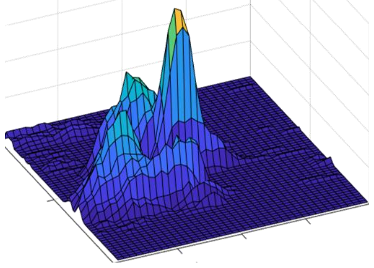


2D Histogram Image

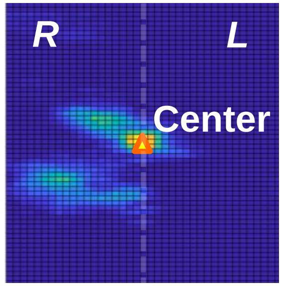


Symmetric Movement (Control Group)

R	***L***
7742	**8058**
49%	**51%**



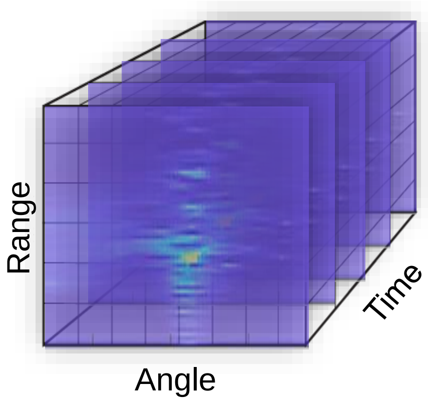
2D Histogram Image

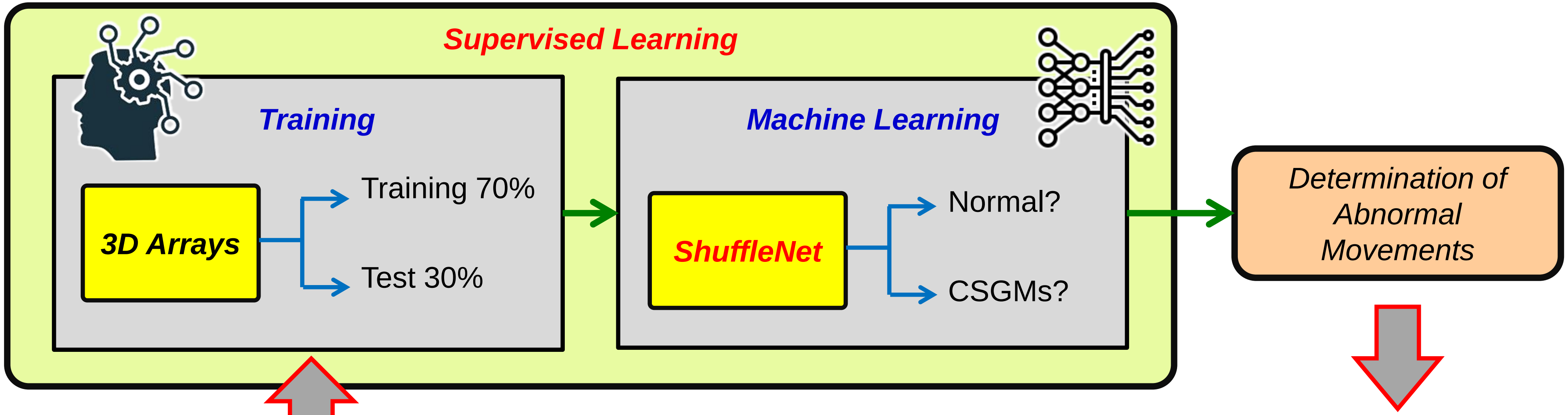


Asymmetric Movement (Patient Group)

R	***L***
11872	**4311**
73%	**27%**

Cramped Synchronized GMs (CSGMs) Detection





Supervised Learning

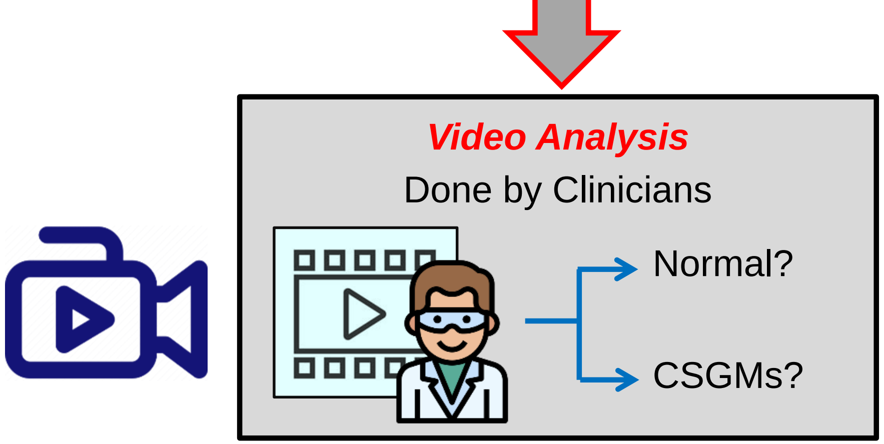
Training

3D Arrays
- Training 70%
- Test 30%

Machine Learning

ShuffleNet
- Normal?
- CSGMs?

Determination of Abnormal Movements



Video Analysis

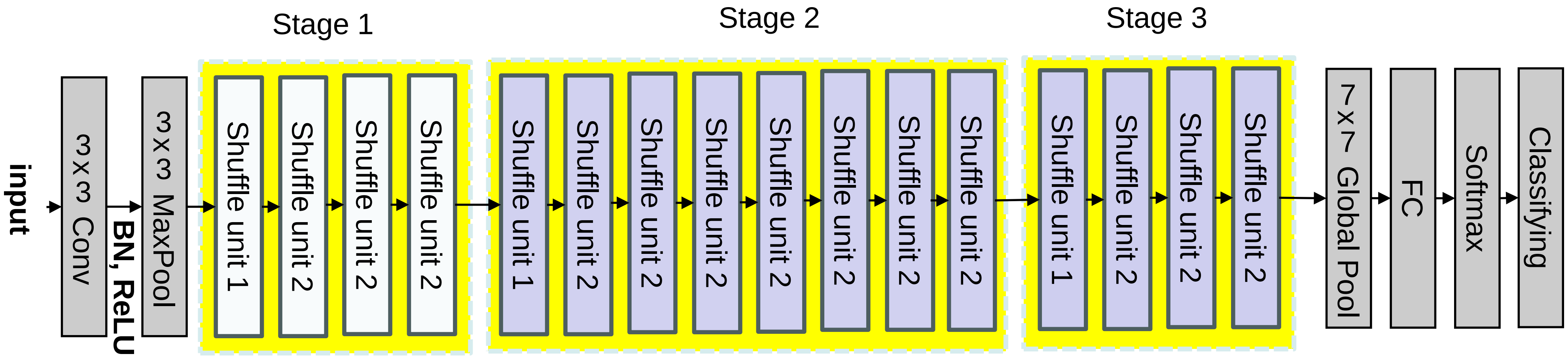
Done by Clinicians
- Normal?
- CSGMs?

	Radar-Based ML	
Video Analysis	Normal	CSGMs
Normal	453	85
CSGMs	59	512

Accuracy	0.87
Sensitivity	0.90
Specificity	0.84
Cohen’s Kappa	0.74

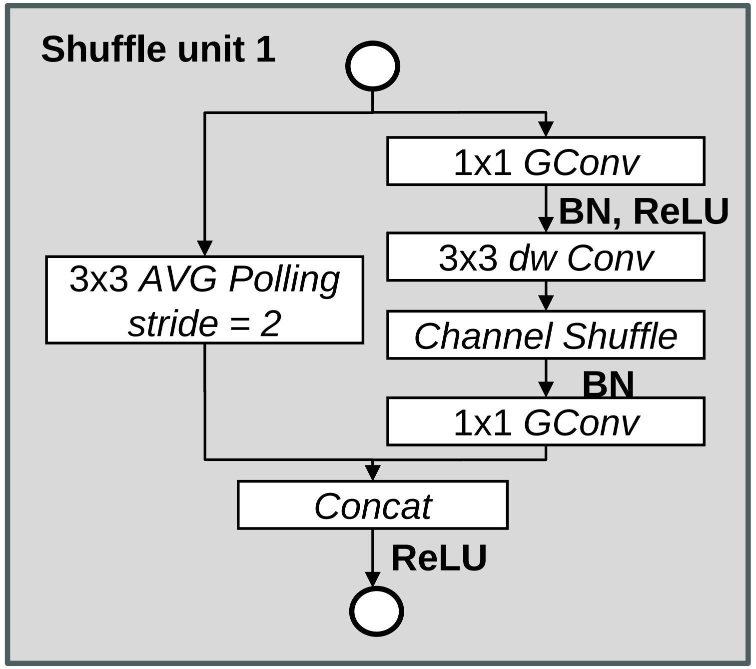
ShuffleNet is a convolutional neural network designed specially for mobile devices with very limited computing power.

ShuffleNet Structure

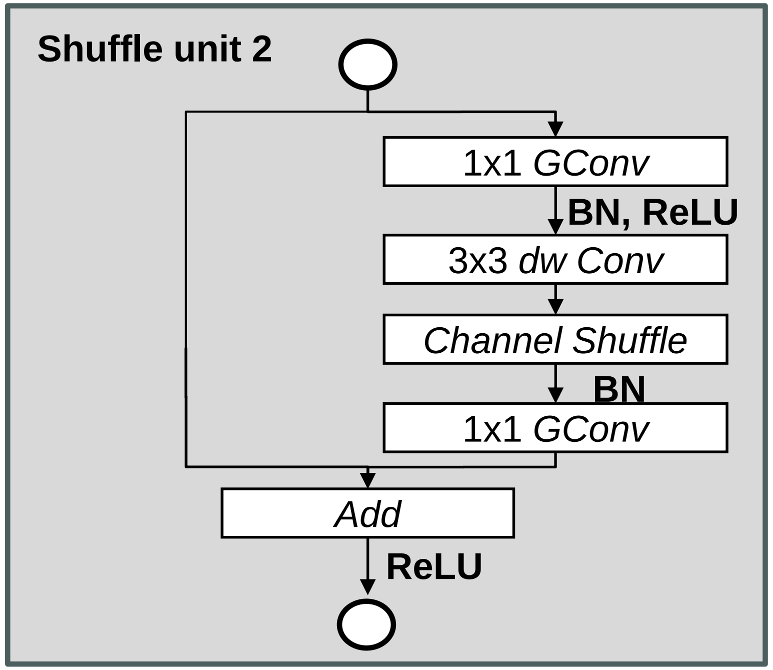


Stage 1
Stage 2
Stage 3

input
3x3 Conv
BN, ReLU
3x3 MaxPool
Shuffle unit 1
Shuffle unit 2
Shuffle unit 2
Shuffle unit 2
Shuffle unit 1
Shuffle unit 2
Shuffle unit 2
Shuffle unit 2
Shuffle unit 2
Shuffle unit 2
Shuffle unit 2
Shuffle unit 2
Shuffle unit 1
Shuffle unit 2
Shuffle unit 2
Shuffle unit 2
7x7 Global Pool
FC
Softmax
Classifying



Shuffle unit 1
1x1 *GConv*
BN, ReLU
3x3 *dw Conv*
Channel Shuffle
BN
1x1 *GConv*
3x3 *AVG Polling stride = 2*
Concat
ReLU



Shuffle unit 2
1x1 *GConv*
BN, ReLU
3x3 *dw Conv*
Channel Shuffle
BN
1x1 *GConv*
Add
ReLU

Neuroriskability

- *Possibility of Having Neuro-Developmental Impairments (NDIs)*

- *Calculation of Neuroriskability*

Number of Detected Asymmetric Movement		***Number of Detected Abnormal Movement***		***Neuroriskability*** (%) **(B+D)/(A+B+C+D)**
Symmetric **A**	Asymmetric **B**	Normal **C**	CSGMs **D**	

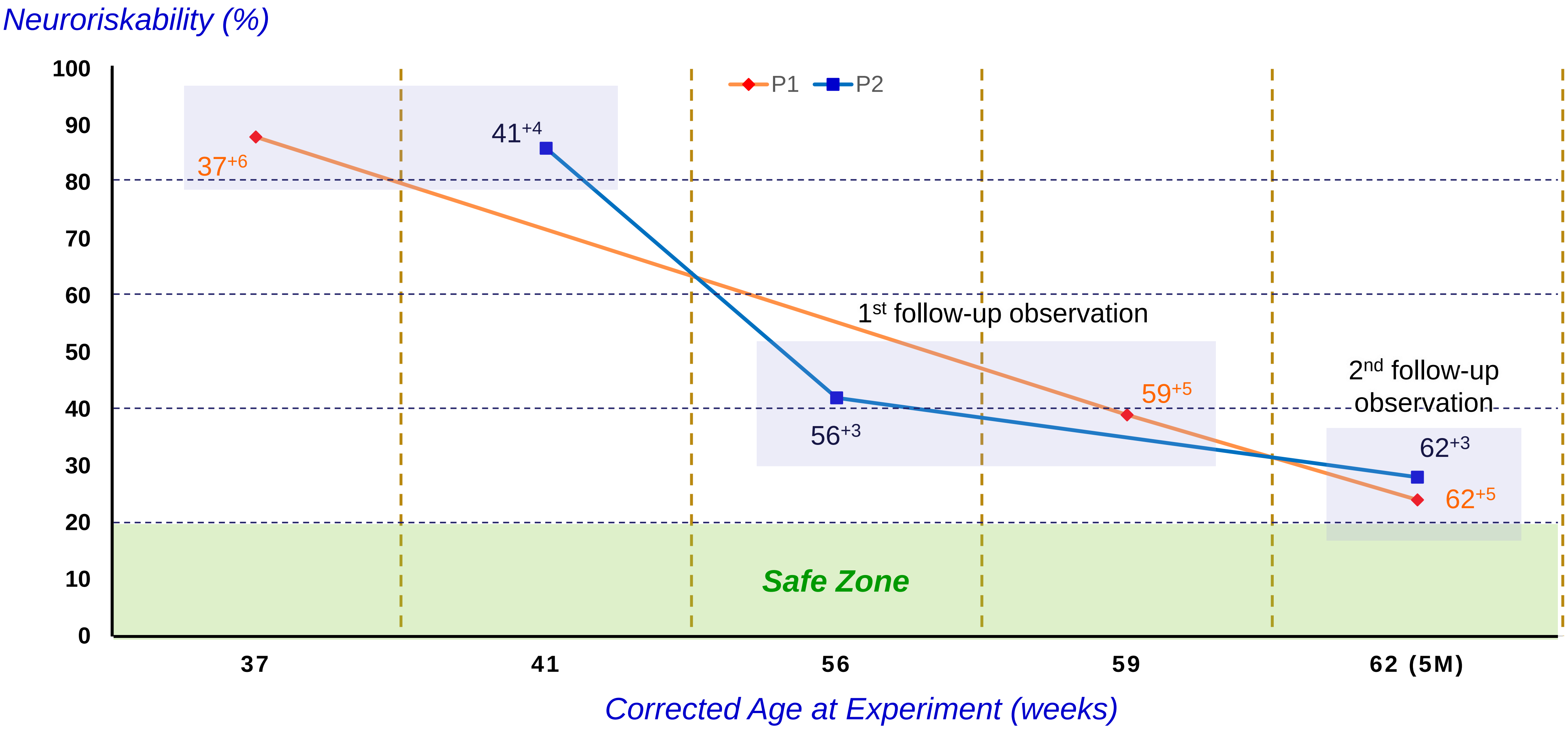
Neuroriskability Results

- *Neuroriskability was computed using randomly selected **45** 3D arrays from each baby.*

Participant	***Number of Asymmetric Movement Detection***		***Number of Abnormal Movement Detection***		***Neuroriskability*** **(B+D)/(A+B+C+D)** (%)
	Symmetric, **A**	Asymmetric, **B**	Normal, **C**	CSGMs, **D**	
C1	37 (82%)	8 (18%)	39 (91%)	6 (9%)	16%
C2	34 (76%)	11 (24%)	40 (89%)	5 (11%)	18%
C3	32 (71%)	13 (29%)	41 (91%)	4 (9%)	19%
Sub-Total	103 (76%)	32 (24%)	12 (90%)	13 (10%)	17%
P1	9 (20%)	36 (80%)	1 (4%)	44 (96%)	88%
P2	6 (13%)	39 (87%)	7 (16%)	38 (84%)	86%
Sub-Total	15 (17%)	75 (83%)	8 (9%)	82 (91%)	87%

Follow-Up Results of Patient Group (P1 and P2)

It was confirmed that the improvements in neuroriskability were comparable with the neurological examination results performed by medical specialists at the clinic.



Waist-to-Hip Ratio (WHR) Monitoring in Obese Youth

- "Evaluating waist-to-hip ratio in youth using frequency-modulated continuous wave radar and machine learning," *Scientific Reports*. Sep. 2024. (Under review)

Why Waist-to-Hip Ratio (WHR) Monitoring?

- ***Obesity** is a significant global public health issue.*
  - It is linked to serious metabolic diseases, such as *abdominal obesity*, *high blood sugar*, *high blood pressure*, *high HDL cholesterol*, and *high triglycerides*.
  - ***Body Mass Index (BMI):***
    - Most commonly used to diagnose obesity.
    - It, however, does not provide information on the proportion and distribution of fat.
  - ***Waist-to-Hip ratio (WHR):***
    - Effective indicator of *central obesity*
    - Central obesity is a more significant risk factor for cardiovascular diseases and mortality than BMI-defined obesity.

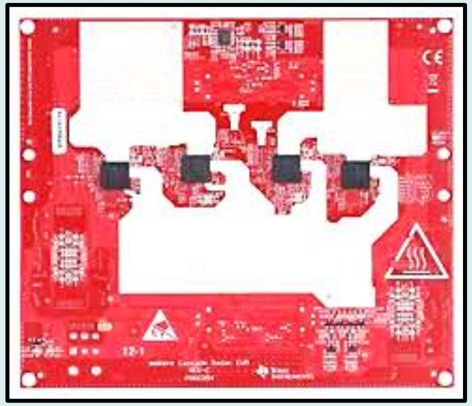
- ***Measuring WHR with tape (conventional method)** can be inconvenient, and potentially and socially unacceptable in children of pubertal age or in certain cultures.*

- ***Measuring WHR with radar** offers convenience and simplicity for easy measurement.*

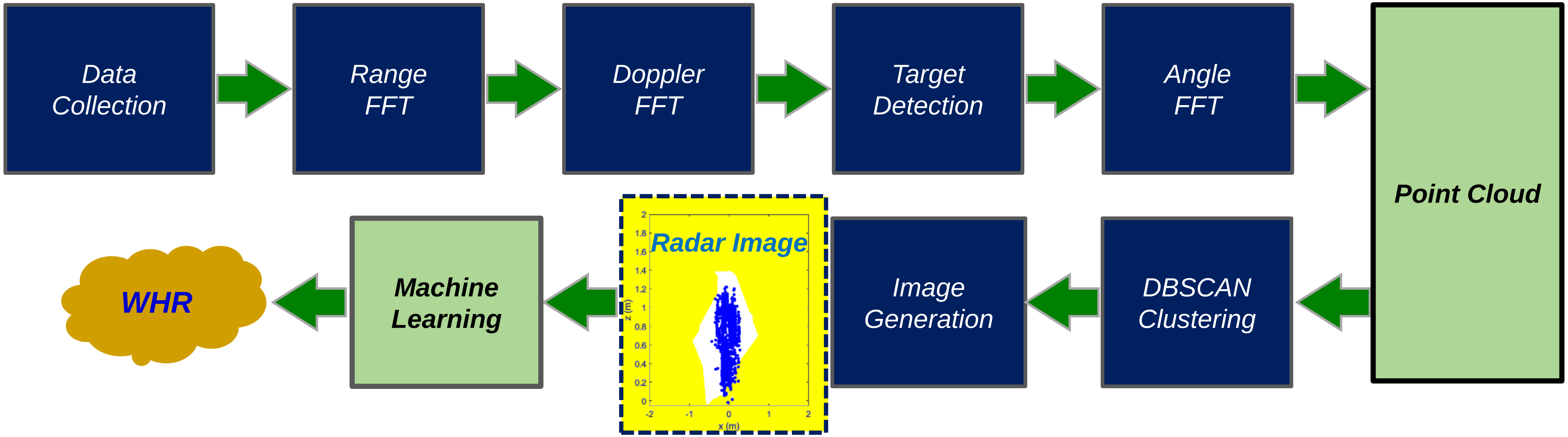
Non-contact **Daily** **Convenient**

Design Strategy

AWR2243 Cascade FMCW Radar



Radar Parameters	Description
Starting frequency	77 GHz
Bandwidth	3.3 GHz
Frame rate	50 frames per second
Number of chirps	32 chirps per frame
ADC sample per chirp	256 samples
Number of Tx antennas	12 Tx Antenna
Number of Rx antennas	16 Rx Antenna

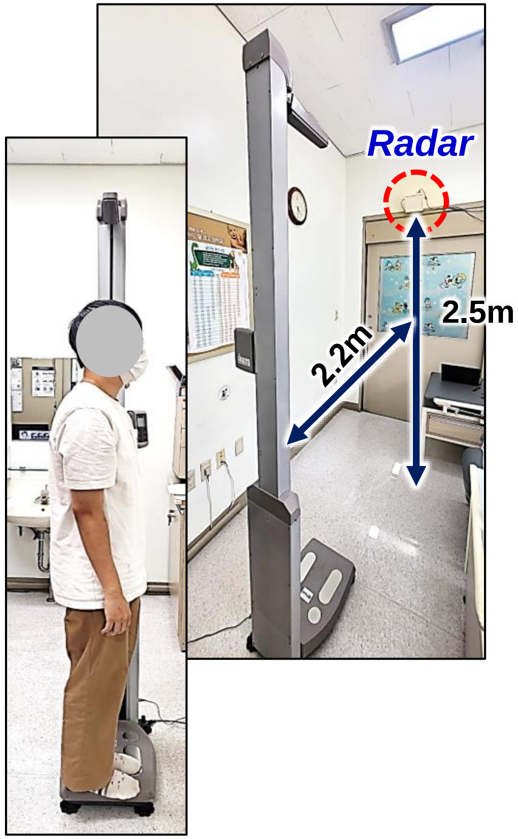


Data Collection → Range FFT → Doppler FFT → Target Detection → Angle FFT → Point Cloud → DBSCAN Clustering → Image Generation → Radar Image → Machine Learning → WHR

250 radar images for each participant at every 5 sec

Experimental Setup

- *100 Participants*



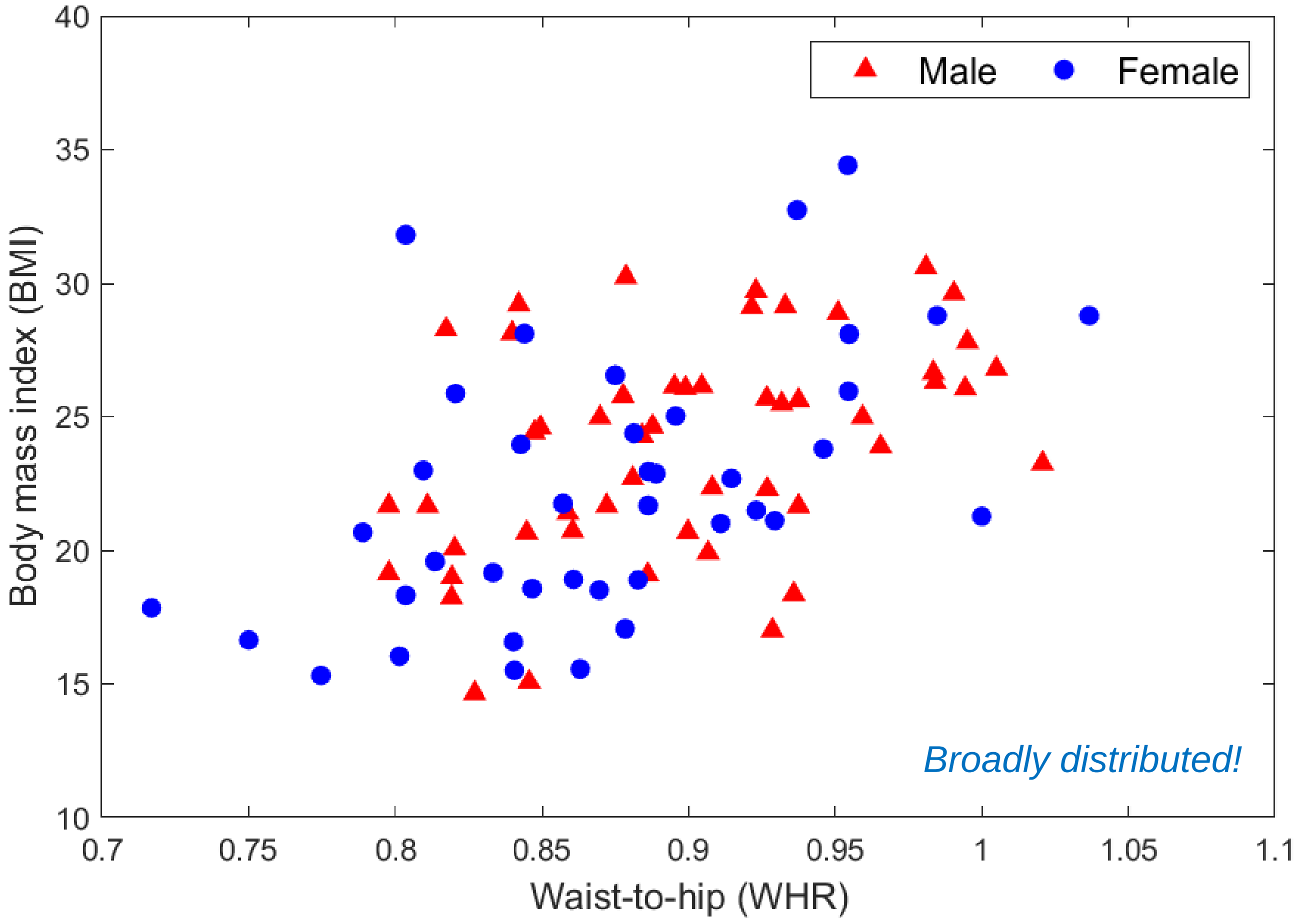
Demographics of Participants

Variable	*Low WHR (WHR ≤ 0.86)*	*Moderate WHR (0.86 < WHR < 0.91)*	*High WHR (WHR ≥ 0.91)*	*Total*
Age (Years)	11.49 ± 1.88	10.95 ± 1.94	10.87 ± 1.87	11.10 ± 1.90
Gender (N)				
Male	17 (53.1 %)	14 (43.8 %)	14 (38.9 %)	45 (45 %)
Female	15 (46.9 %)	18 (56.2 %)	22 (61.1 %)	55 (55 %)
Sub-total	**32**	**32**	**36**	**100**
Height (cm)	150.28 ± 13.20	146.86 ± 11.28	150.04 ± 13.74	149.10 ± 12.79
Height z-score	0.46 ± 0.97	0.50 ± 0.92	0.97 ± 1.08	0.54 (-0.05 - 1.19)
Weight (kg)	43.05 (36.85 - 57.02)	49.82 ± 13.34	60.29 ± 19.62	50.35 (39.00 - 63.23)
Weight z-score	0.69 ± 1.20	1.25 ± 1.06	2.17 ± 1.09	1.40 ± 1.27
Waist Circumference (cm)	70.70 ± 10.14	76.57 ± 9.27	88.74 ± 12.11	79.07 ± 13.02
Hip Circumference (cm)	86.23 ± 11.63	86.68 ± 10.06	92.78 ± 11.59	88.74 ± 11.44
WHR	0.82 (0.80 - 0.84)	0.88 ± 0.01	0.95 (0.93 - 0.98)	0.89 ± 0.06
BMI (kg/m^2)	21.09 ± 4.56	22.68 ± 3.40	25.98 ± 4.35	23.36 ± 4.60
BMI z-score	0.60 ± 1.42	1.36 ± 1.08	2.32 ± 0.98	1.67 (0.42 - 2.50)

※ Data are presented as mean ± standard deviation for normally distributed variables and median (Q1-Q3) for non-normally distributed variables.

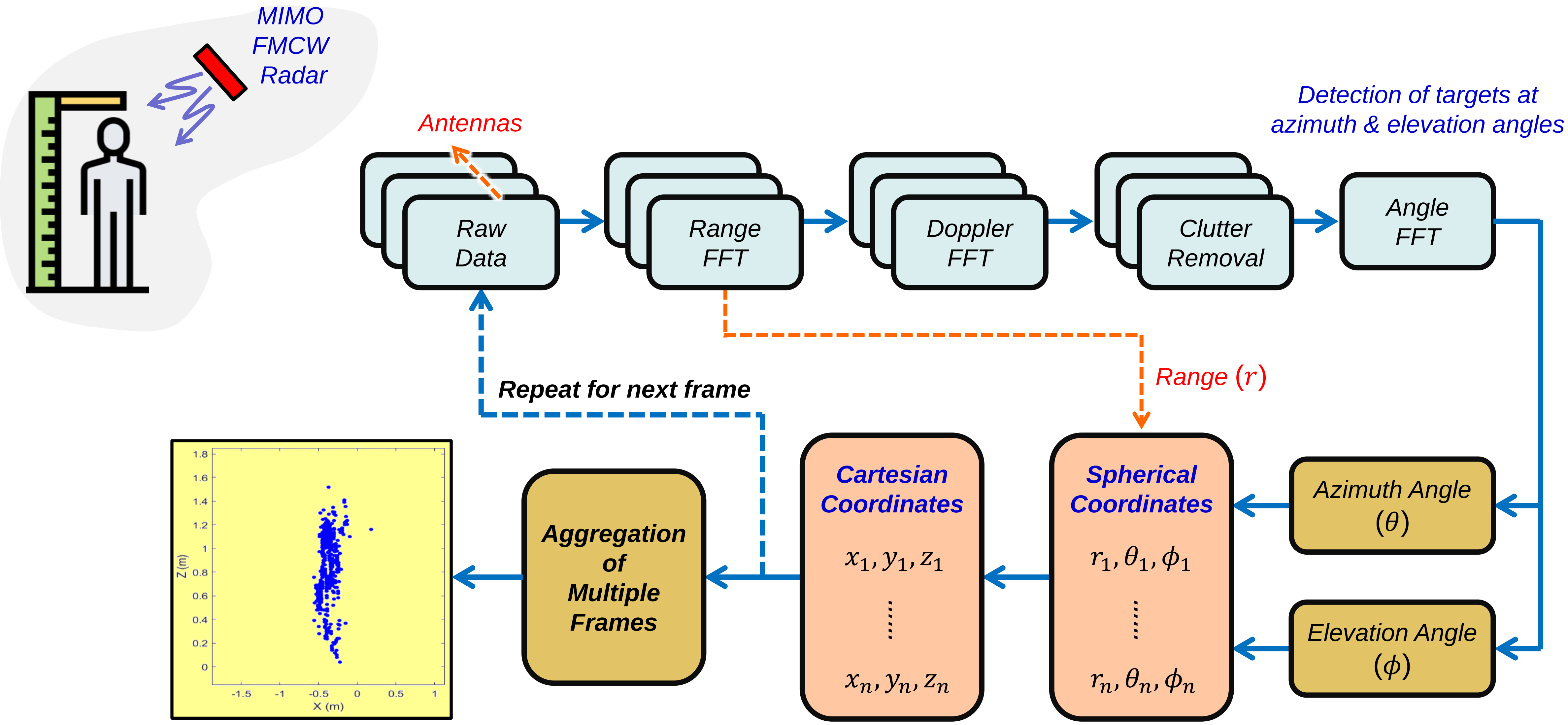
Demographic Distribution

- *Scatter Plot for Participants*



Broadly distributed!

Point Cloud



MIMO FMCW Radar

Antennas

Detection of targets at azimuth & elevation angles

Raw Data

Range FFT

Doppler FFT

Clutter Removal

Angle FFT

Range (r)

Repeat for next frame

Azimuth Angle (θ)

Elevation Angle (ϕ)

Spherical Coordinates

r_1, θ_1, ϕ_1

$\vdots$

r_n, θ_n, ϕ_n

Cartesian Coordinates

x_1, y_1, z_1

$\vdots$

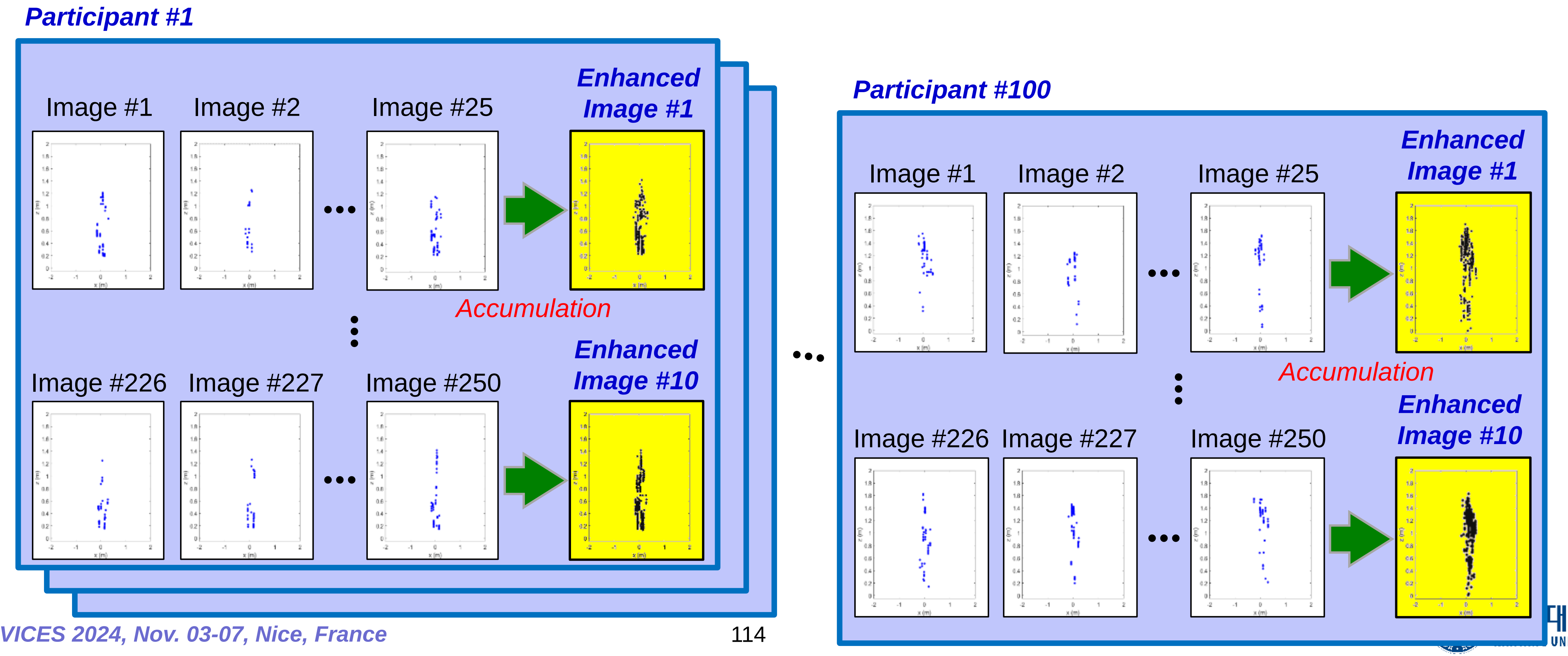
x_n, y_n, z_n

Aggregation of Multiple Frames

n: *number of detected target points*

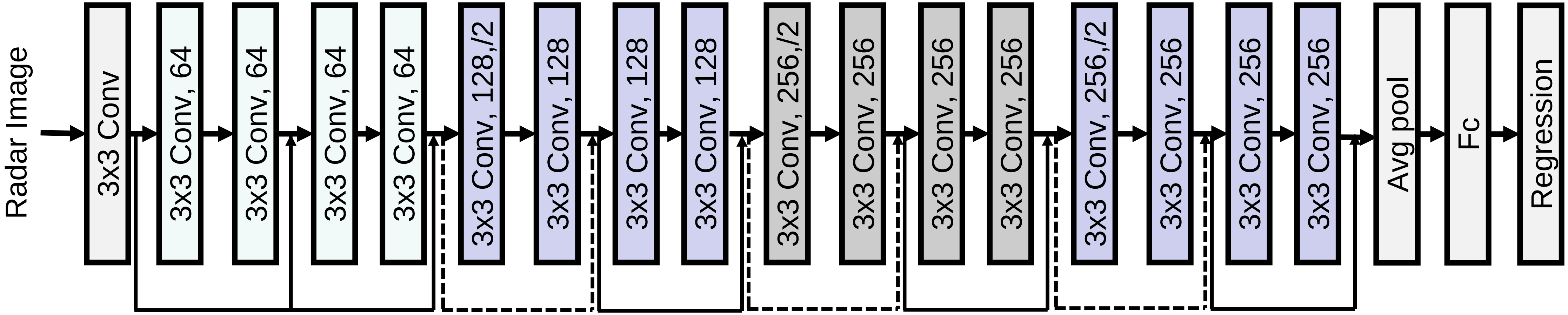
Radar Image Generation and Enhancement

- *Generated 250 radar images at every 5 sec for each participant.*
- *Accumulated every 25 radar images to generate 10 enhanced images for each participant.*
  - 8 images for *Training*, and 2 images for *Testing*.



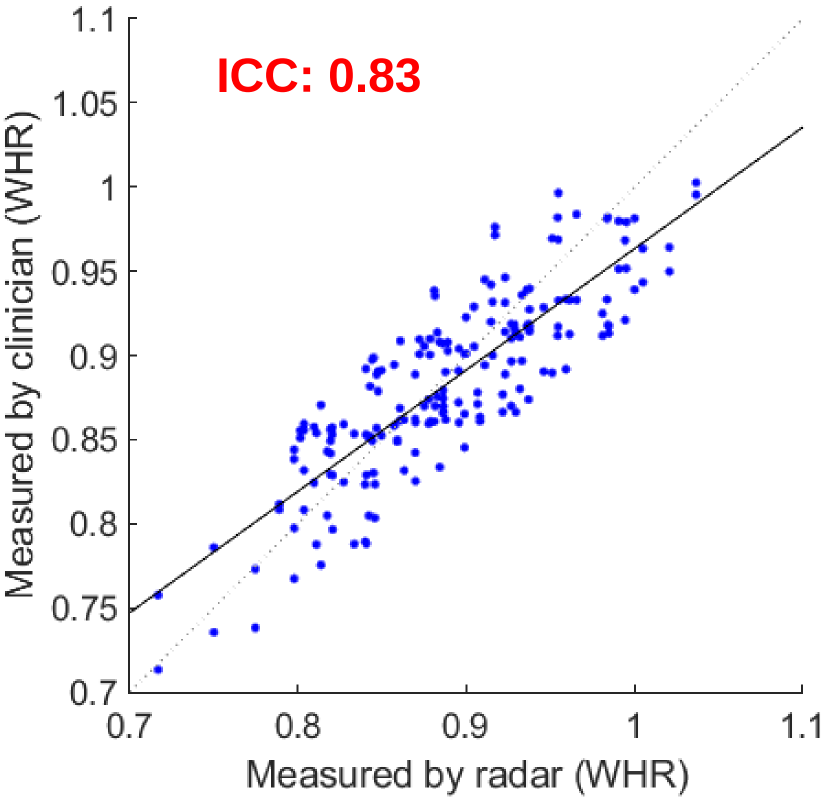
Machine Learning Structure

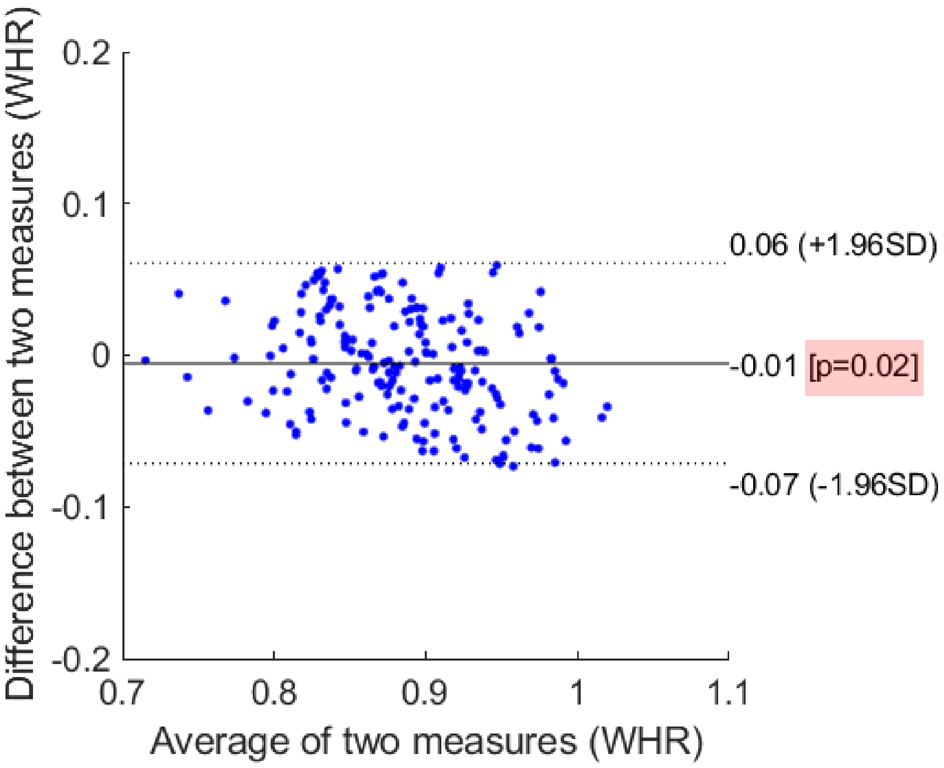
- ***ResNet-18** for WHR Measurements*



Performance of Radar-Based WHR Measurements

- *Intra-Class Correlation (ICC)*





Classification of Three Types of WHR Group

- *Confusion Matrix*

		Measurements by Clinician			***Overall***
		Low WHR	***Moderate WHR***	***High WHR***	***Accuracy*: 0.82**
Measurements by Radar	***Low WHR***	54	8		***Precision*: 0.82**
	Moderate WHR	10	51	14	***Recall*: 0.82**
	High WHR		5	58	***F1-Score*: 0.82**

Baseline for Risk Groups

WHR Group	*WHR Baseline*
Low WHR	WHR ≤ 0.86
Moderate WHR	0.86 < WHR < 0.91
High WHR	WHR ≥ 0.91


thank you