Wi-PT-Hand: WiFi Sensing based Low-cost Physical Rehabilitation Tracking for Hand Movements

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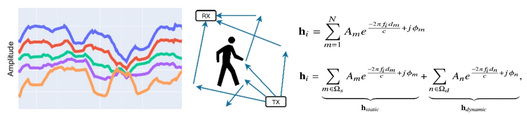
Abstract

This proposed system includes (i) segmentation of the therapy time into activity and non-activity durations, (ii) recognition of the exercise performed in an activity segment, and (iii) counting of the number of repetitions of the same exercise performed within that segment.

What is WiFi Sensing?

In WiFi sensing, WiFi signals are used for sensing activities by multipath RF signal summation, several signal processing steps and classified by ML models afterwards.



$$\mathbf{h}_i = \sum_{m=1}^{N} A_m e^{\frac{-2\pi f_i d_m}{c} + j\phi_m}$$

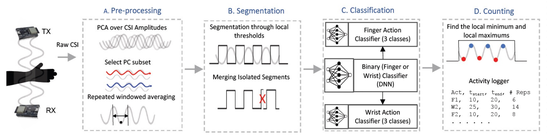
$$\mathbf{h}_i = \underbrace{\sum_{m \in \mathbb{L}_s} A_m e^{\frac{-2\pi f_i d_m}{c} + j\phi_m}}_{\mathbf{h}_{\text{static}}} + \underbrace{\sum_{n \in \mathbb{L}_d} A_n e^{\frac{-2\pi f_i d_n}{c} + j\phi_n}}_{\mathbf{h}_{\text{dynamic}}}.$$

Related Works

Existing studies propose either segmentation for whole body movements or classification, whereas we offer segmentation, classification and counting for subtle movements involving wrist and fingers.

Overview

We perform six hand physiotherapy gestures in a custom WiFi field using ESP32 microcontrollers, collect CSI, apply PCA & our developed three algorithms to get action segments & counts, and classify those actions by three DNN models.

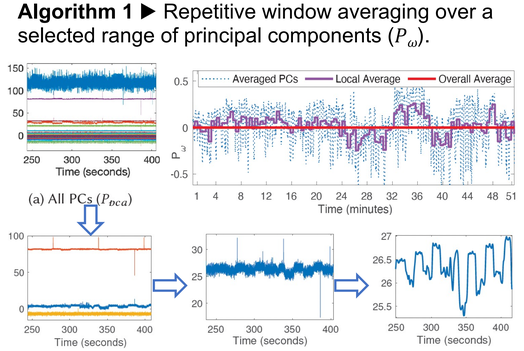


WiFi CSI Data Collection

Segmentation and Counting

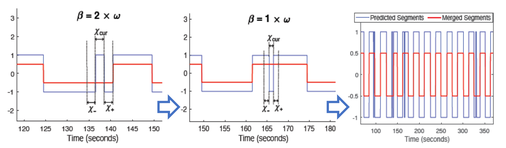
We use Bayesian optimizer to optimize seven hyperparameters for the following three algorithms.

Algorithm 1 ▶ Repetitive window averaging over a selected range of principal components (P_ω).



(a) All PCs (P_{pca}) (b) Selected $\rho = 3$ PCs (c) Avg. of the selected PCs (P) (d) Repetitive average (P_ω)

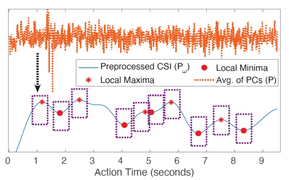
Algorithm 2 ▶ Segment activities (χ) by comparing series values with its counter local-average section.



(a) Merging divided non-activity segment (b) Merging divided activity segment (c) Fixing Multiple Isolated Segments

Algorithm 3 ▶ Merge isolated tiny segments in (χ) with the surrounding activity or non-activity segment.

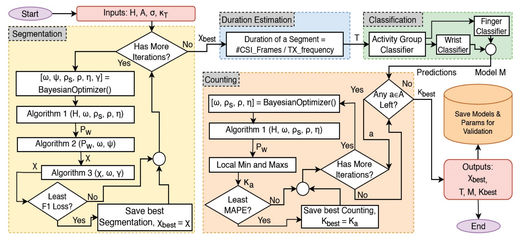
Counting ▶ The number of local optima in P_ω coincides with the number of repetitions of the hand gestures.



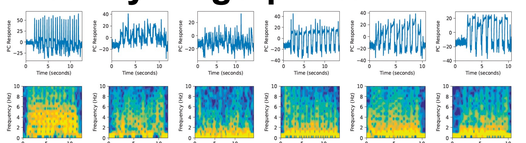
Activity Classification

Three optimized DNN models work hierarchically to classify six actions, three each in two groups – wrist and finger. Segmented CSI windows are passed as the inputs of the models.

Overall System Flowchart



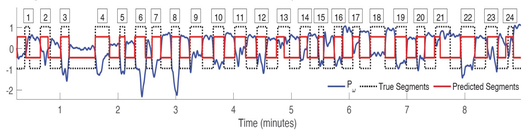
Activity Fingerprints



(a) Pitch Action (b) Roll Action (c) Yaw Action (d) Fist (e) OK Sign (f) V Sign

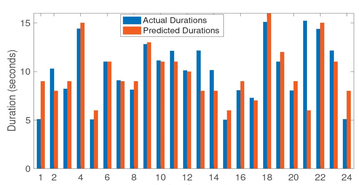
Results: Segmentation

Our segmentation algorithms achieve 94.89% CSI frame-level (10ms resolution) accuracy and 100% segment identification accuracy.

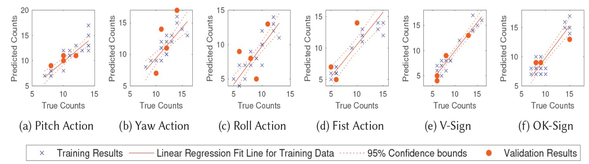


Method	Train/ Validate	ω	ψ	ρ_s	ρ	η	γ	Accuracy (%) by CSI-Frames	F1-Score	Segmentation Number			
										Accuracy(%)	FP	FN	Total
OA	D1/D1	50	-	2	2	3	3	81.92%	80.57%	90.45%	14	9	241
OA	D1/D2							84.65%	82.84%	83.67%	4	4	49
OA	D2/D2	50	-	2	2	3	4	92.07%	91.03%	100%	0	0	49
LA	D1/D1	100	19	2	2	5	2	91.41%	90.37%	97.51%	4	2	241
LA	D1/D2							90.27%	88.94%	100%	0	0	49
LA	D2/D2	50	27	2	27	10	7	94.89%	94.42%	100%	0	0	49

Duration Est. ▶ Our system can estimate the action durations with 1.11 sec. of mean absolute error (MAE).



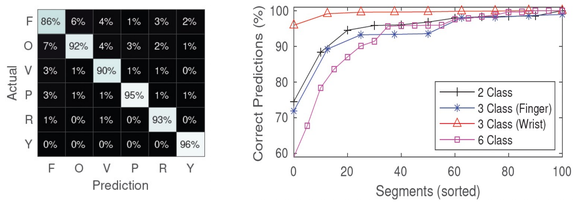
Results: Counting



(a) Pitch Action (b) Yaw Action (c) Roll Action (d) Fist Action (e) V-Sign (f) OK-Sign

Results: Activity Classification

Our hierarchical classifier has an overall accuracy of 91.2%.



Generalizability

We have good accuracy in all three sections with several other volunteers after optimizing the hyperparameters only for one person.

Volunteer Number	Accuracy(%) By CSI Frame	Segment Identification (%)	Counting Error	Classification Accuracy (%)			
				Binary	Finger	Wrist	Overall
1	90.27%	100.0%	1.37 ± 0.89	96.44%	90.02%	99.17%	91.22%
2	90.32%	100.0%	1.91 ± 1.33	96.11%	81.41%	87.65%	81.24%
3	80.17%	92.42%	1.69 ± 1.38	98.64%	84.29%	90.46%	86.19%

Conclusion

The proposed system considers small-scale movements like wrist and finger movements and it can not only classify an activity but also can detect when, for how long, and how many times that activity is performed using only the ubiquitous WiFi signals around us. It also has potential to run on low-memory edge devices due to using DNN model and is easily scalable due to the hierarchical architecture.

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