



MEMORY-EFFICIENT HIGH-ACCURACY FOOD INTAKE ACTIVITY RECOGNITION WITH 3D MMWAVE RADARS

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FOOD INTAKE ACTIVITY RECOGNITION

- Motivation:
 - Rise of lifestyle-related diseases
 - → Monitoring food intake gains importance
- Problems with food logging/food diaries:
 - Error-prone, inconvenient, and time-consuming
 - → Need for an **automated** recognition system

Monday		Tuesday
	Breakfast	,
	Snack	
	Lunch	
	Snack	
	Dinner	
	Snack	
Wednesday		Thursday
	Breakfast	
	Snack	
	Lunch	
	Snack	
	Dinner	
	Snack	
Friday		Saturday
	Breakfast	
	Snack	
	Lunch	
	Snack	
	Dinner	
	Snack	
Sunday		Notes:

FOOD INTAKE ACTIVITY RECOGNITION

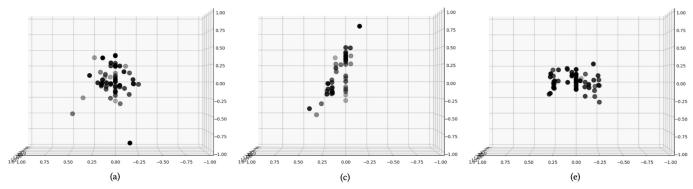
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 - Rise of lifestyle-related diseases
 - → Monitoring food intake gains importance
- Problems with food logging/food diaries:
 - Error-prone, inconvenient, and time-consuming
 - → Need for an **automated** recognition system
- Problems with RGB cameras:
 - Privacy concerns drive users away
 - Vulnerable to poor/fluctuating lighting
 - → Explore alternative sensors, e.g., the **mmWave radar**

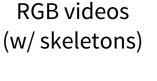


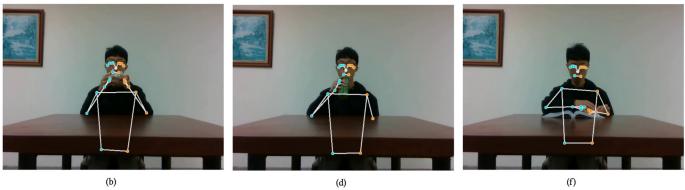


MMWAVE POINT CLOUD DATASET [MMSys '23]

Sparse Dynamic 3D Point Cloud



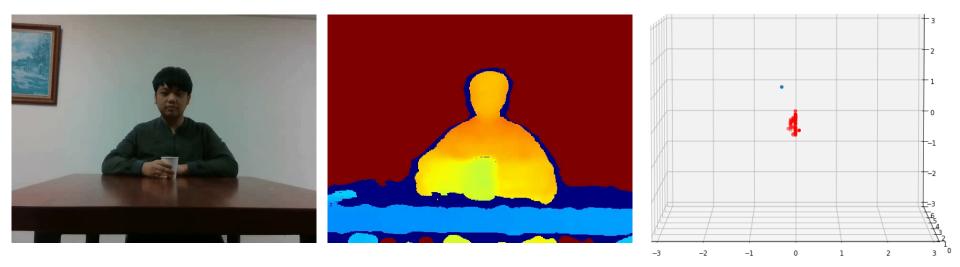




[MMSys '23] Y. Wu, H. Chiang, S. Shirmohammadi, and C. Hsu. 2023.

A Dataset of Food Intake Activities Using Sensors with Heterogeneous Privacy Sensitivity Levels. In Proc. of the ACM MMSys '23. 416–422. ³

SAMPLE SENSOR DATA



RGB Video

Depth Video

Sparse Dynamic 3D Point Cloud

SAMPLE SENSOR DATA



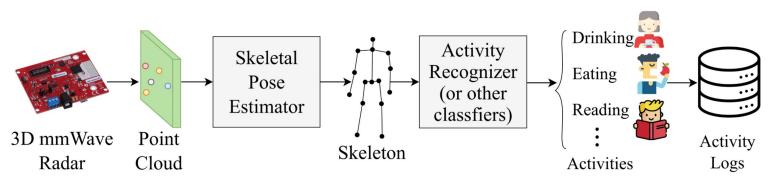
RGB Video

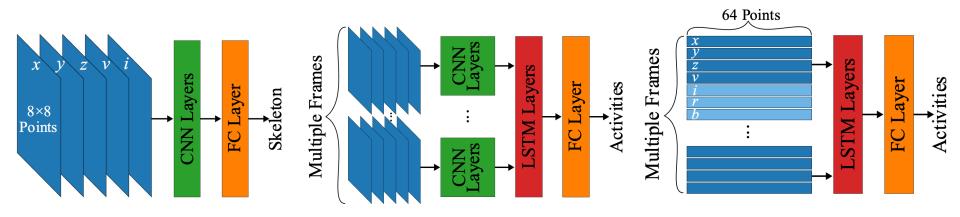
Depth Video

Sparse Dynamic 3D Point Cloud

SKELETAL POSE ESTIMATION

- Challenges:
 - Food intake activities involve **smaller movements**
 - Differentiating them requires higher precision
- Solution:
 - Skeletal Pose Estimation (a.k.a. Human Joint Estimation)
 - Leverage the human body structure to capture subtle nuances





^① Skeletal Pose Estimator (SPE) ² Dynamic Point Cloud Recognizer (DPR)

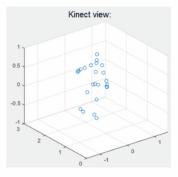
PROPOSED SOLUTIONS \mathcal{V} ${\mathcal X}$ Zrers 'ayer Skeleton 8×8 Points CNN [I]

⁽¹⁾ Skeletal Pose Estimator (SPE)

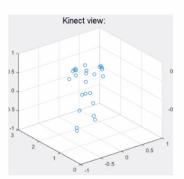
MARS [1]

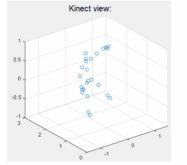
mmWave-Based Assistive Rehabilitation System for Smart Healthcare

-0.5

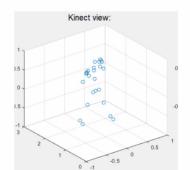


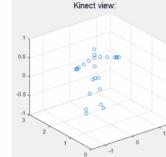
10) Right limb extension



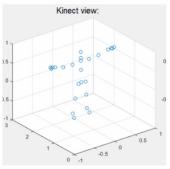


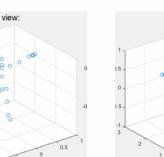
9) Left limb extension

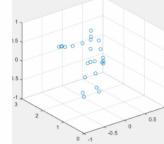




Right side lunge 8)



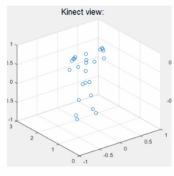




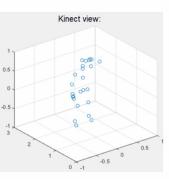
7) Left side lunge

Kinect view:

Kinect view



6) Squad



1) Left upper limb extension

5) Right front lunge

4) Left front lunge

3) Both upper limb extension

2) Right upper limb extension

[1] S. An and U. Ogras. 2021. MARS: mmWave-based Assistive Rehabilitation System for Smart Healthcare. ACM TECS 20, 5s, Article 72, 1–22.

	MARS	AlexNet	GoogLeNet	ResNet-18	ResNet-34	ResNet-50
Nose	8.28 (±0.17)	6.91 (±0.06)	4.73 (±0.05)	4.41 (±0.05)	4.22 (±0.05)	4.75 (±0.08)
L. Shldr	6.66 (±0.10)	5.65 (±0.05)	3.91 (±0.04)	$3.74 (\pm 0.04)$	3.58 (±0.04)	3.93 (±0.05)
R. Shldr	$6.58 (\pm 0.11)$	5.54 (±0.05)	3.86 (±0.04)	$3.67 (\pm 0.04)$	3.52 (±0.04)	3.91 (±0.06)
L. Elbow	8.68 (±0.15)	7.13 (±0.05)	$4.84 (\pm 0.04)$	4.59 (±0.04)	4.39 (±0.04)	4.83 (±0.05)
R. Elbow	8.38 (±0.16)	7.05 (±0.05)	4.97 (±0.04)	4.76 (±0.04)	4.57 (±0.04)	4.94 (±0.04)
L. Wrist	$11.52 (\pm 0.13)$	9.60 (±0.06)	6.53 (±0.05)	$6.36 (\pm 0.05)$	6.06 (±0.05)	6.55 (±0.06)
R. Wrist	$11.78 (\pm 0.10)$	10.19 (±0.06)	7.29 (±0.05)	7.15 (±0.05)	6.85 (±0.05)	7.33 (±0.06)
L. Pinky	$12.51 (\pm 0.13)$	$10.44 (\pm 0.07)$	7.14 (±0.05)	6.96 (±0.05)	6.62 (±0.05)	7.13 (±0.06)
R. Pinky	13.27 (±0.15)	11.47 (±0.07)	8.24 (±0.06)	$8.08 (\pm 0.06)$	7.74 (±0.06)	8.28 (±0.06)
L. Index	$12.54 (\pm 0.13)$	$10.50 (\pm 0.07)$	7.20 (±0.06)	7.00 (±0.05)	6.67 (±0.05)	7.21 (±0.06)
R. Index	13.16 (±0.11)	11.41 (±0.07)	8.23 (±0.06)	$8.06 (\pm 0.06)$	7.73 (±0.06)	8.26 (±0.06)
L. Thumb	$11.63 (\pm 0.13)$	9.70 (±0.06)	6.62 (±0.05)	6.46 (±0.05)	6.15 (±0.05)	6.63 (±0.05)
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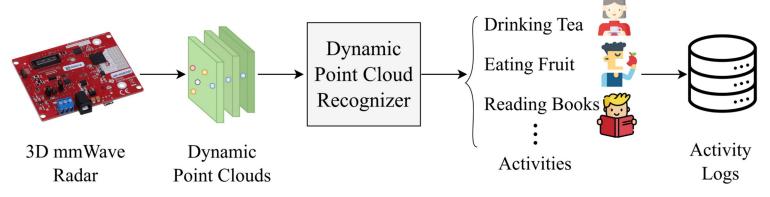
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END-TO-END SOLUTION

- End-to-end learning
 - An ML technique where we train a **single neural network** for complex tasks
 - Directly using raw input data without manual feature extraction

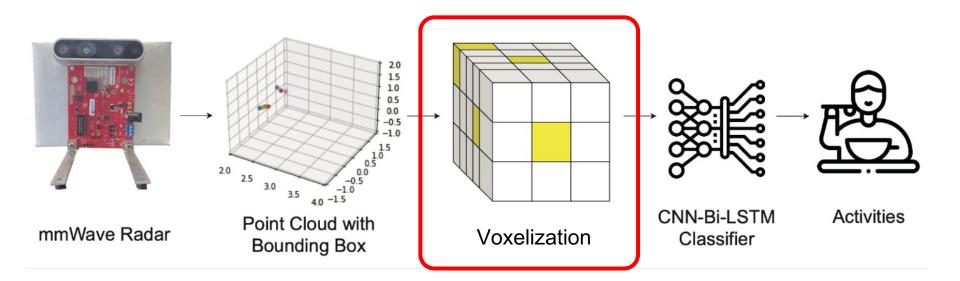


- Food Intake Activity (FIA) [MADiMa '22]
 - → Uses **voxelization**, which is quite memory inefficient for sparse point clouds

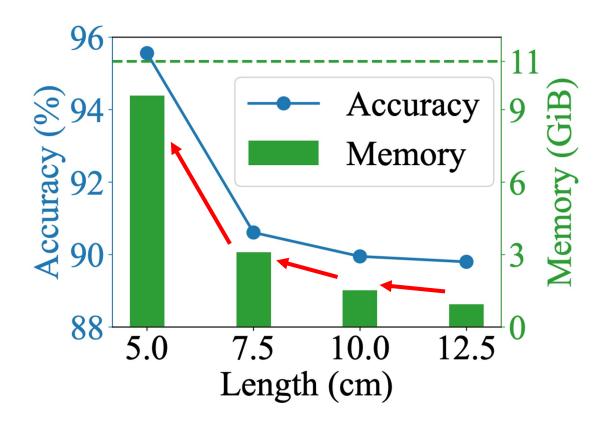
[MADiMa '22] Y. Wu, Y. Chen, S. Shirmohammadi, and C. Hsu. 2022.

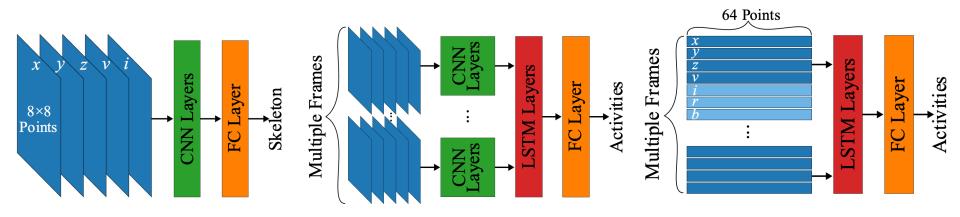
Al-Assisted Food Intake Activity Recognition Using 3D mmWave Radars. In Proc. of the ACM MADiMa '22. 81–89.

FIA PIPELINE



FIA VOXEL SIZE \downarrow ACCURACY \uparrow MEMORY \uparrow



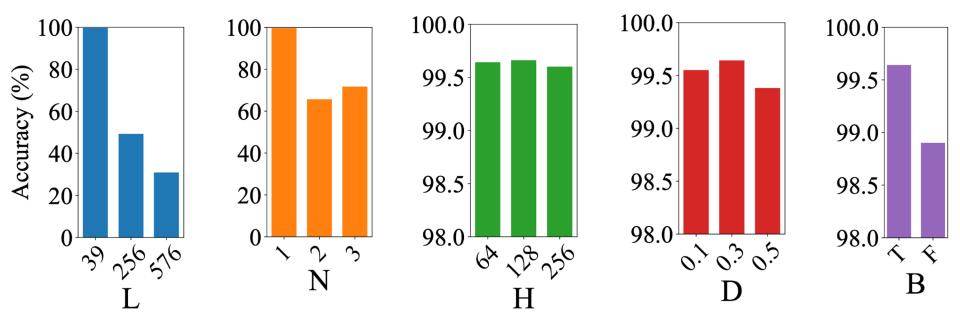


¹ Skeletal Pose Estimator (SPE) ⁽²⁾ Dynamic Point Cloud Recognizer (DPR)

PROPOSED SOLUTIONS Multiple Frames *ayers* ayer S tivit STM Ct T

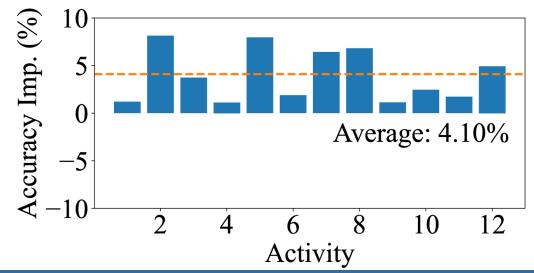
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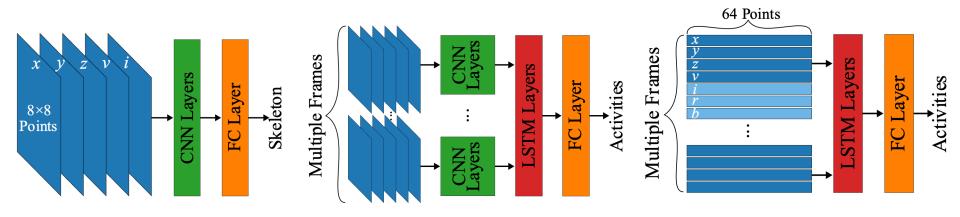
FINDING THE OPTIMAL PARAMETERS



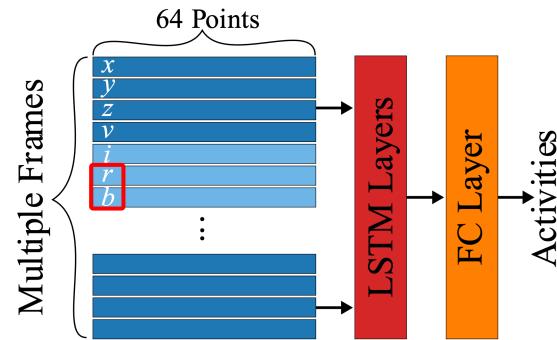
$\text{IMPROVEMENT OF } DPR^{\textcircled{2}} \text{ OVER FIA}$

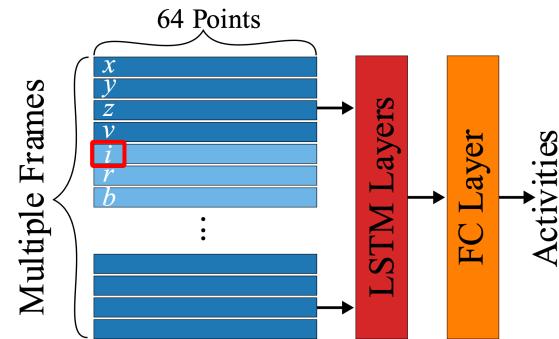
- Activity Recognition Accuracy
 - 95.56% → 99.66% (4.10% improvement)
- GPU Memory Consumption
 - 9817 MiB → 2131 MiB (**78.29% reduction**)





¹ Skeletal Pose Estimator (SPE) ² Dynamic Point Cloud Recognizer (DPR)





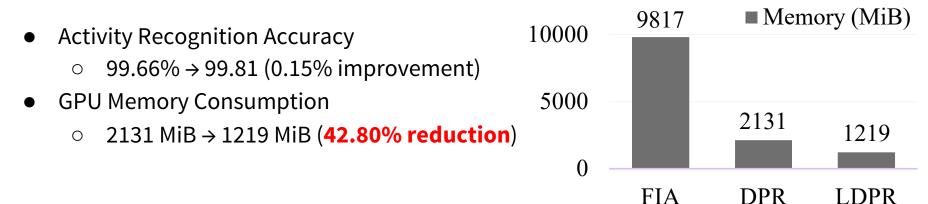
${\rm LDPR}^{\tiny (3)} \text{ ACCURACY USING DIFFERENT FEATURES}$

Accuracy	$\{x, y, z\}$	$\{r,b\}$	$\{x, y, z, r, b\}$
With <i>i</i>	98.51%	99.74%	99.78%
Without <i>i</i>	99.81%	99.74%	99.81%

LDPR³ ACCURACY USING DIFFERENT FEATURES

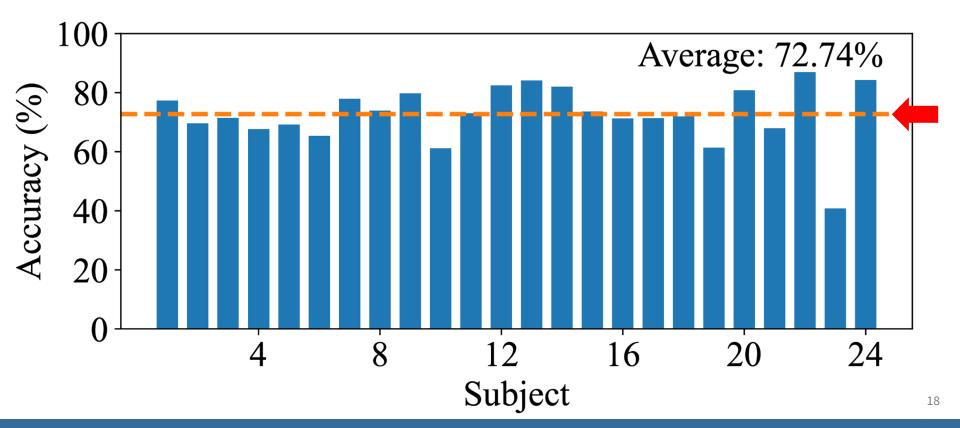
Accuracy	$\{x, y, z\}$	$\{r,b\}$	$\{x, y, z, r, b\}$
With <i>i</i>	98.51%	99.74%	99.78%
Without <i>i</i>	99.81%	99.74%	99.81%

IMPROVEMENT OF LDPR 3 OVER DPR 2

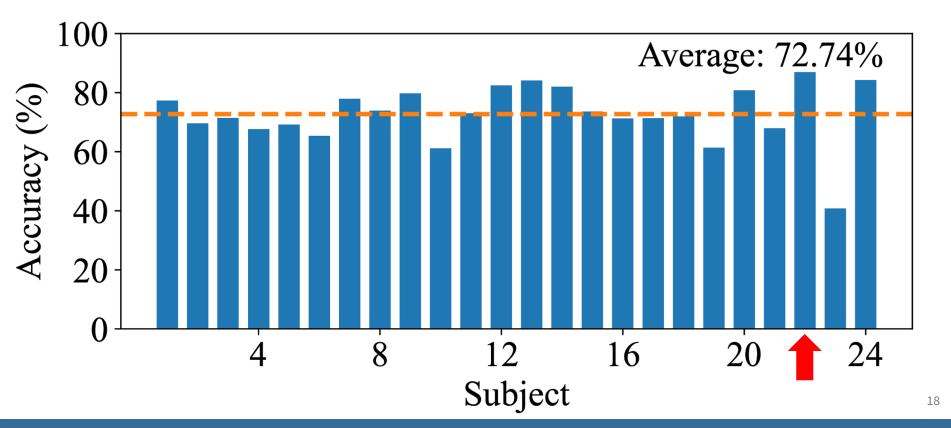


- Besides the standard 80-20 split, we also experimented with the leave-one-out test
 - Each subject is selected for testing
 - Remaining 23 subjects for training
 - Replicates the situation of **recognizing a new subject**

LDPR³ ACCURACY: LEAVE-ONE-OUT TEST



LDPR³ ACCURACY: LEAVE-ONE-OUT TEST



CONFUSION MATRIX: BEST/WORST SUBJECT

Cup -	83.04%	0.89%	0.00%	0.00%	14.29%	0.00%	0.00%	0.00%	1.79%	0.00%	0.00%	0.00%		Cup -	53.10%	21.24%	15.04%	2.65%	4.42%	3.54%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Bottle –	4.46%	95.54%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		Bottle -	- 4.39%	36.84%	36.84%	0.00%	0.88%	0.00%	0.00%	0.88%	0.00%	20.18%	0.00%	0.00%
Straw -	0.00%	0.00%	83.93%	1.79%	2.68%	0.00%	0.00%	0.89%	10.71%	0.00%	0.00%	0.00%	- 0.8	Straw -	- 0.88%	0.00%	38.60%	0.00%	0.88%	0.00%	23.68%	0.00%	0.00%	1.75%	3.51%	30.70%
Burger –	0.00%	0.00%	0.00%	98.18%	0.00%	1.82%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		Burger -	5.26%	19.30%	40.35%	1.75%	1.75%	13.16%	0.00%	0.00%	0.00%	0.88%	2.63%	14.91%
Fruit -	0.00%	0.00%	0.00%	0.00%	88.18%	0.00%	0.00%	4.55%	6.36%	0.00%	0.91%	0.00%	- 0.6	Fruit -	- 0.88%	0.00%	39.47%	0.00%	50.88%	0.88%	0.00%	0.88%	6.14%	0.88%	0.00%	0.00%
Noodles -	0.00%	0.00%	0.90%	3.60%	0.00%	93.69%	0.00%	0.00%	0.00%	1.80%	0.00%	0.00%	0.0	Noodles -	- 6.09%	0.00%	5.22%	0.00%	4.35%	0.87%	1.74%	0.00%	13.04%	46.09%	22.61%	0.00%
Sitting -	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	89.29%	0.00%	0.00%	0.00%	0.00%	10.71%		Sitting -	- 0.88%	0.00%	0.00%	0.00%	0.00%	0.88%	52.63%	2.63%	0.00%	0.00%	2.63%	40.35%
Call –	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	97.32%	2.68%	0.00%	0.00%	0.00%	- 0.4	Call -	- 0.00%	0.00%	28.95%	0.00%	57.89%	0.00%	0.00%	7.89%	3.51%	1.75%	0.00%	0.00%
Wiping -	0.00%	0.00%	0.00%	0.00%	5.41%	0.00%	0.00%	45.95%	48.65%	0.00%	0.00%	0.00%		Wiping -	- 33.62%	0.00%	7.76%	0.00%	51.72%	3.45%	0.00%	0.00%	3.45%	0.00%	0.00%	0.00%
Writing -	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	99.11%	0.89%	0.00%	- 0.2	Writing -	- 0.00%	0.00%	0.00%	0.00%	0.87%	0.00%	2.61%	0.00%	0.00%	86.96%	9.57%	0.00%
Reading -	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	14.55%	85.45%	0.00%		Reading -	- 0.00%	0.00%	0.88%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	11.50%	87.61%	0.00%
Scrolling -	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	9.73%	0.00%	0.00%	0.00%	0.00%	90.27%		Scrolling -	- 0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	8.93%	0.00%	0.00%	5.36%	0.00%	85.71%
	Cup -	Bottle -	Straw -	Burger -	Fruit -	Noodles -	Sitting -	Call -	Wiping -	Writing -	Reading -	Scrolling -	- 0.0		Cup -	Bottle -	Straw -	Burger -	Fruit -	Noodles -	Sitting -	Call -	Wiping -	Writing -	Reading -	Scrolling -

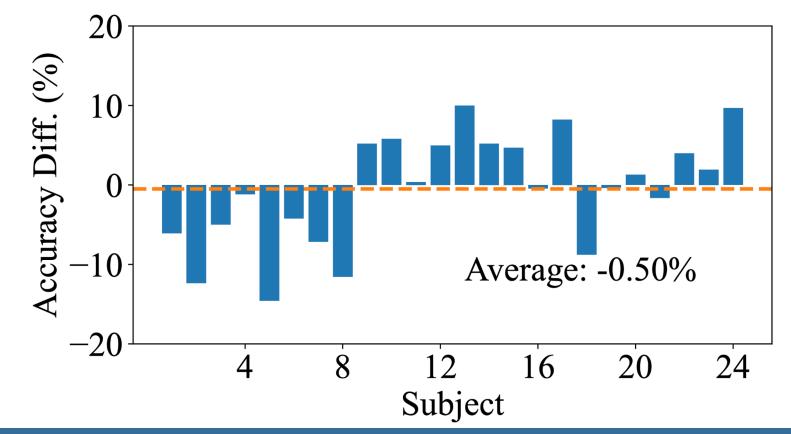
Cup -	Bottle -	Straw -	Burger -	Fruit -	Noodles -	Sitting -	- Call	Wiping -	Writing -	Reading -	Scrolling -		- 0.0
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	8.93%	0.00%	0.00%	5.36%	0.00%	85.71%		0.0
0.00%	0.00%	0.88%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	11.50%	87.61%	0.00%	-	- 0.1
0.00%	0.00%	0.00%	0.00%	0.87%	0.00%	2.61%	0.00%	0.00%	86.96%	9.57%	0.00%		- 0.2
33.62%	0.00%	7.76%	0.00%	51.72%	3.45%	0.00%	0.00%	3.45%	0.00%	0.00%	0.00%		0.5
0.00%	0.00%	28.95%	0.00%	57.89%	0.00%	0.00%	7.89%	3.51%	1.75%	0.00%	0.00%	_	- 0.3
0.88%	0.00%	0.00%	0.00%	0.00%	0.88%	52.63%	2.63%	0.00%	0.00%	2.63%	40.35%	-	- 0.4
6.09%	0.00%	5.22%	0.00%	4.35%	0.87%	1.74%	0.00%	13.04%	46.09%	22.61%	0.00%	-	- 0.5
0.88%	0.00%	39.47%	0.00%	50.88%	0.88%	0.00%	0.88%	6.14%	0.88%	0.00%	0.00%		
5.26%	19.30%	40.35%	1.75%	1.75%	13.16%	0.00%	0.00%	0.00%	0.88%	2.63%	14.91%		- 0.6
0.88%	0.00%	38.60%	0.00%	0.88%	0.00%	23.68%	0.00%	0.00%	1.75%	3.51%	30.70%		- 0.7
4.39%	36.84%	36.84%	0.00%	0.88%	0.00%	0.00%	0.88%	0.00%	20.18%	0.00%	0.00%		- 0.8
55.10%	21.24%	15.04%	2.65%	4.42%	3.54%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		

CONFUSION MATRIX: BEST/WORST SUBJECT

Cup	83.04%	0.89%	0.00%	0.00%	14.29%	0.00%	0.00%	0.00%	1.79%	0.00%	0.00%	0.00%		Cup -	53.10%	21.24%	15.04%	2.65%
Bottle	- 4.46%	95.54%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		Bottle -	4.39%	36.84%	36.84%	0.00%
Straw	- 0.00%	0.00%	83.93%	1.79%	2.68%	0.00%	0.00%	0.89%	10.71%	0.00%	0.00%	0.00%	- 0.8	Straw -	0.88%	0.00%	38.60%	0.00%
Burger	- 0.00%	0.00%	0.00%	98.18%	0.00%	1.82%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%		Burger -	5.26%	19.30%	40.35%	1.75%
Fruit	- 0.00%	0.00%	0.00%	0.00%	88.18%	0.00%	0.00%	4.55%	6.36%	0.00%	0.91%	0.00%	- 0.6	Fruit -	0.88%	0.00%	39.47%	0.00%
Noodles	- 0.00%	0.00%	0.90%	3.60%	0.00%	93.69%	0.00%	0.00%	0.00%	1.80%	0.00%	0.00%	0.0	Noodles -	6.09%	0.00%	5.22%	0.00%
Sitting	- 0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	89.29%	0.00%	0.00%	0.00%	0.00%	10.71%		Sitting -	0.88%	0.00%	0.00%	0.00%
Call	- 0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	97.32%	2.68%	0.00%	0.00%	0.00%	- 0.4	Call -	0.00%	0.00%	28.95%	0.00%
Wiping	- 0.00%	0.00%	0.00%	0.00%	5.41%	0.00%	0.00%	45.95%	48.65%	0.00%	0.00%	0.00%		Wiping -	33.62%	0.00%	7.76%	0.00%
Writing	- 0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	99.11%	0.89%	0.00%	- 0.2	Writing -	0.00%	0.00%	0.00%	0.00%
Reading	- 0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	14.55%	85.45%	0.00%		Reading -	0.00%	0.00%	0.88%	0.00%
Scrolling	- 0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	9.73%	0.00%	0.00%	0.00%	0.00%	90.27%		Scrolling -	0.00%	0.00%	0.00%	0.00%
	Cup -	Bottle -	Straw -	Burger –	Fruit -	Noodles -	Sitting -	Call -	Wiping -	Writing -	Reading -	Scrolling -	- 0.0		Cup -	Bottle -	Straw -	Burger -

53.10%	21.24%	15.04%	2.65%	4.42%	3.54%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%			0.0
4.39%	36.84%	36.84%	0.00%	0.88%	0.00%	0.00%	0.88%	0.00%	20.18%	0.00%	0.00%			- 0.8
0.88%	0.00%	38.60%	0.00%	0.88%	0.00%	23.68%	0.00%	0.00%	1.75%	3.51%	30.70%		-	- 0.7
5.26%	19.30%	40.35%	1.75%	1.75%	13.16%	0.00%	0.00%	0.00%	0.88%	2.63%	14.91%		-	- 0.6
0.88%	0.00%	39.47%	0.00%	50.88%	0.88%	0.00%	0.88%	6.14%	0.88%	0.00%	0.00%			
6.09%	0.00%	5.22%	0.00%	4.35%	0.87%	1.74%	0.00%	13.04%	46.09%	22.61%	0.00%		-	- 0.5
0.88%	0.00%	0.00%	0.00%	0.00%	0.88%	52.63%	2.63%	0.00%	0.00%	2.63%	40.35%		-	- 0.4
0.00%	0.00%	28.95%	0.00%	57.89%	0.00%	0.00%	7.89%	3.51%	1.75%	0.00%	0.00%			- 0.3
33.62%	0.00%	7.76%	0.00%	51.72%	3.45%	0.00%	0.00%	3.45%	0.00%	0.00%	0.00%			0.5
0.00%	0.00%	0.00%	0.00%	0.87%	0.00%	2.61%	0.00%	0.00%	86.96%	9.57%	0.00%		-	- 0.2
0.00%	0.00%	0.88%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	11.50%	87.61%	0.00%		-	- 0.1
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	8.93%	0.00%	0.00%	5.36%	0.00%	85.71%			
Cup -	Bottle -	Straw -	Burger –	Fruit -	Noodles -	Sitting -	Call -	Wiping -	Writing -	Reading -	Scrolling -	r	-	- 0.0

ACCURACY DIFF. BETWEEN LDPR $^{(3)}$ and DPR $^{(2)}$



SUMMARY

Task:

• Food intake activity recognition using mmWave point clouds

Proposed solutions:

- Skeletal Pose Estimator (SPE)
- Dynamic Point Cloud Recognizer (DPR)
- Lightweight Dynamic Point Cloud Recognizer (LDPR)

Ongoing works:

- Further enhancing the **precision of the estimated skeletons**
- Enhance the model's **generalization capability**
- Apply these solutions to other scenarios, e.g., **Driver Monitoring System** (DMS)

ANY QUESTIONS?