IEEE INFOCOM 2023

Argosleep: Monitoring Sleep Posture from Commodity Millimeter-Wave Devices

Aakriti Adhikari, Sanjib Sur

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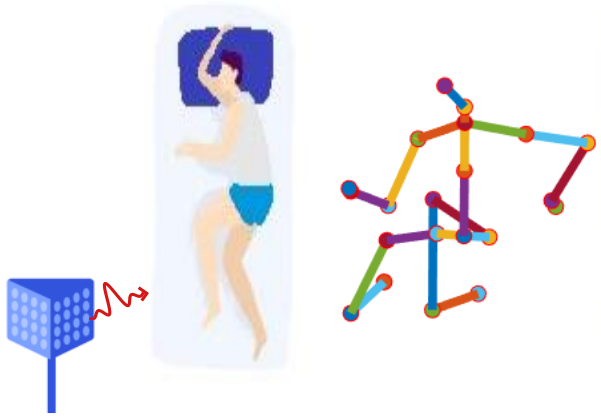


UNIVERSITY OF SOUTH CAROLINA
College of Engineering and Computing

SyReX
Systems Research on X

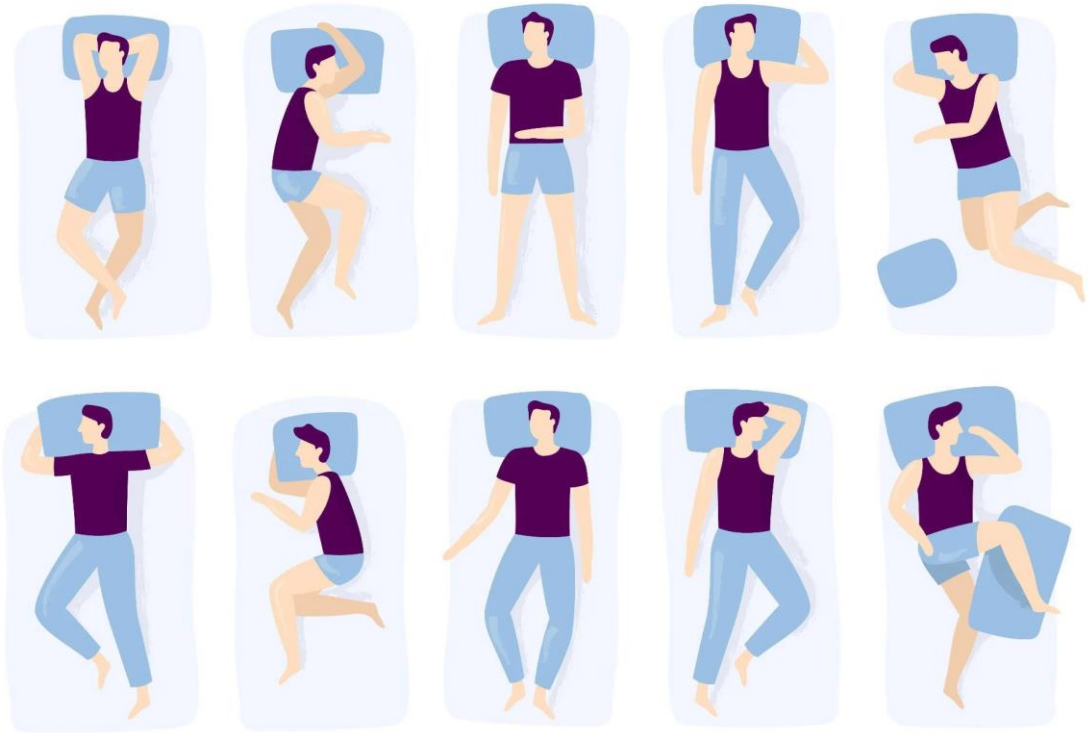
Importance of Sleep

- Sleep disorders have been linked with a wide range of health consequences

Sleep is essential for proper functioning of human body

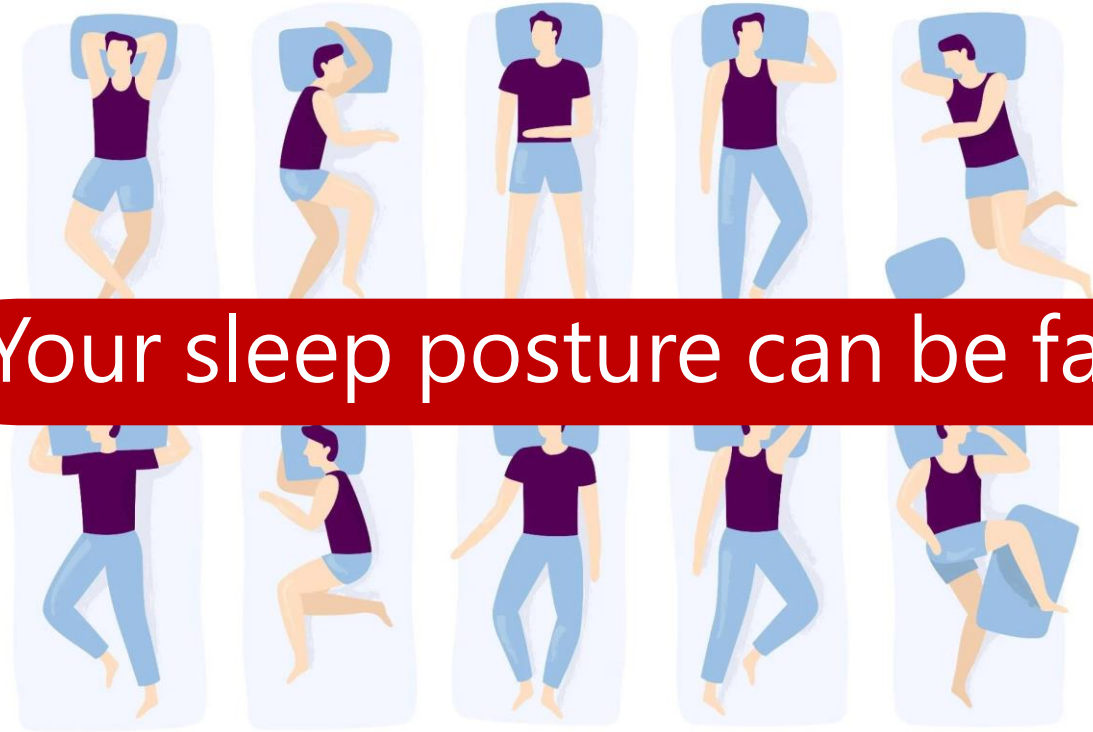
Importance of Sleep Posture

Importance of Sleep Posture



- We have our favorite sleep postures

Importance of Sleep Posture



Your sleep posture can be fatal

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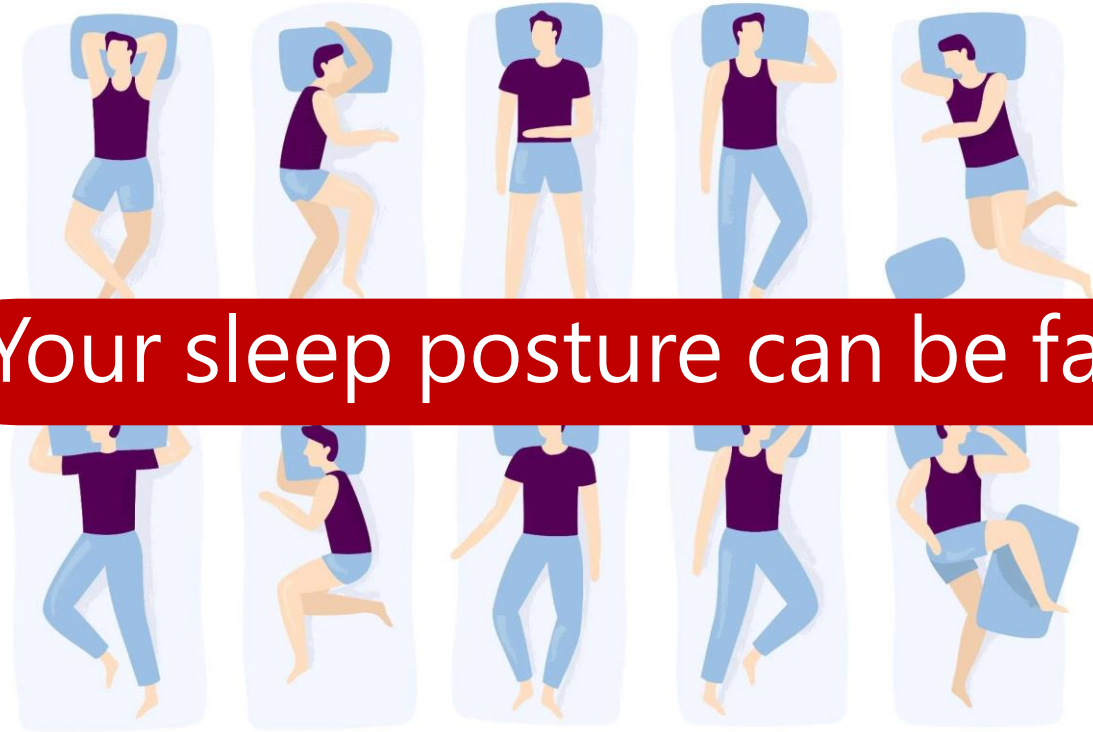

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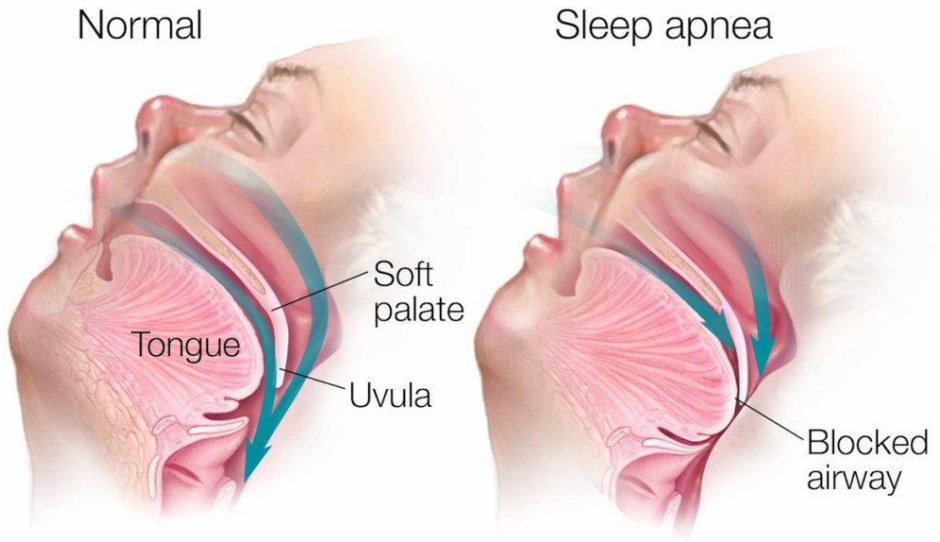

- **Supine posture** exacerbates sleep apnea
- Sleeping on left side eases heartburn
- Side sleeping aids in digestion

Sleep posture is correlated with many health conditions

Importance of Sleep Posture

Sleep Posture Monitoring

Sleep posture monitoring is essential for long-term good health

Importance of Sleep Posture

- Sleep posture as an indicator of Parkinson's progression

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Sleep Posture Monitoring

- Sleep posture monitoring is required post-surgery

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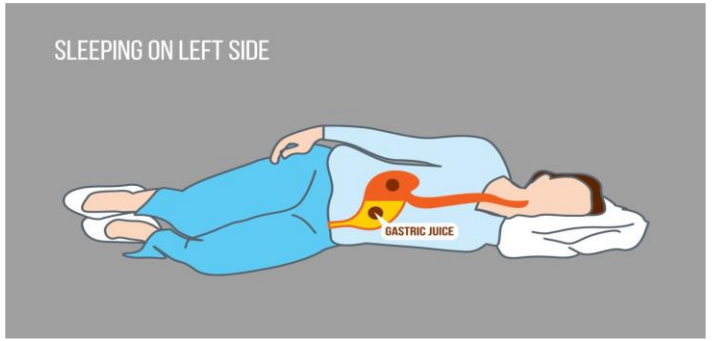
Sleep Posture Monitoring

- Sleep posture monitoring is required to adopt to new posture



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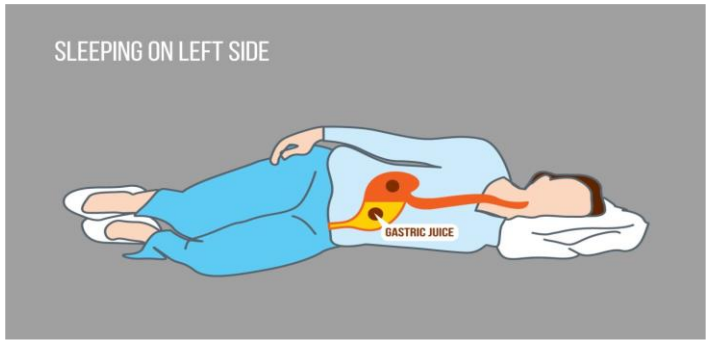
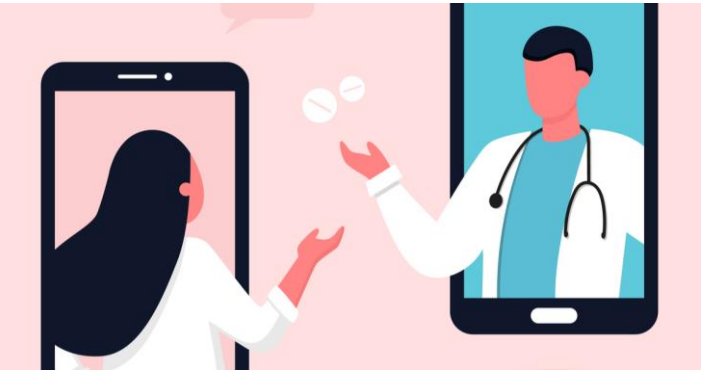


- Sleep posture monitoring to provide insight into sleep quality



Sleep posture monitoring is essential for long-term good health

Existing Techniques

Existing Techniques

In-clinic

Expensive and requires overnight stay

Not an accurate representation

Existing Techniques

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Expensive and requires overnight stay

Not an accurate representation

At-home

- Contact-based Systems

Cumbersome and brings discomfort

Expensive (pressure mattress > $2500)

Existing Techniques

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Expensive and requires overnight stay

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At-home

- Contact-based Systems

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Expensive (pressure mattress > $2500)

- Contact-less Systems

Hindered by low-lighting and occlusion

Low resolution in Wi-Fi

Opportunity: Millimeter-Wave in 5G

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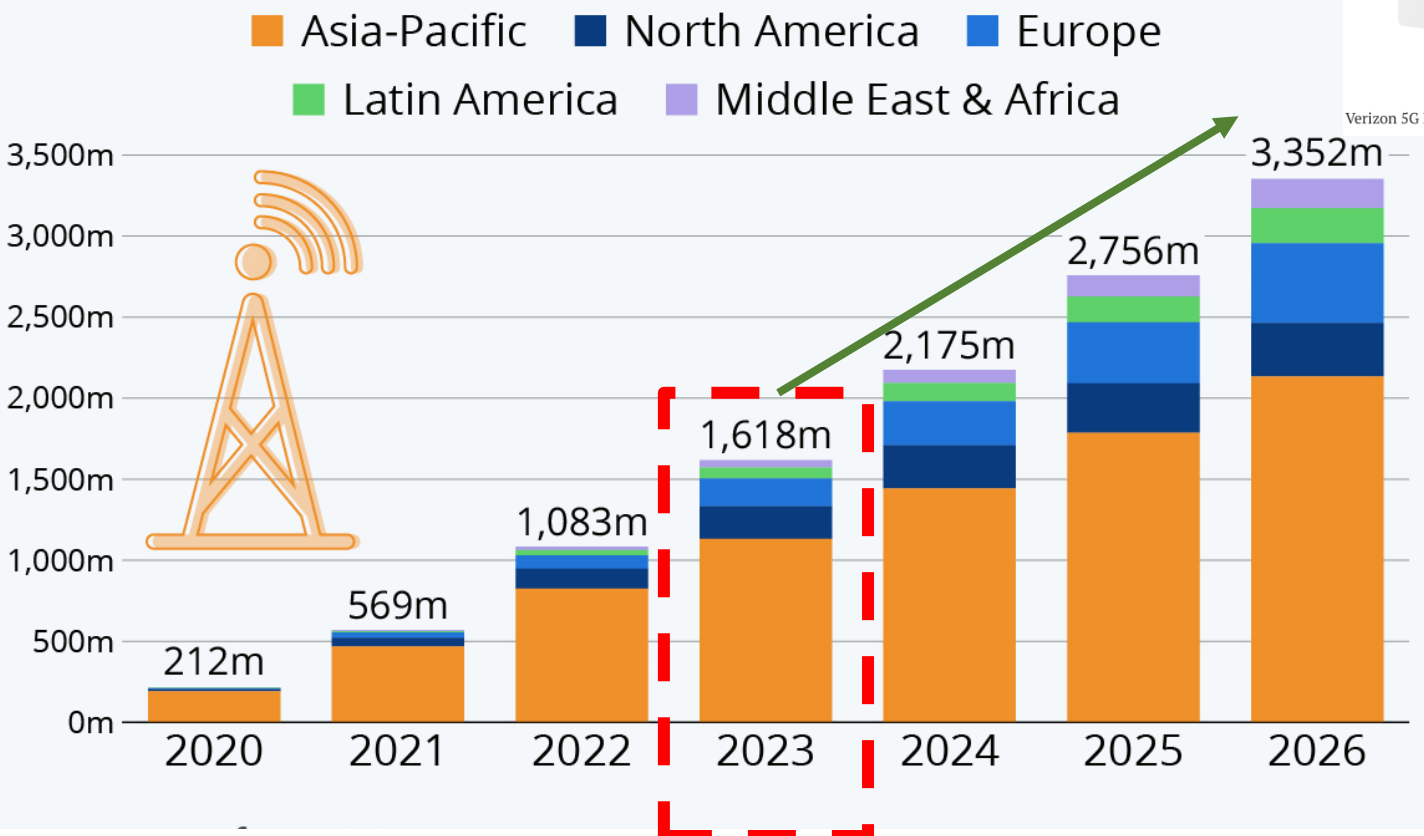
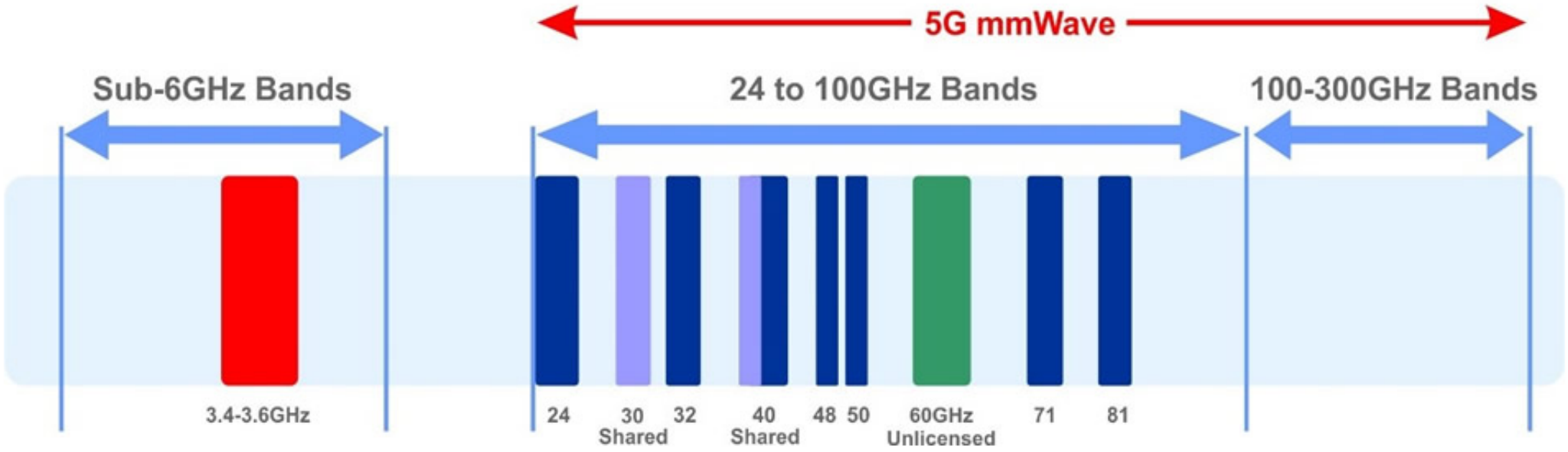
Global 5G Adoption to Hit One Billion in 2022

Forecast of 5G smartphone subscriptions by region (in millions)

Verizon 5G Home Gateway (Verizon)



Opportunity: Millimeter-Wave in 5G



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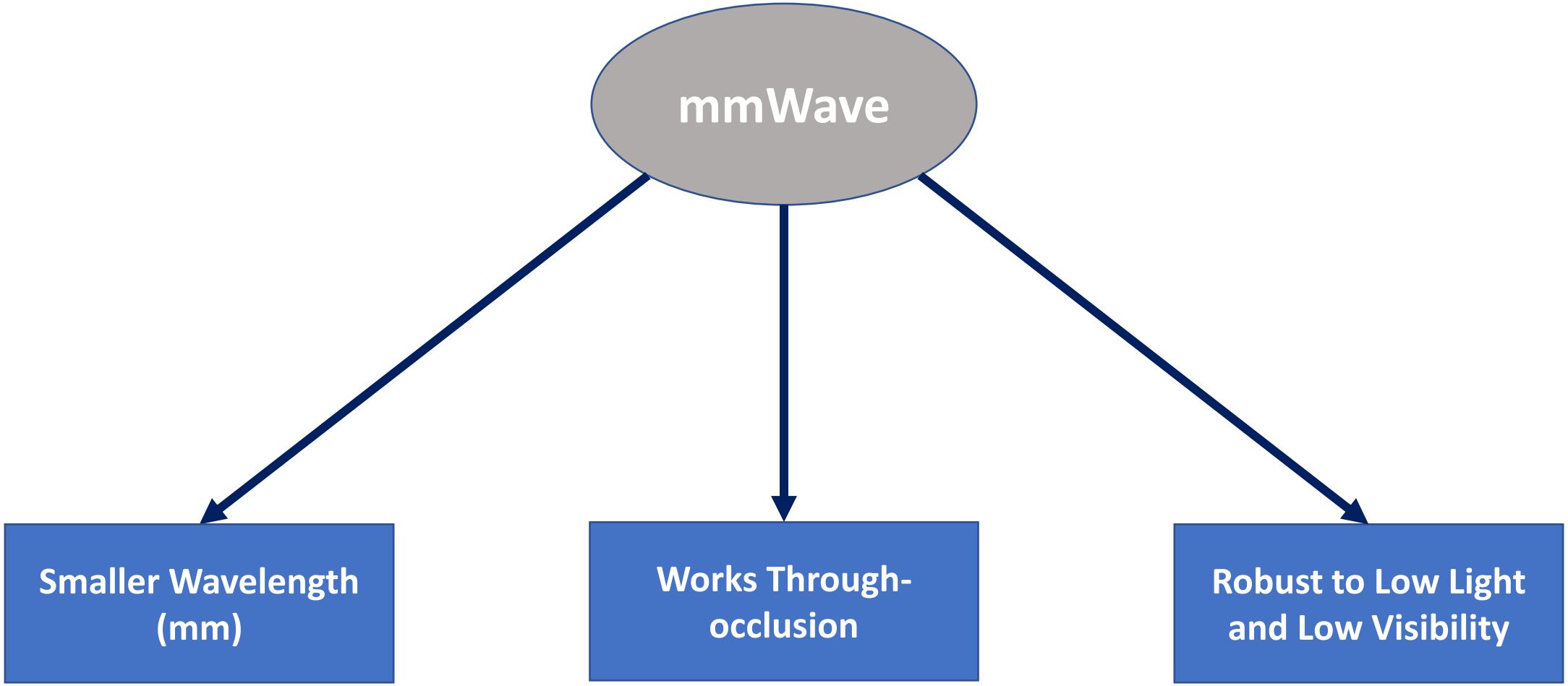

Argosleep: A Sleep Monitoring System

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Works Under Low Light and Low Visibility

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Works Through-occlusion

Argosleep: A Sleep Monitoring System

Works Under Low Light and Low Visibility

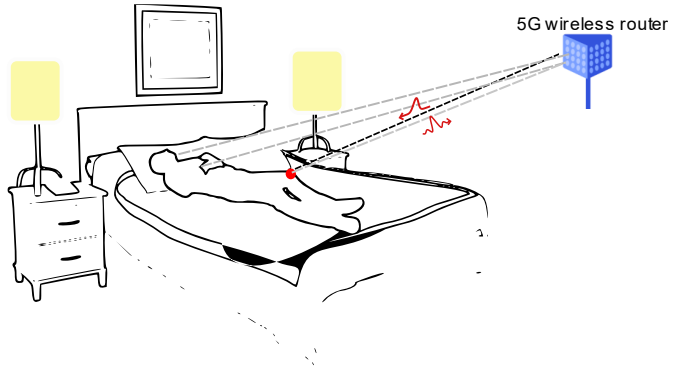
Works Through-occlusion

Provides Fine-grained Monitoring

Argosleep captures accurate sleep posture without invading privacy

Our Proposal: Argosleep

- Human sleeps infront of the mmWave device



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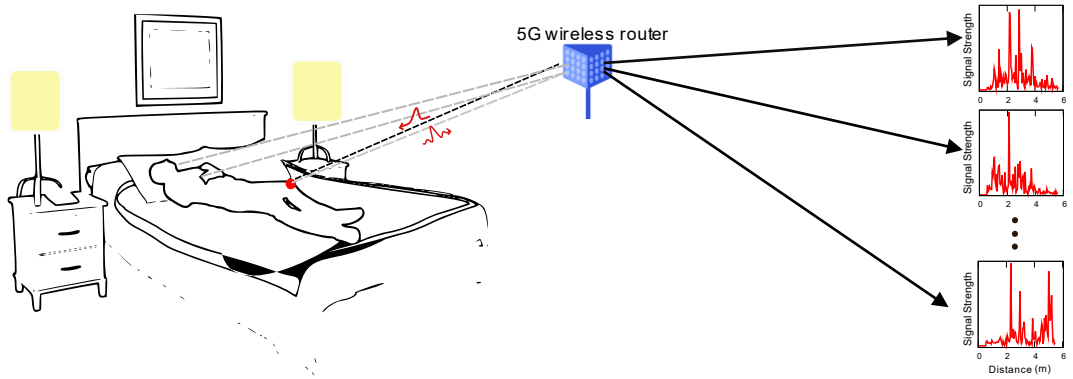
- Human sleeps infront of the mmWave device
- Combines Reflection from Multiple Antennas



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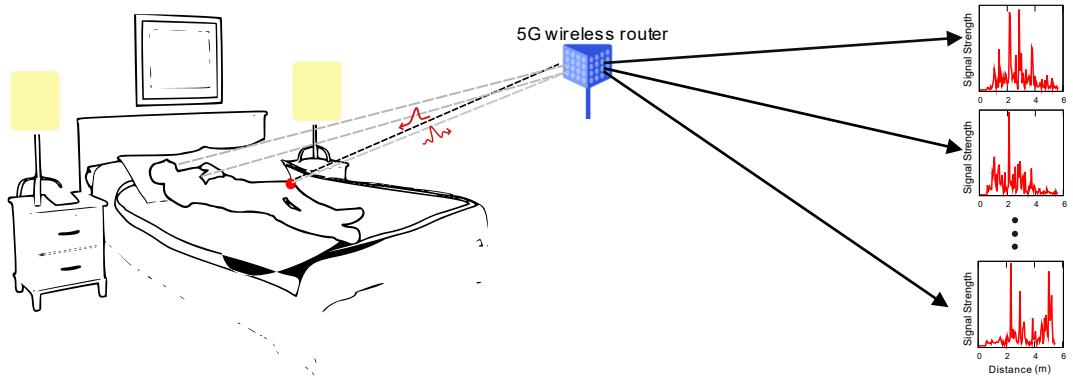
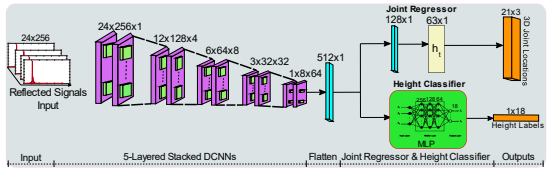
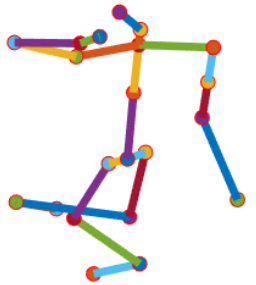


Rest State

- Machine Learning





Sleep Posture Predictor

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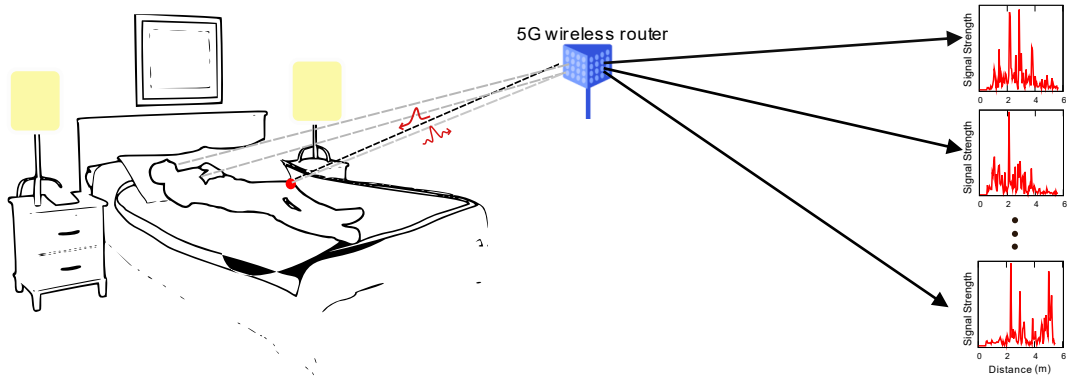
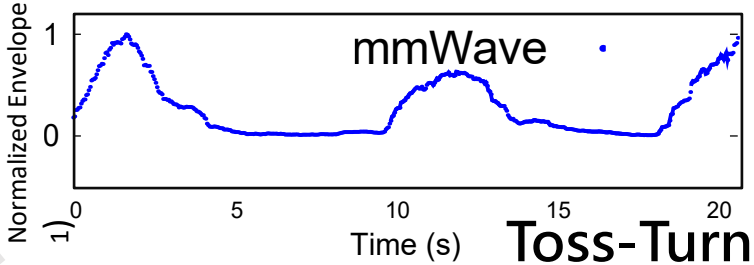
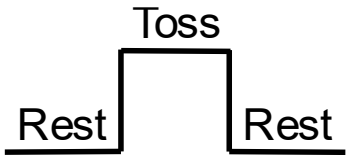


Toss-Turn State

- Turn is detected based on cross-correlation



- State Machine switches between states



Toss-Turn Detector

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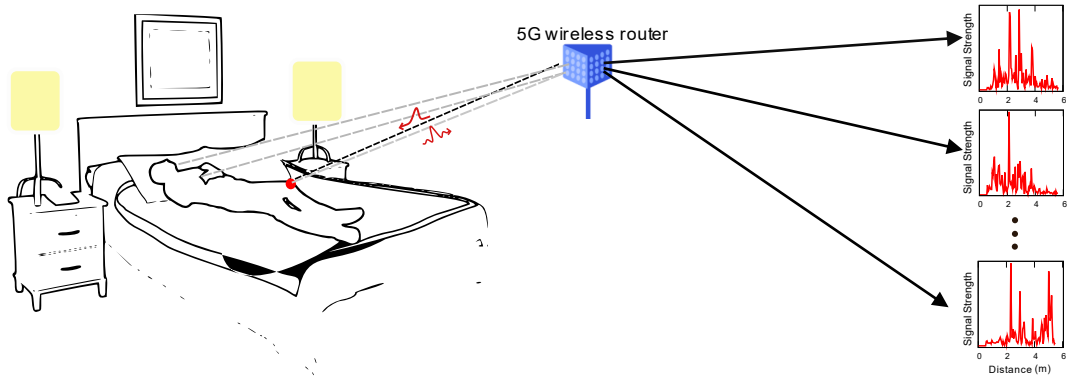

Rest State

Toss-Turn State

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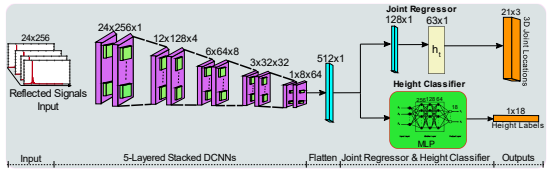

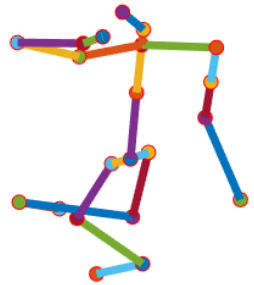

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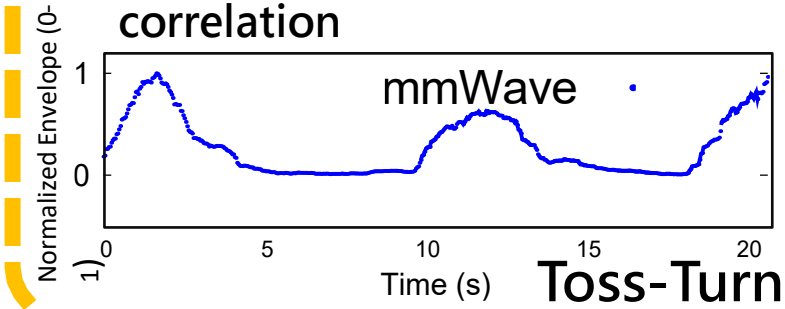

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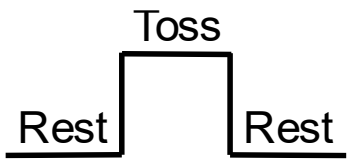
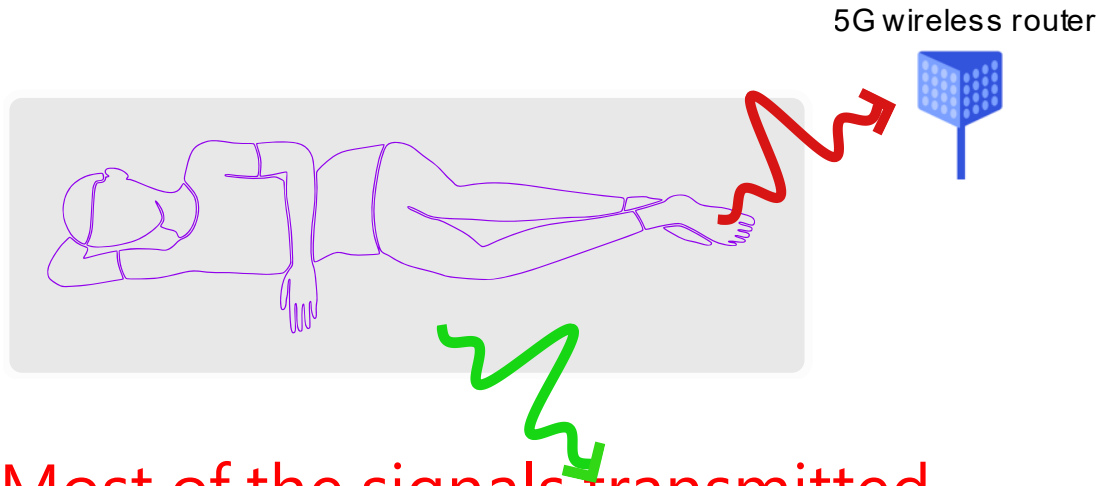


Toss-Turn Detector

Challenges

Challenges

- Specularity and Weak Reflectivity



Most of the signals transmitted do not reach back to the mmWave receiver

mmWave signals are highly specular

Challenges

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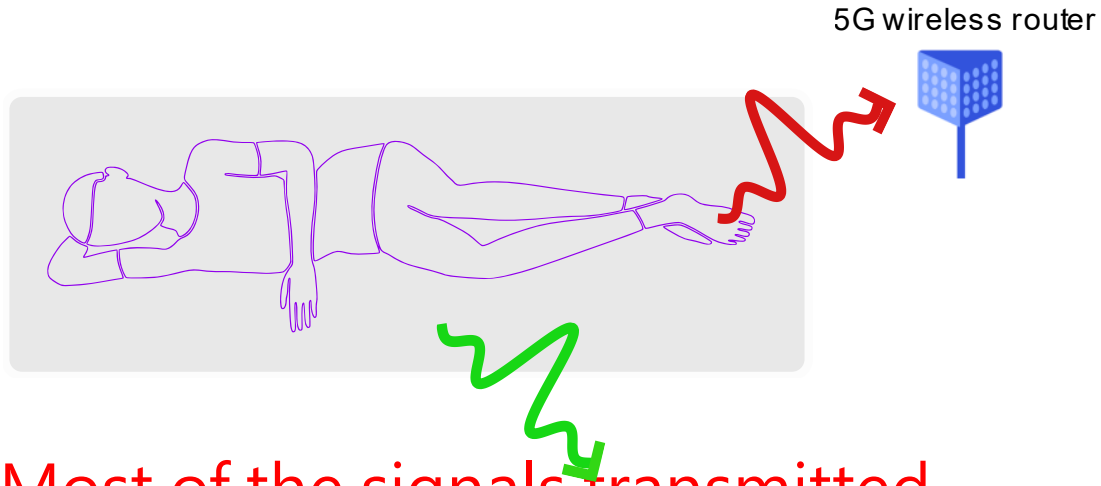

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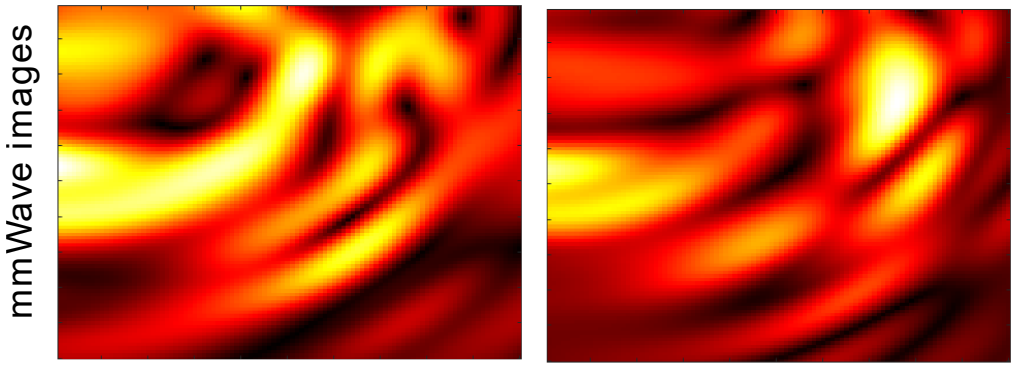
mmWave signals are highly specular

- Low Imaging Resolution



(a) Rest in left lateral posture (b) Rest in supine posture

Imperceptible images with many missing parts

Limited antenna array size

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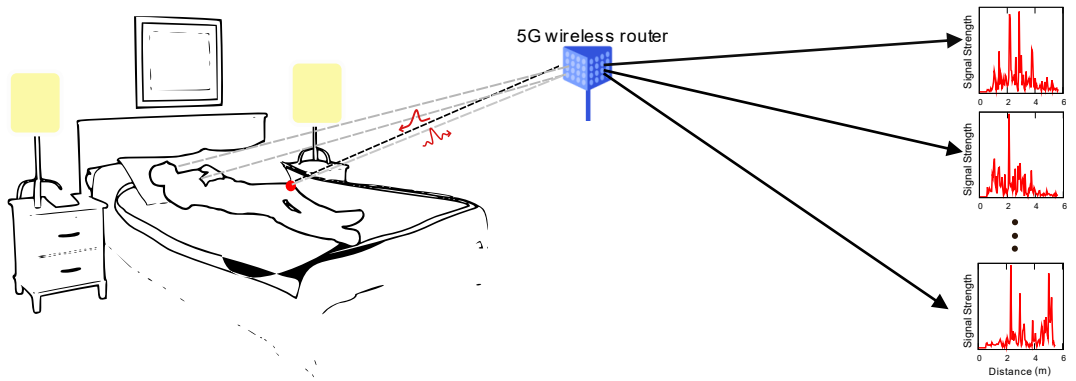
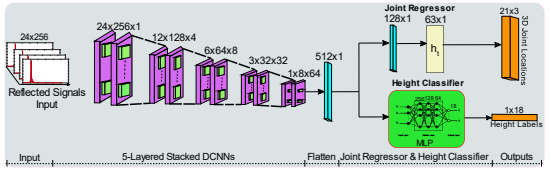
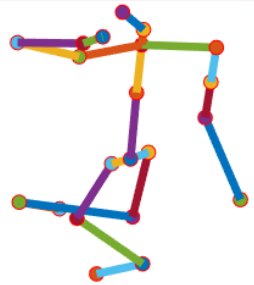


Rest State

Toss-Turn State

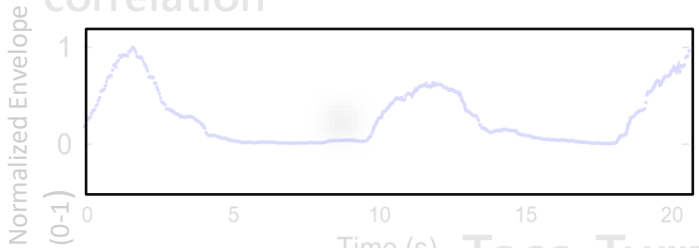
- Machine Learning





Sleep Posture Predictor

- Turn is detected based on cross-correlation

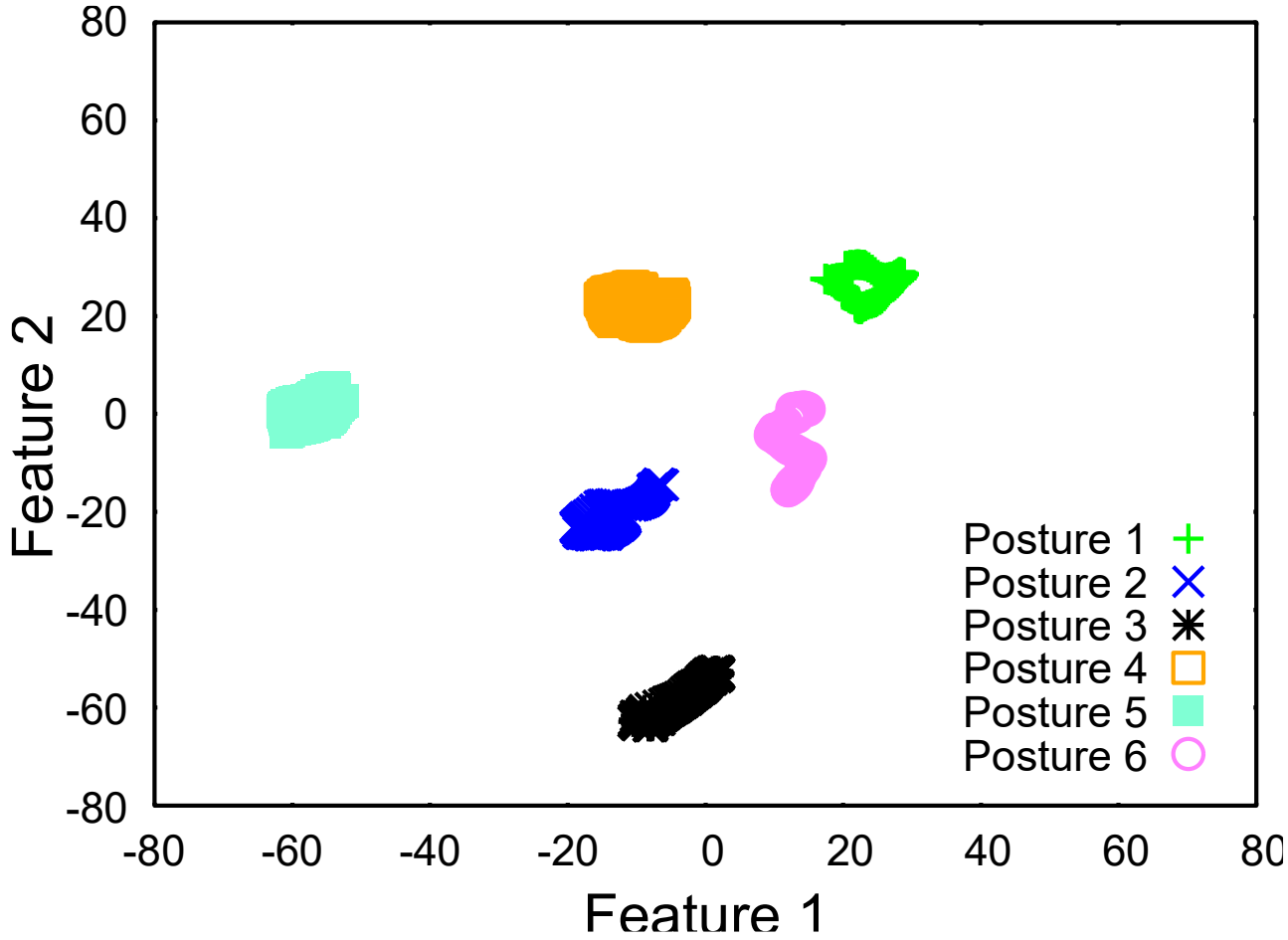


- State Machine switches between states

Toss-Turn Detector

Sleep Posture Predictor: Key Ideas

Reflected signals carry distinct signatures about sleep postures in feature space



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We can use learning model to infer joint locations

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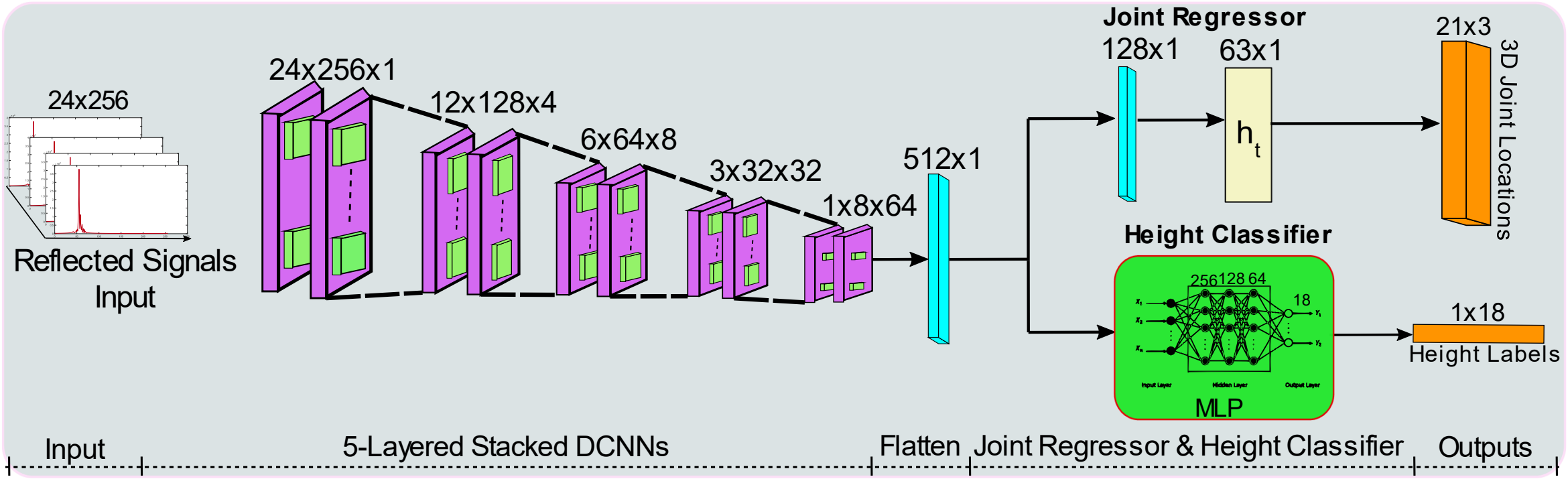
We can use learning model to infer joint locations

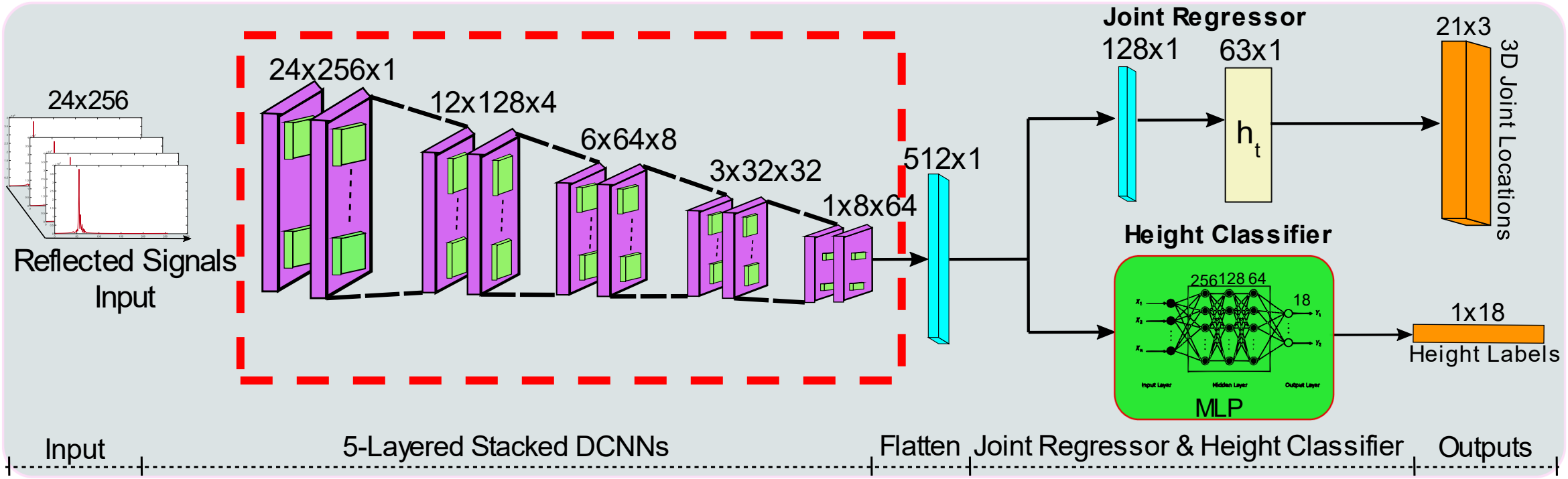
Challenge: How to learn location of joints for different individuals?

Rest Network



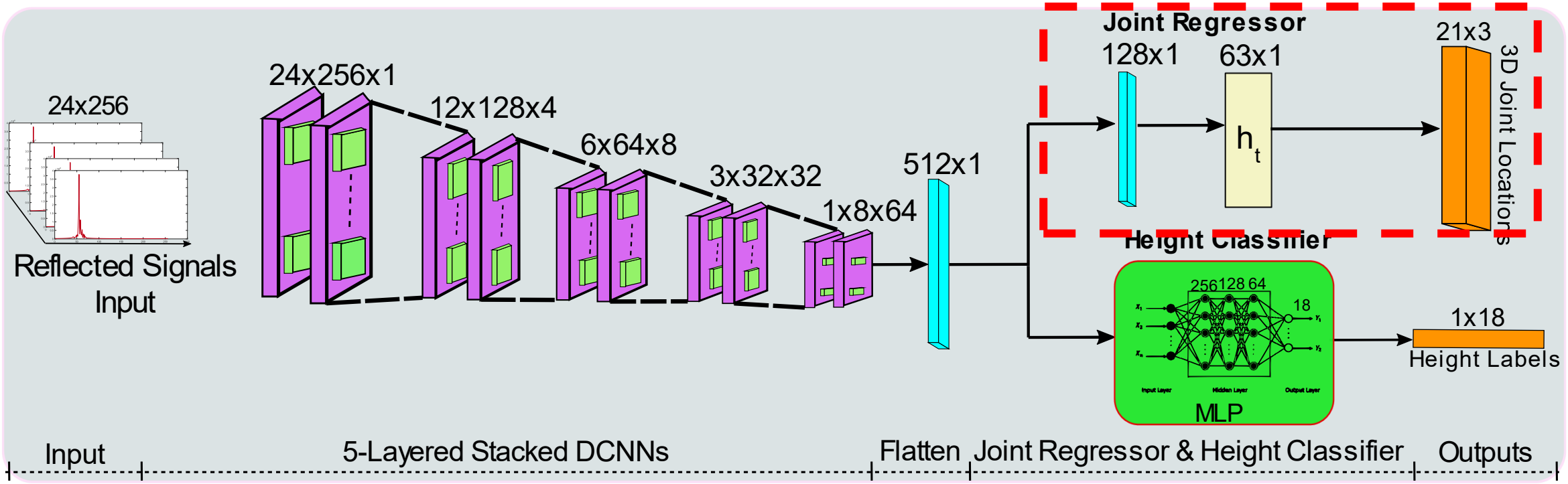
Rest Network predicts location of joints using reflected signals

Rest Network



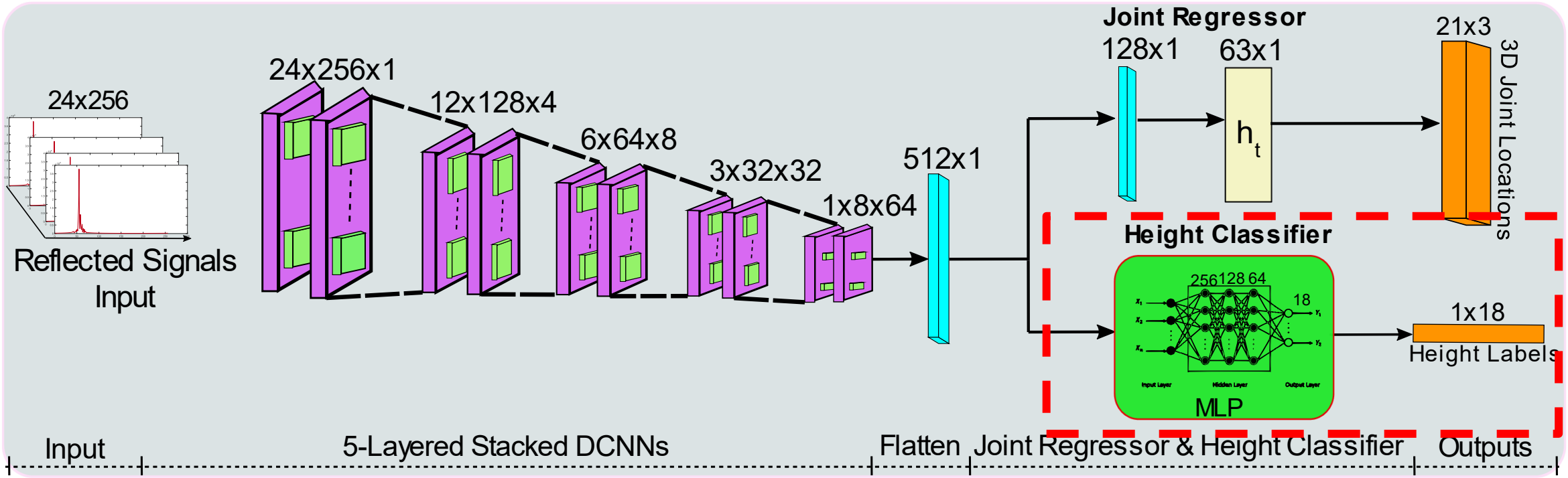
Convolutional layers extracts the relevant features

Rest Network



Most of human body joints follow parent-child hierarchy

Rest Network



3D location of body joints of an individual is correlated to height

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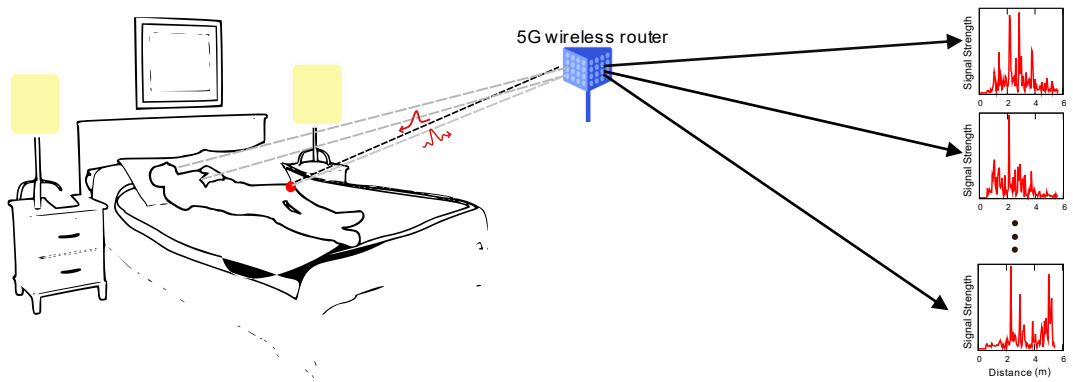
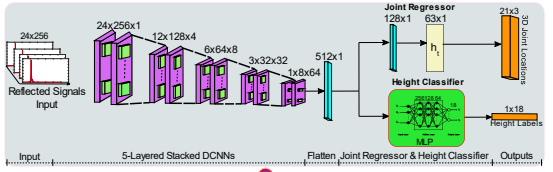
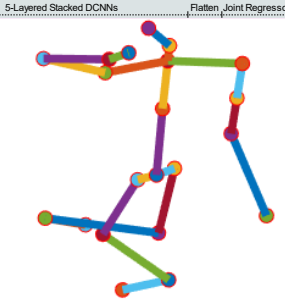


Rest State

Toss-Turn State

- Machine Learning





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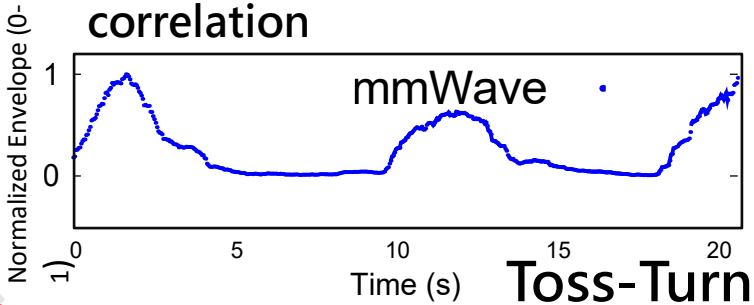

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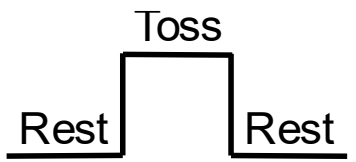


Toss-Turn Detector

Toss-Turn Detector: Key Ideas

Human sleeps for a longer duration and takes toss-turn for shorter duration

We can detect toss-turn as high frequency event

Toss-Turn Detector: Key Ideas

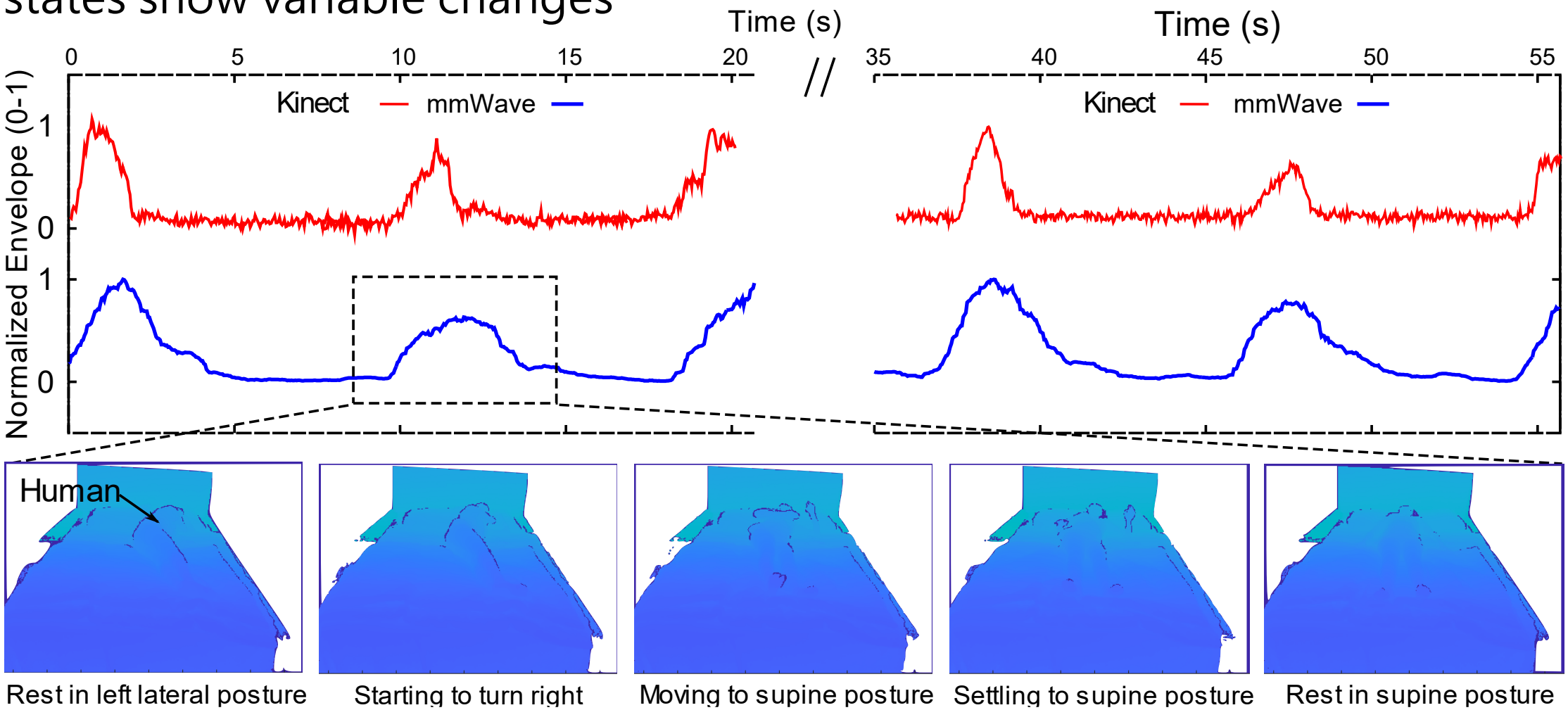
Human sleeps for a longer duration and takes toss-turn for shorter duration

We can detect toss-turn as high frequency event

Challenge: Toss-turn changes are weaker and do not appear sharp

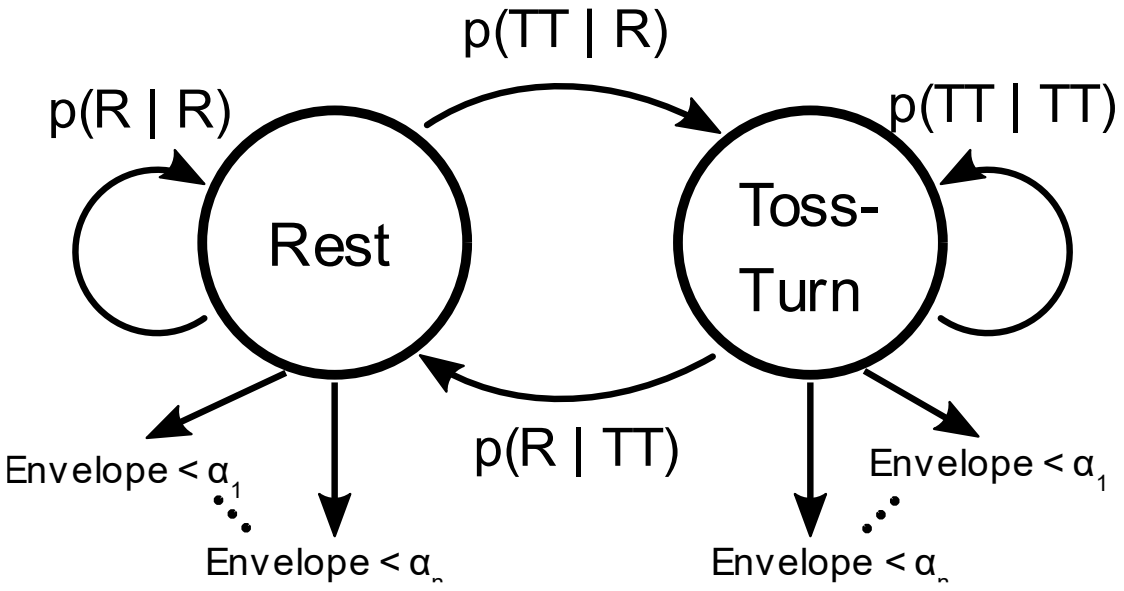
Cross-Correlation based Toss-Turn Detection

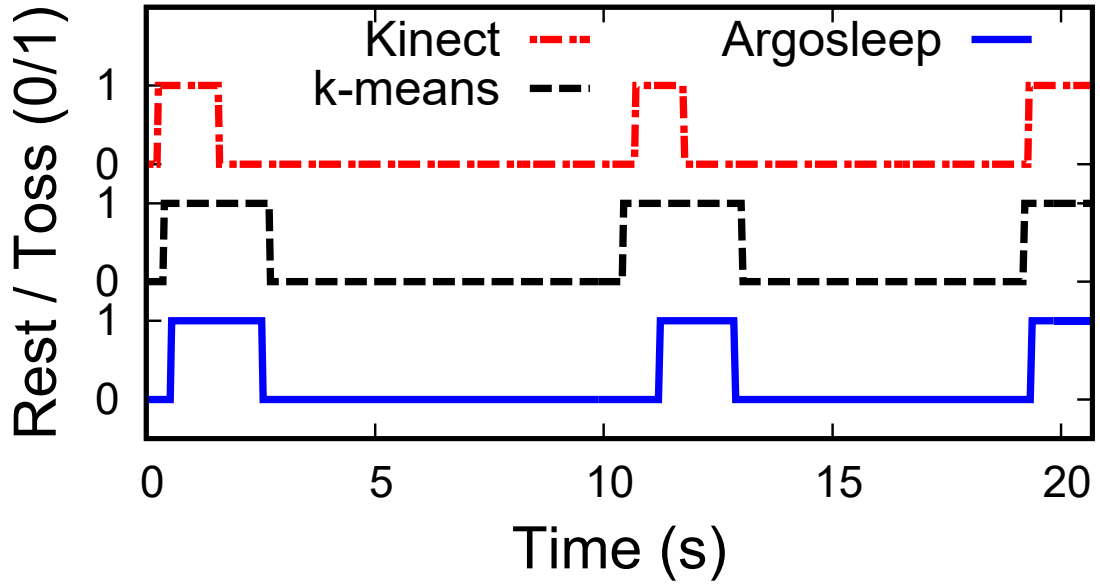
- Rest states show nearly zero rate of change in correlation, while toss-turn states show variable changes



State Machine

- Improves toss-turn detection accuracy
- Provides switching between rest state and toss-turn state

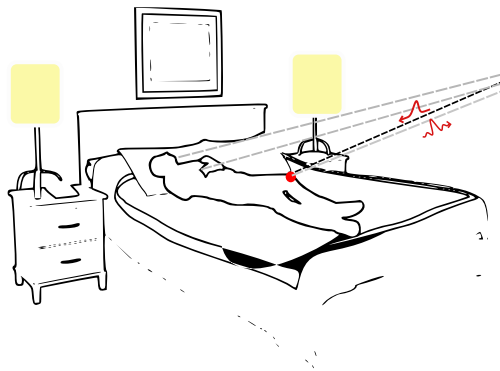




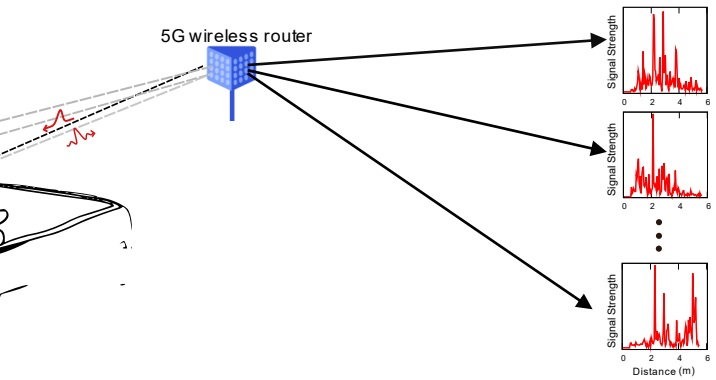
State Machine switches states using two-state Hidden Markov Model

Argosleep Summary

- Human sleeps infront of the mmWave device



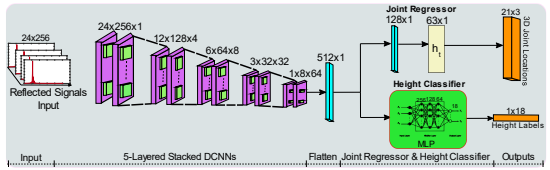
- Combines Reflection from Multiple Antennas

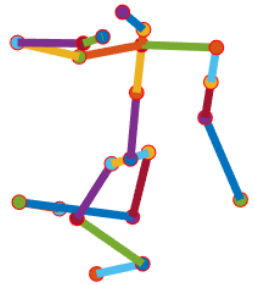


Rest State

Toss-Turn State

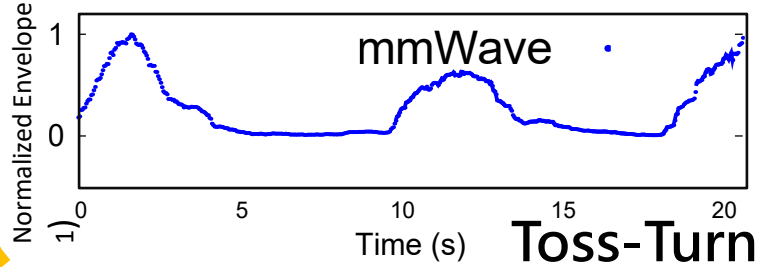
- Machine Learning



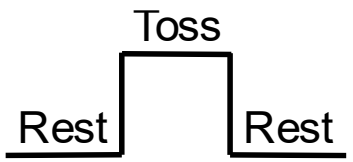


Sleep Posture Predictor

- Turn is detected based on cross-correlation



- State Machine switches between states

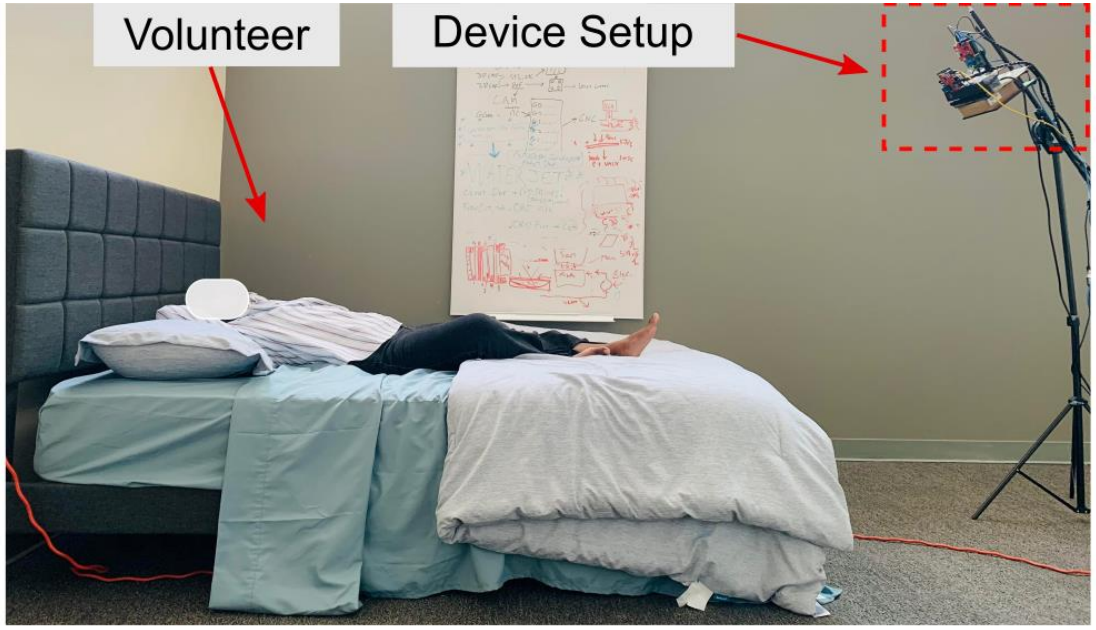


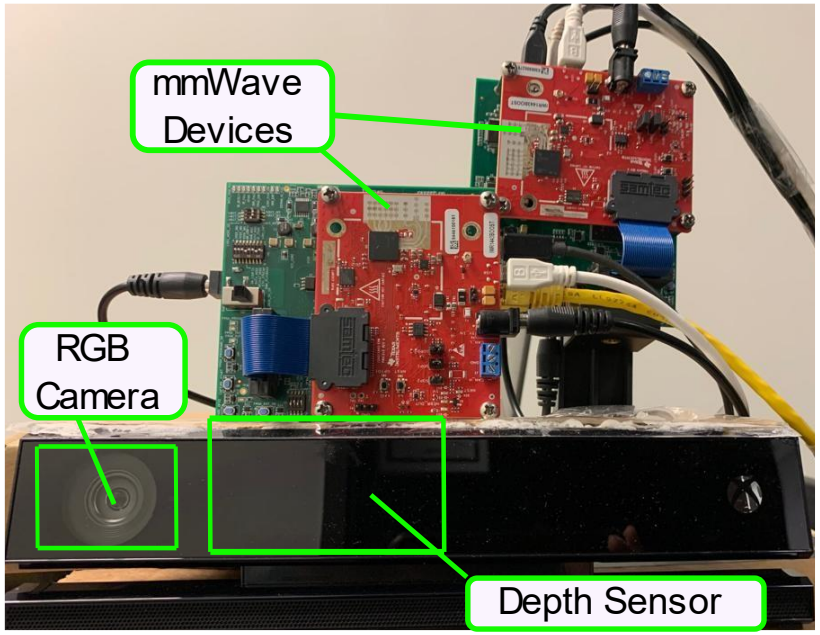
Toss-Turn Detector

Implementation

mmWave Hardware: 77–81 GHz mmWave transceivers, BW 1.62 GHz
TI IWR1443BOOST (Each with one transmit and four receive antennas)

Ground Truth: Microsoft Kinect Xbox One





Data Collection

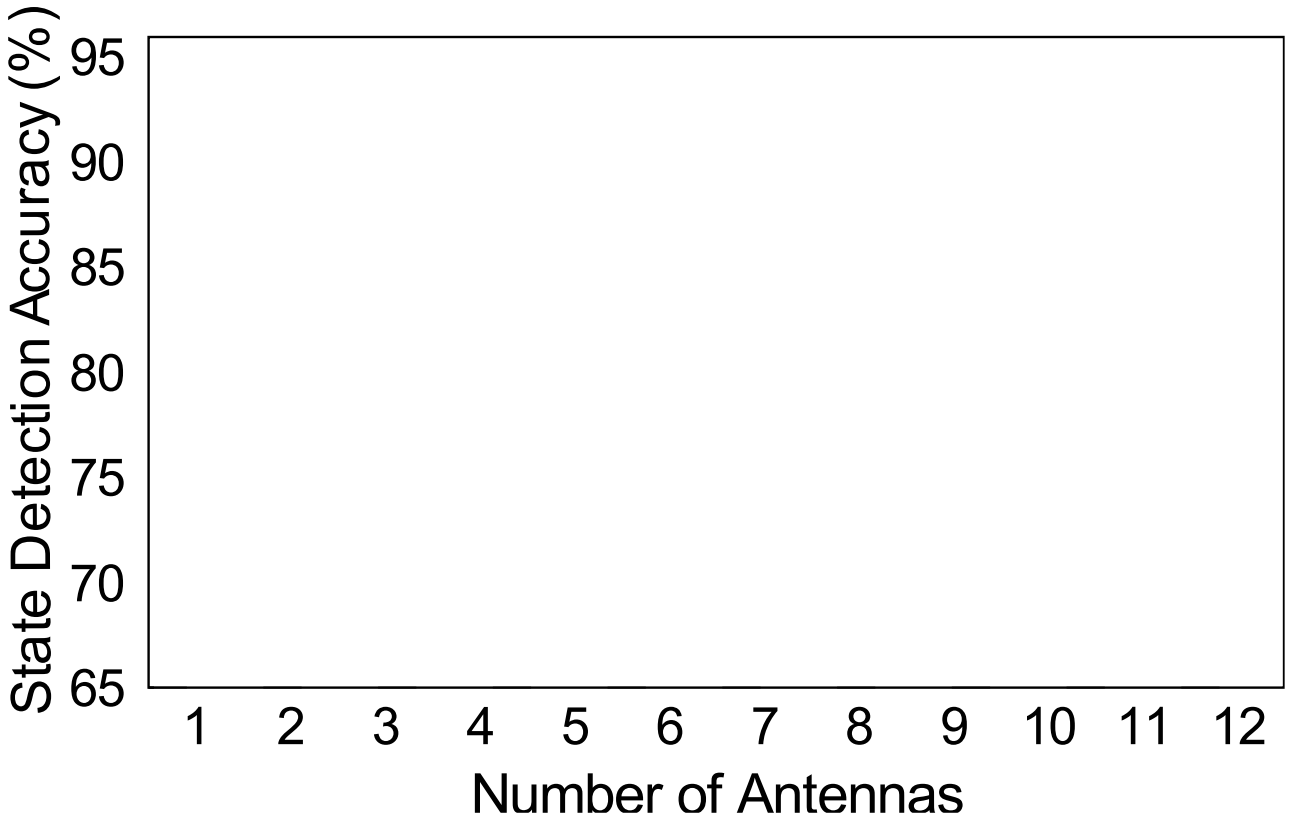
- Subject is asked to sleep at approximately 2.5 m distance from the setup
- Dataset includes input-output pairs of mmWave reflections and 3D joint locations

- **Sleep Posture Predictor Data Collection**
  - We collect datasets from 8 volunteers with 5 diverse poses
  - Each experiment takes 60 seconds to complete

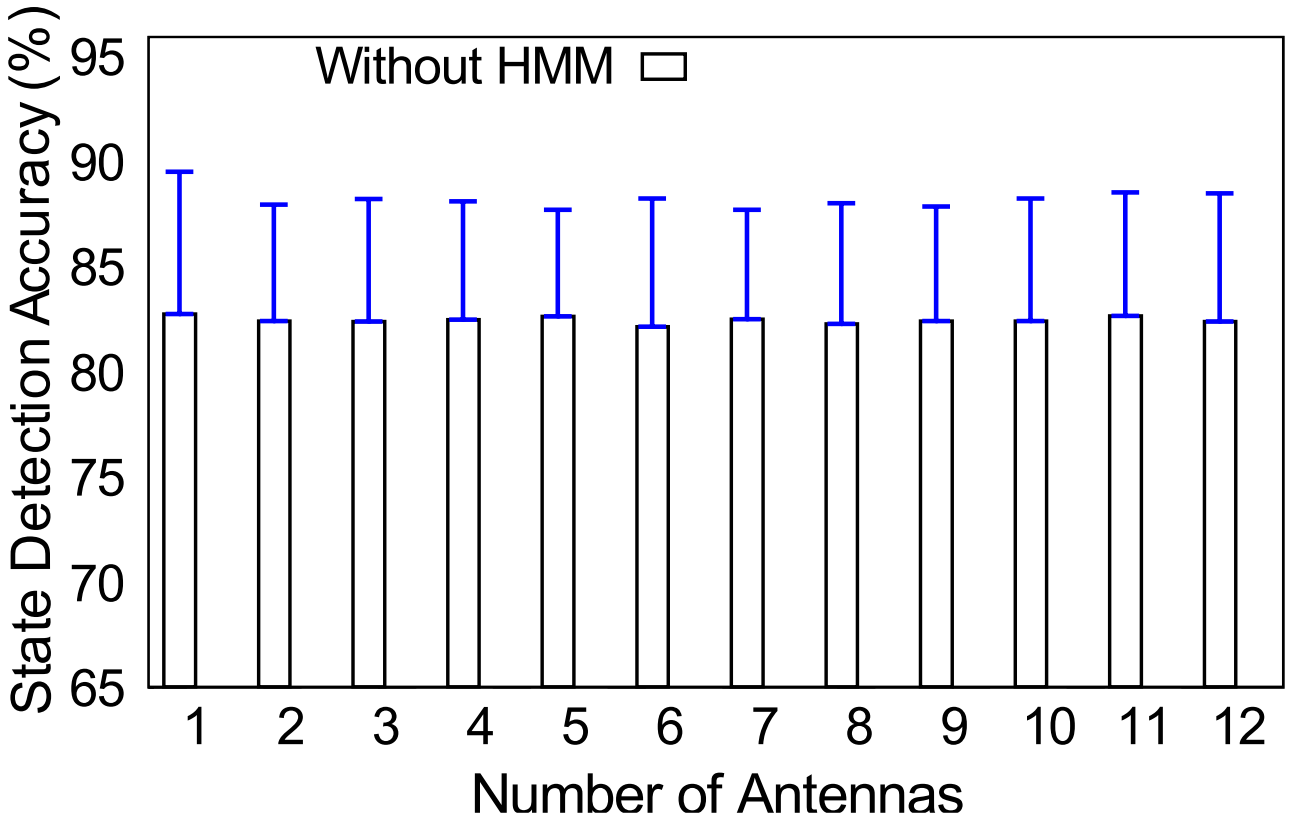
- **Toss-Turn Detector Collection**
  - We collect data from a single volunteer with multiple toss-turns
  - Each experiment takes 60 seconds to complete

In total, 40 K input-output pairs from 8 diverse volunteers

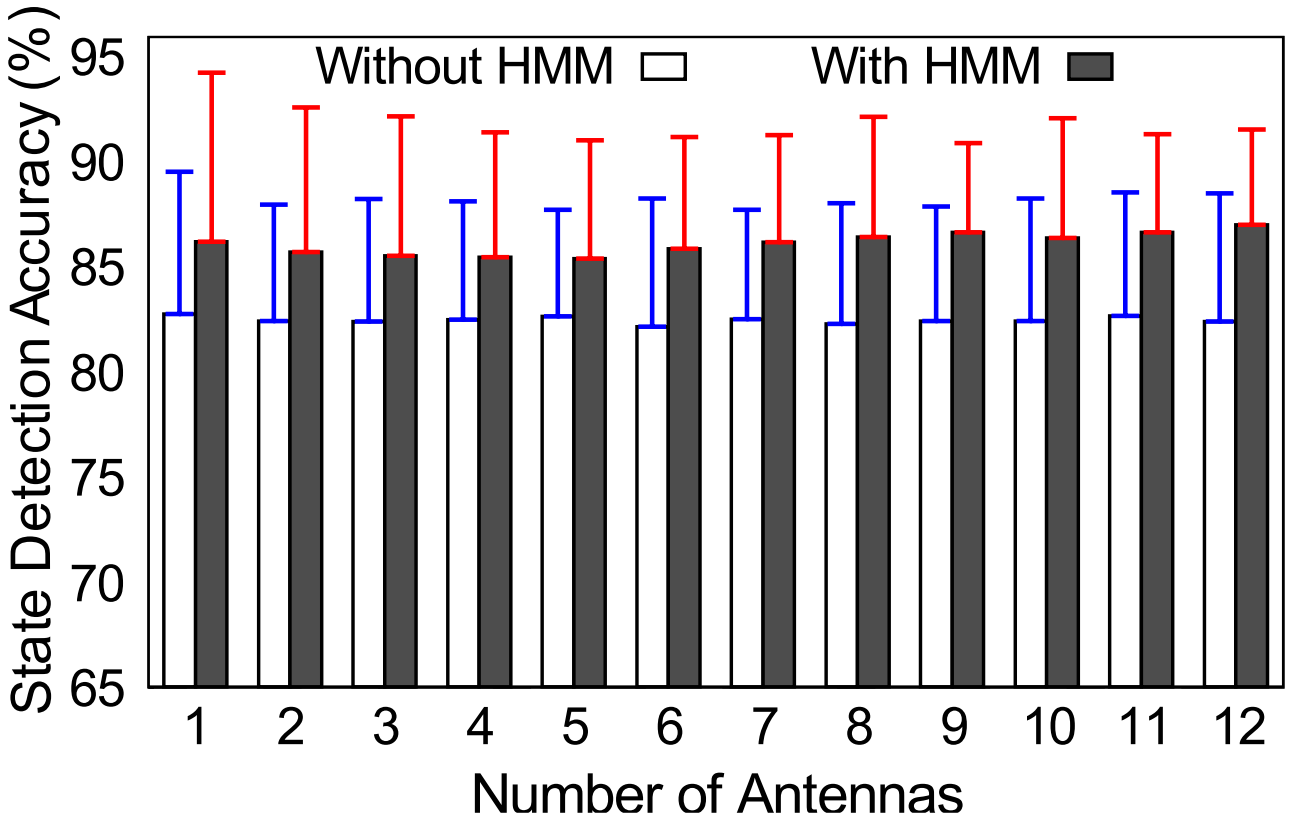
Evaluation: Toss-Turn Detector



Evaluation: Toss-Turn Detector

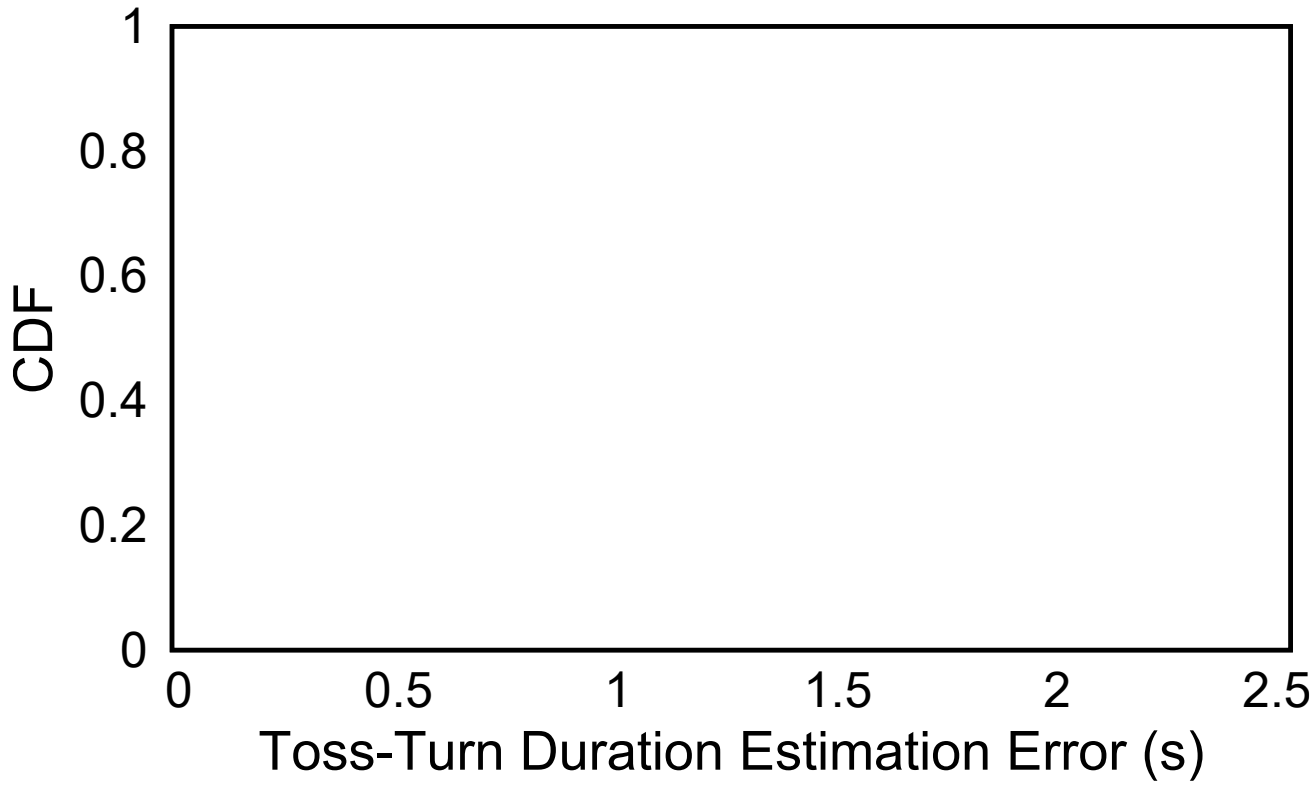


Evaluation: Toss-Turn Detector

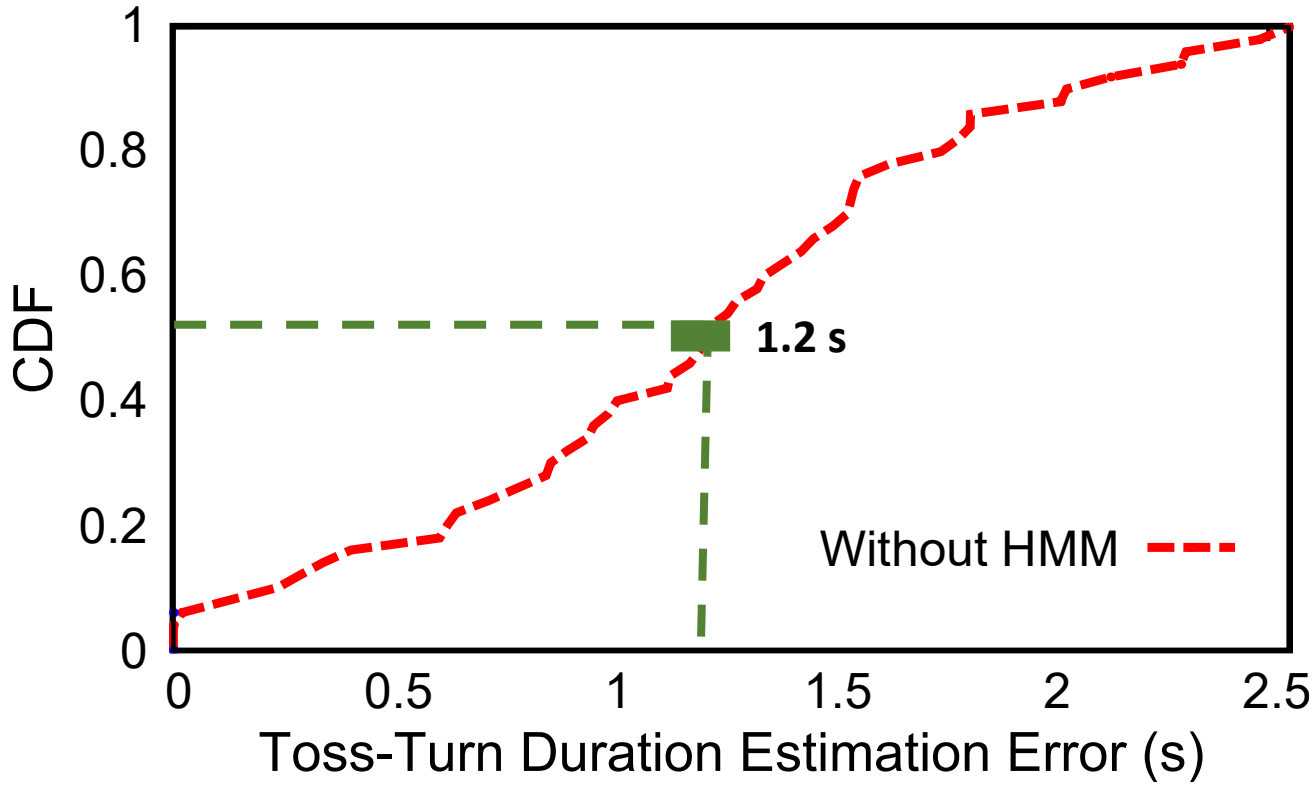


Argosleep detects toss-turn accurately for different antenna settings

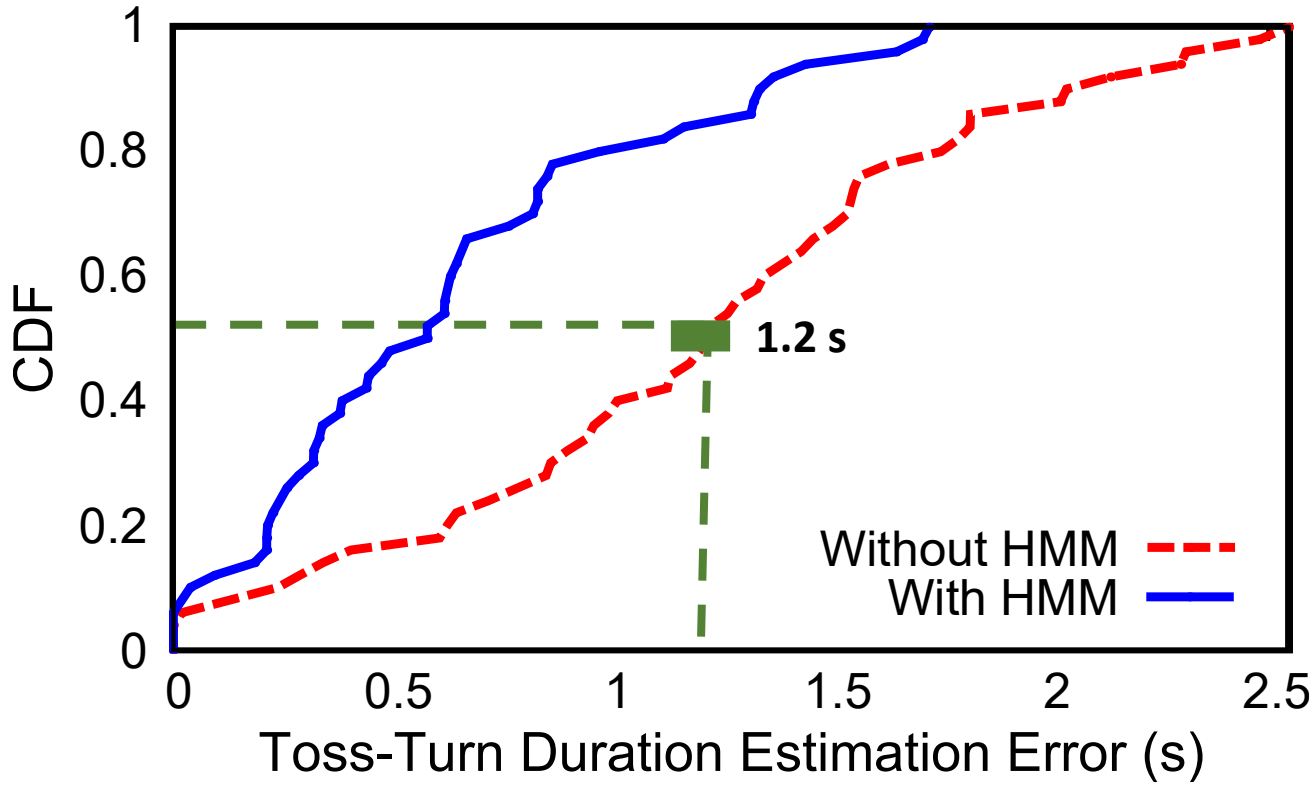
Evaluation: Toss-Turn Detector



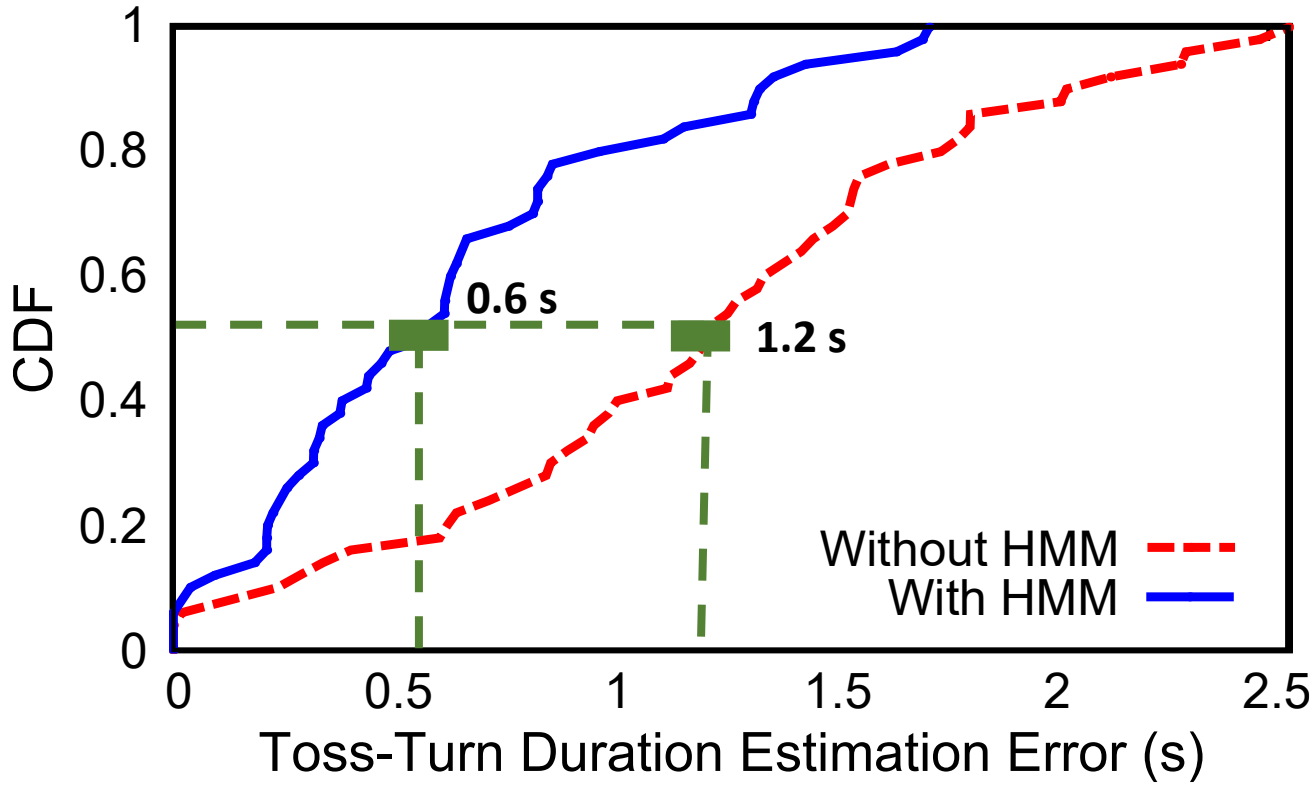
Evaluation: Toss-Turn Detector



Evaluation: Toss-Turn Detector

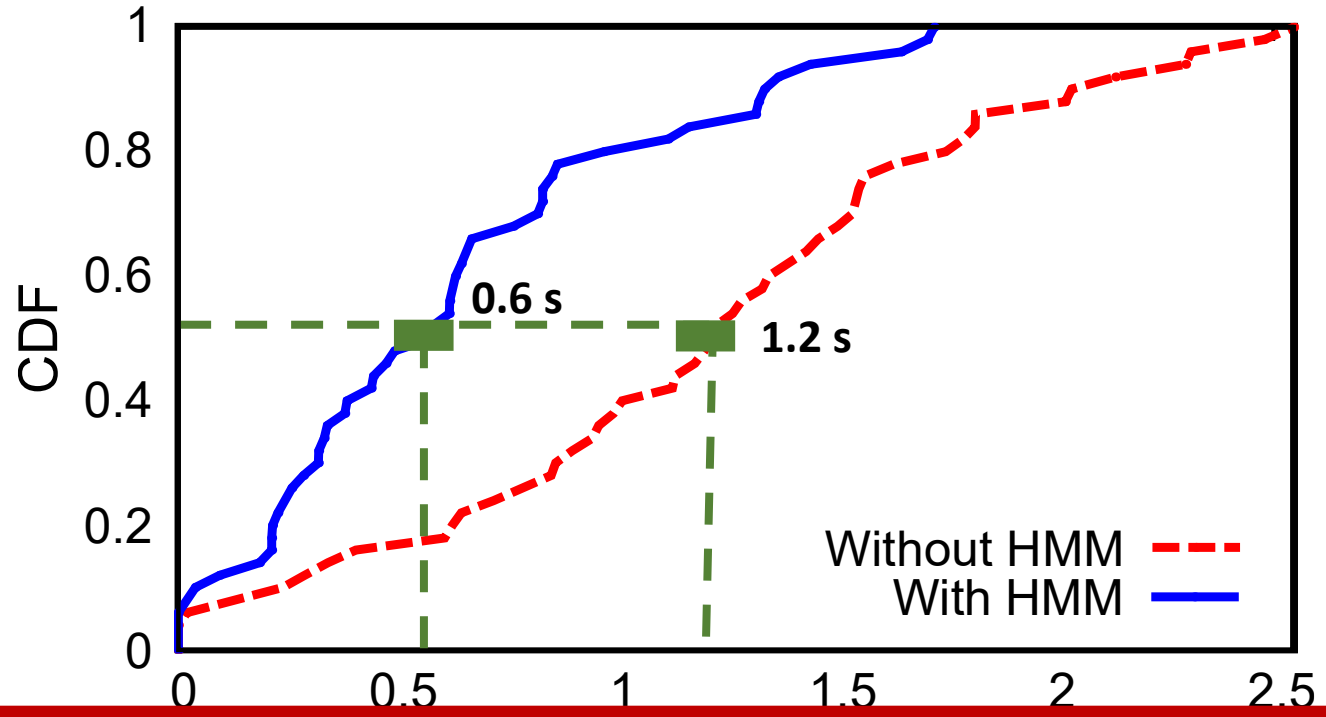


Evaluation: Toss-Turn Detector



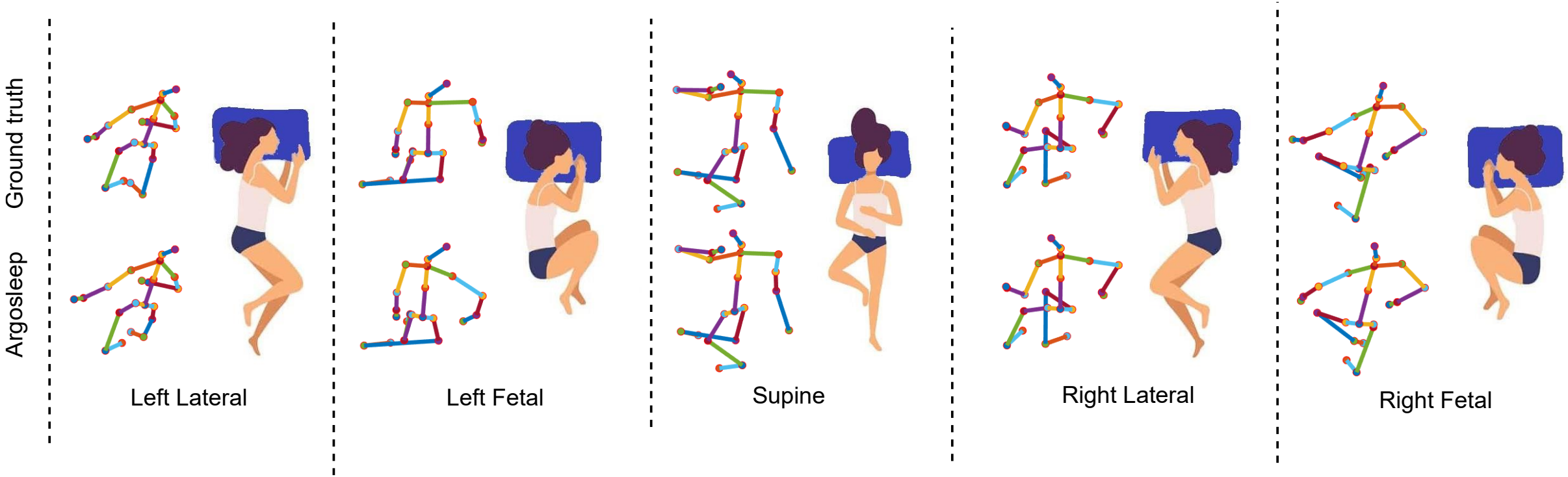
ArgoSleep detects toss-turn event accurately

Evaluation: Toss-Turn Detector



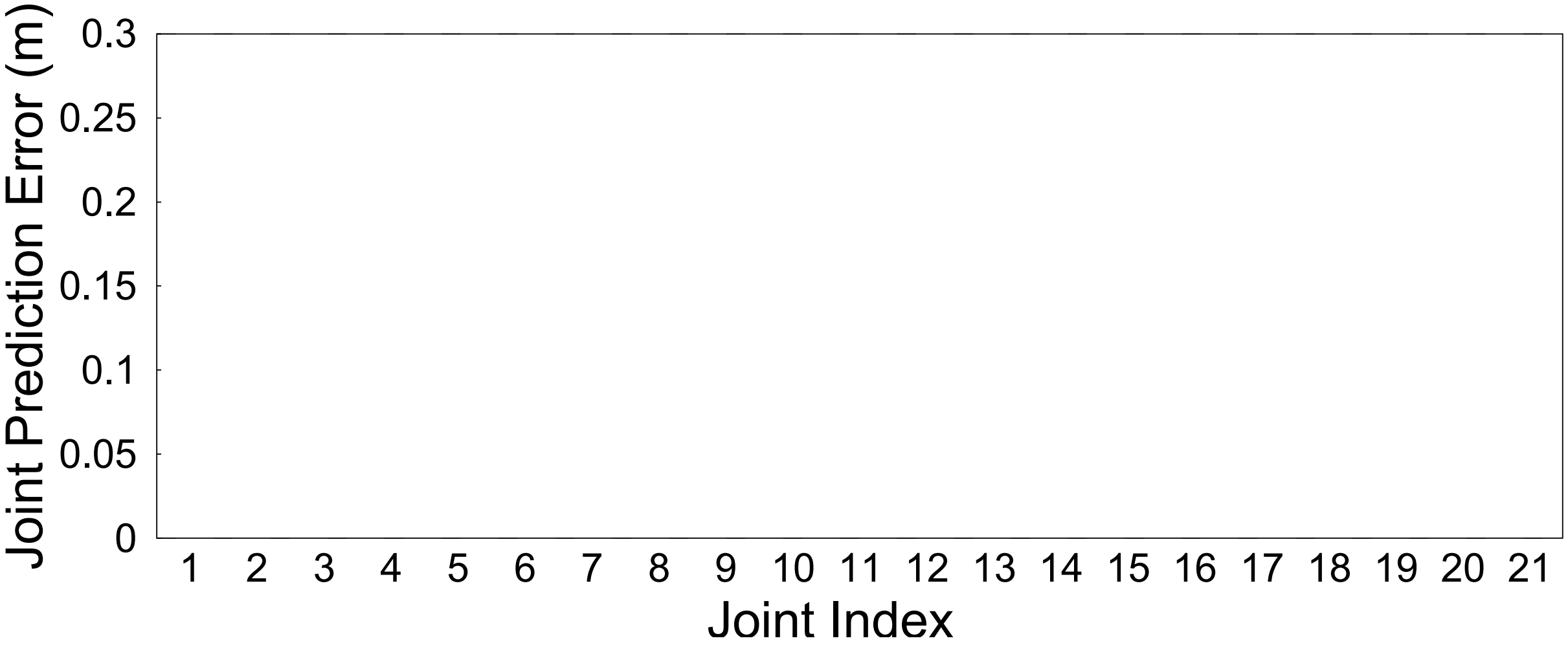
Toss-Turn Detector detects toss-turn events accurately to detect change in states

Evaluation: Sleep Posture Predictor

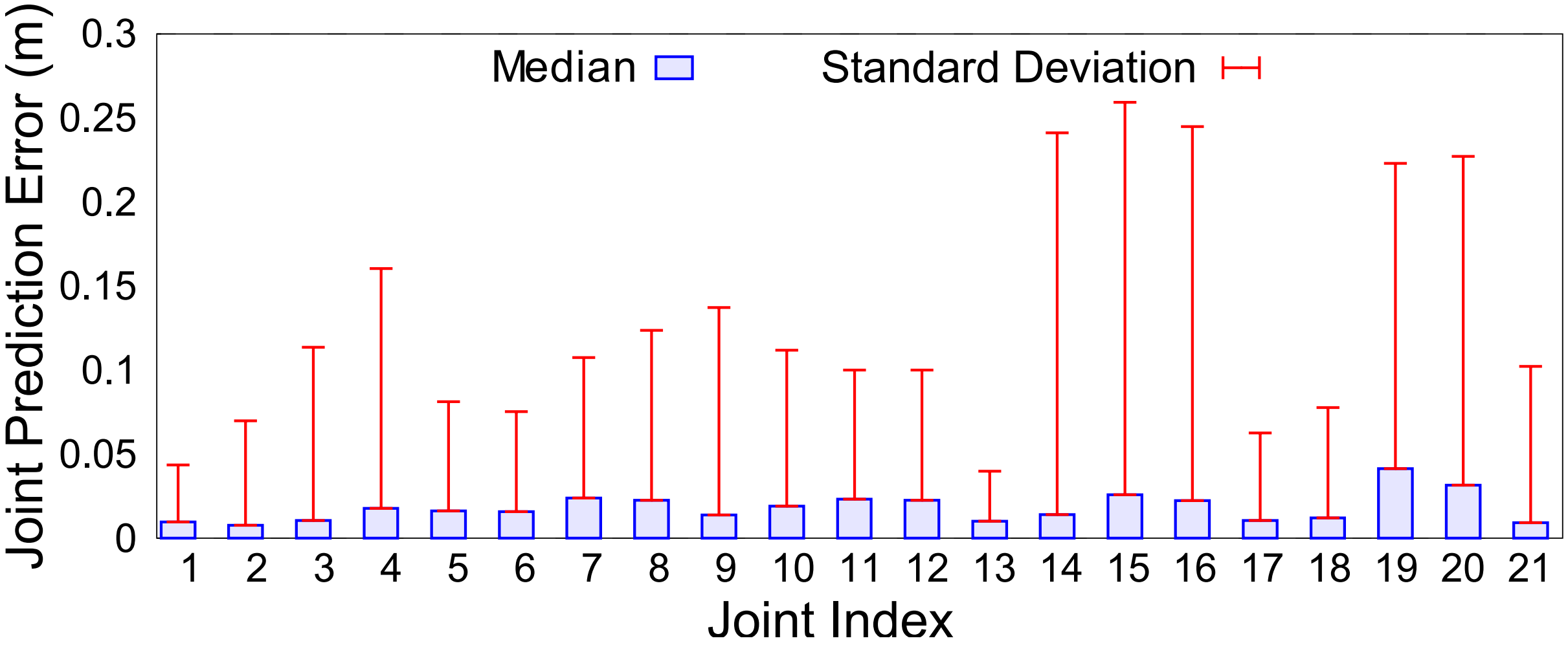


Sleep Posture Predictor predicts joint locations for 5 postures

Evaluation: Sleep Posture Predictor

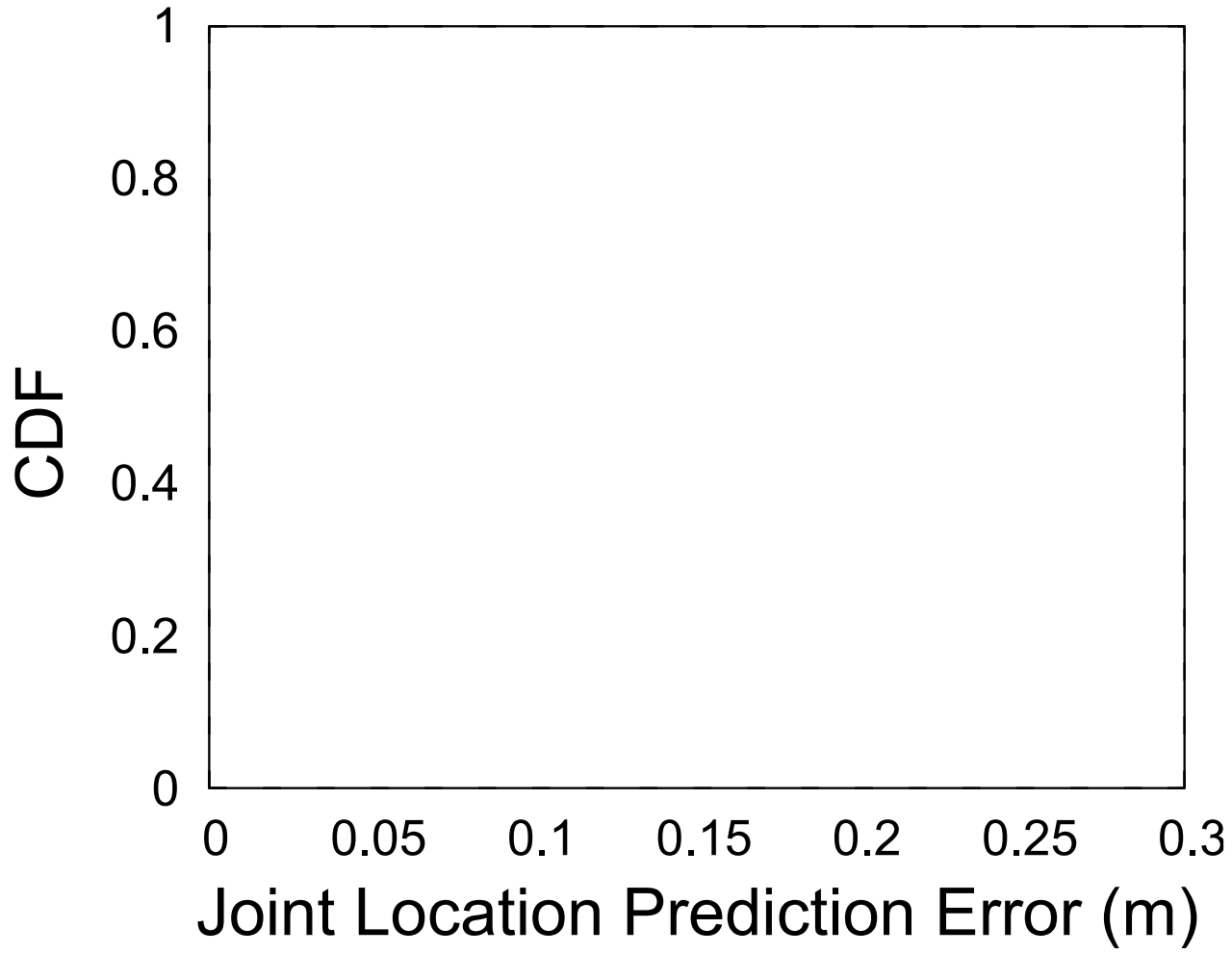


Evaluation: Sleep Posture Predictor

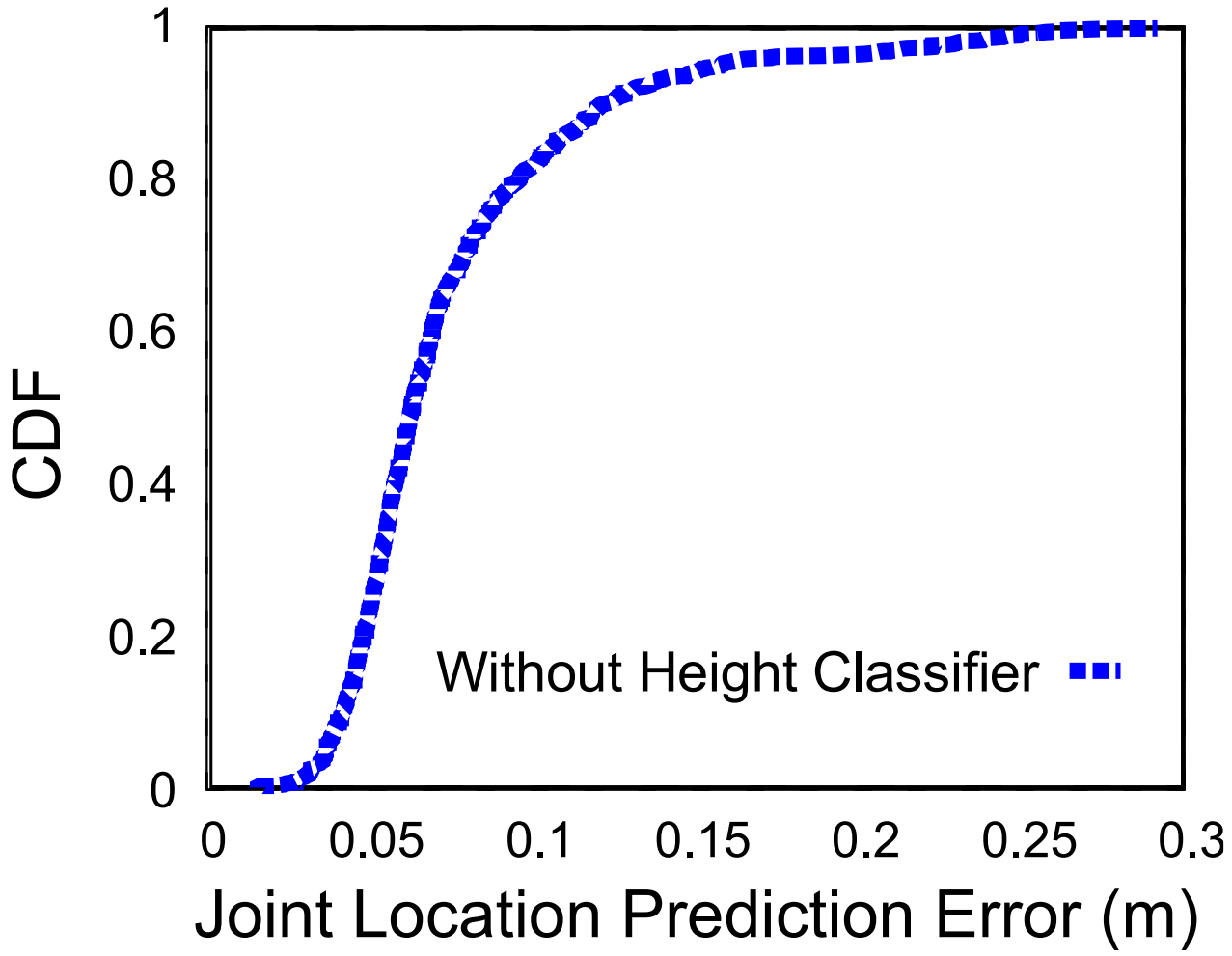


We observe high standard deviation across 14,15,16,19 and 20

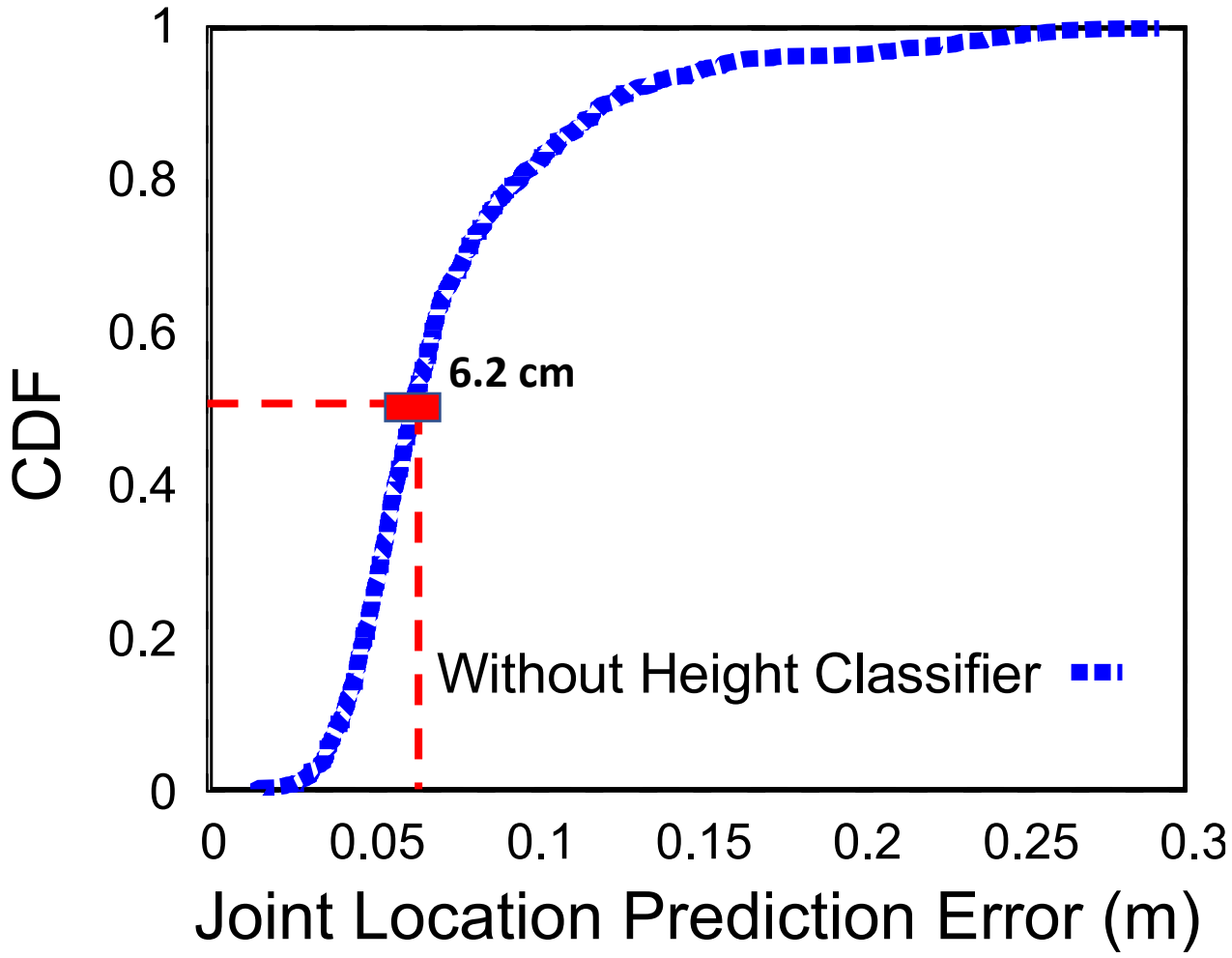
Evaluation: Sleep Posture Predictor



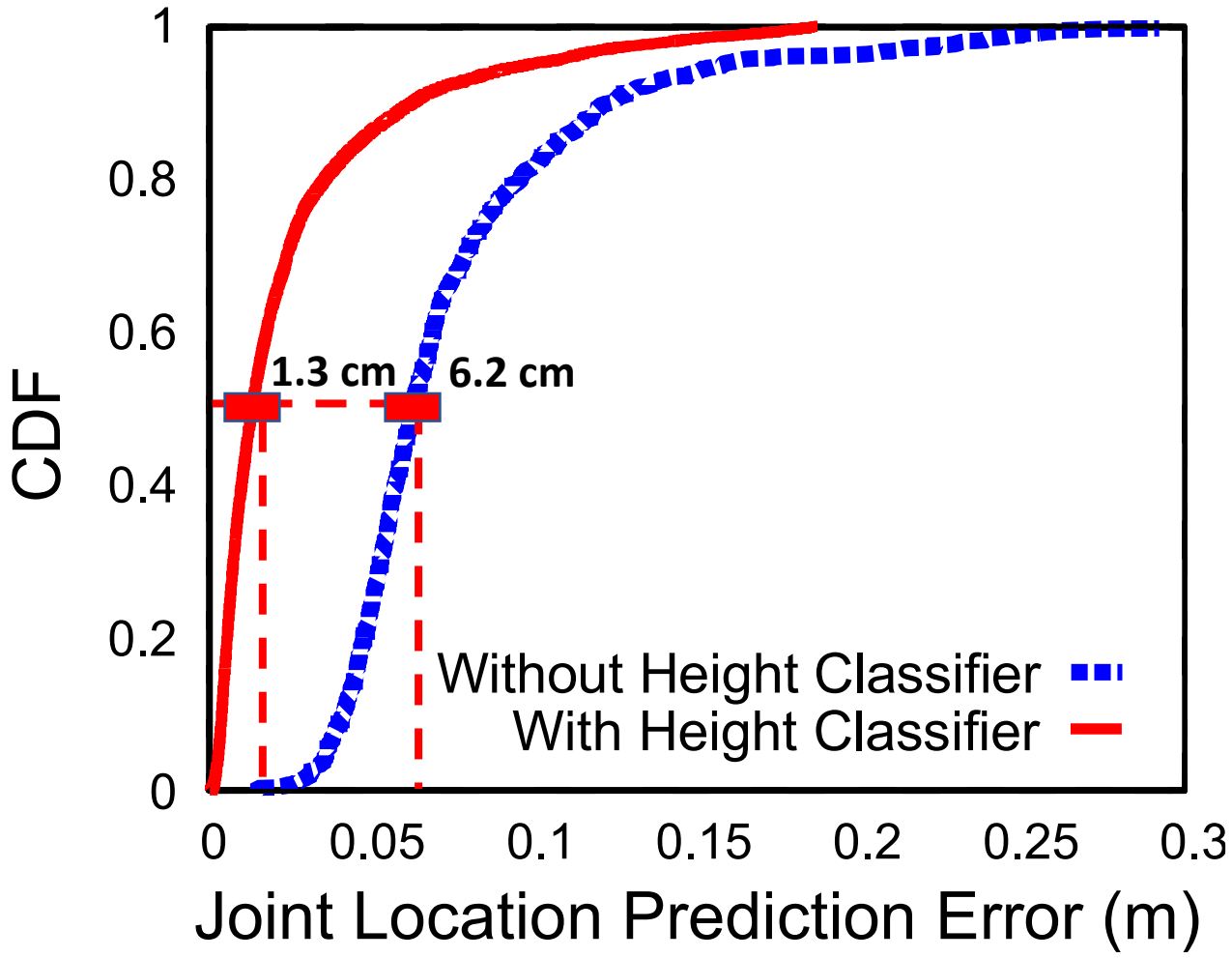
Evaluation: Sleep Posture Predictor



Evaluation: Sleep Posture Predictor

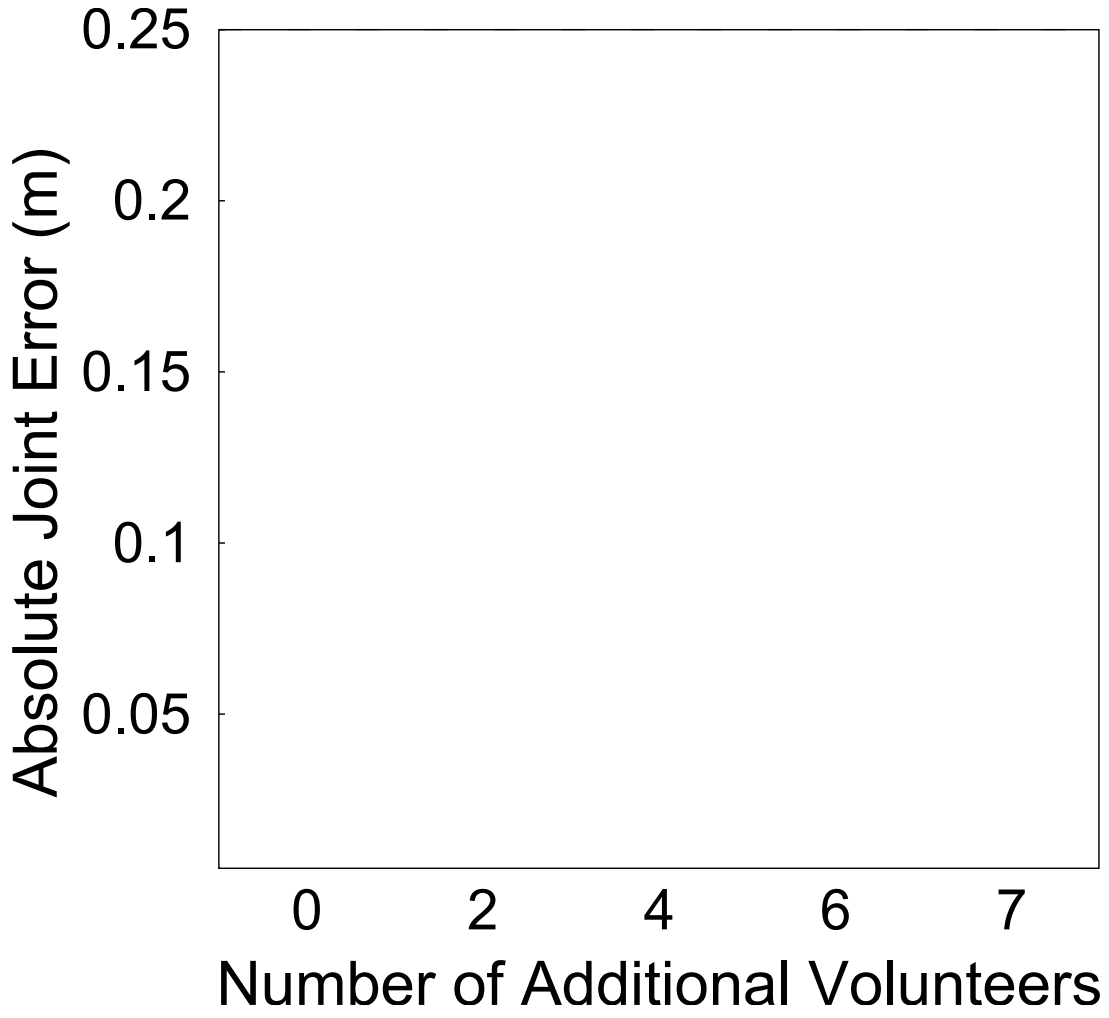


Evaluation: Sleep Posture Predictor

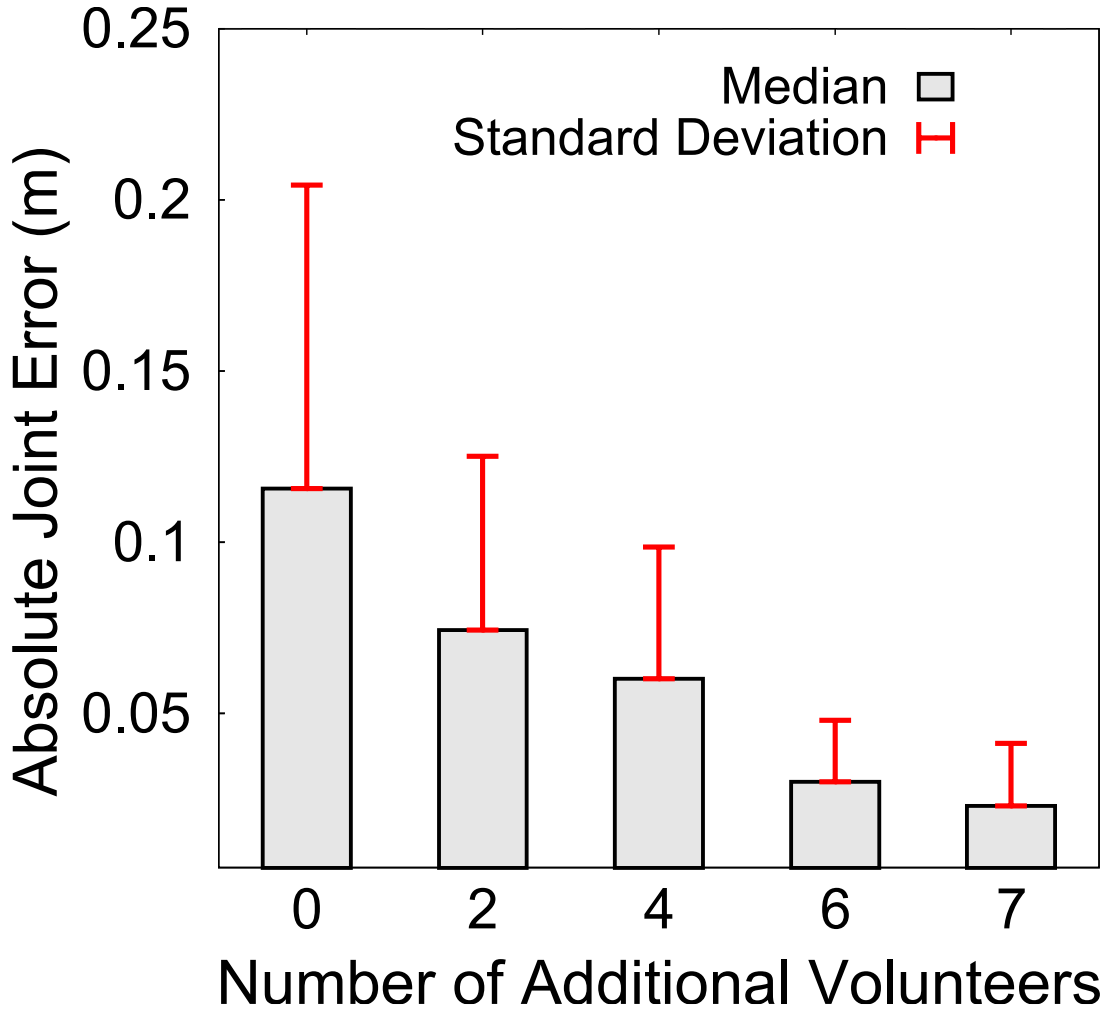


Height Classifier improves the performance of sleep posture predictor

Evaluation: Sleep Posture Predictor

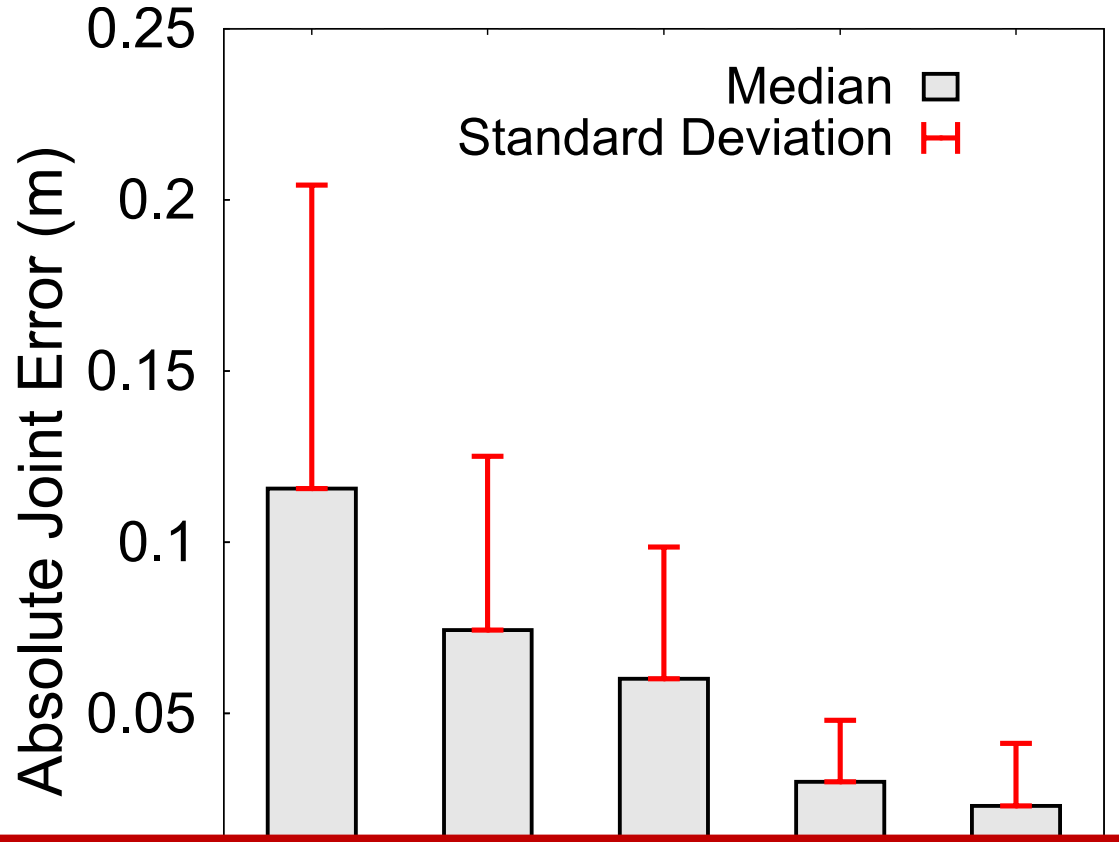


Evaluation: Sleep Posture Predictor



Argosleep generalizes well for multiple volunteers

Evaluation: Sleep Posture Predictor



Sleep Posture Predictor predicts 3D joint locations accurately and generalizes well

Conclusion

- Argosleep predicts 3D location of body joints with accuracy on par with the existing vision-based system
- Argosleep identifies the toss-turn events accurately
- Argosleep brings **fine-grained**, through-occlusion sleep monitoring into **ubiquitous commodity 5G devices**

Conclusion

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- Argosleep identifies the toss-turn events accurately
- Argosleep brings **fine-grained**, through-occlusion sleep monitoring into **ubiquitous commodity 5G devices**

Thank you!

Please check out our paper for more results:

Any Questions: Please email to aakriti@email.sc.edu