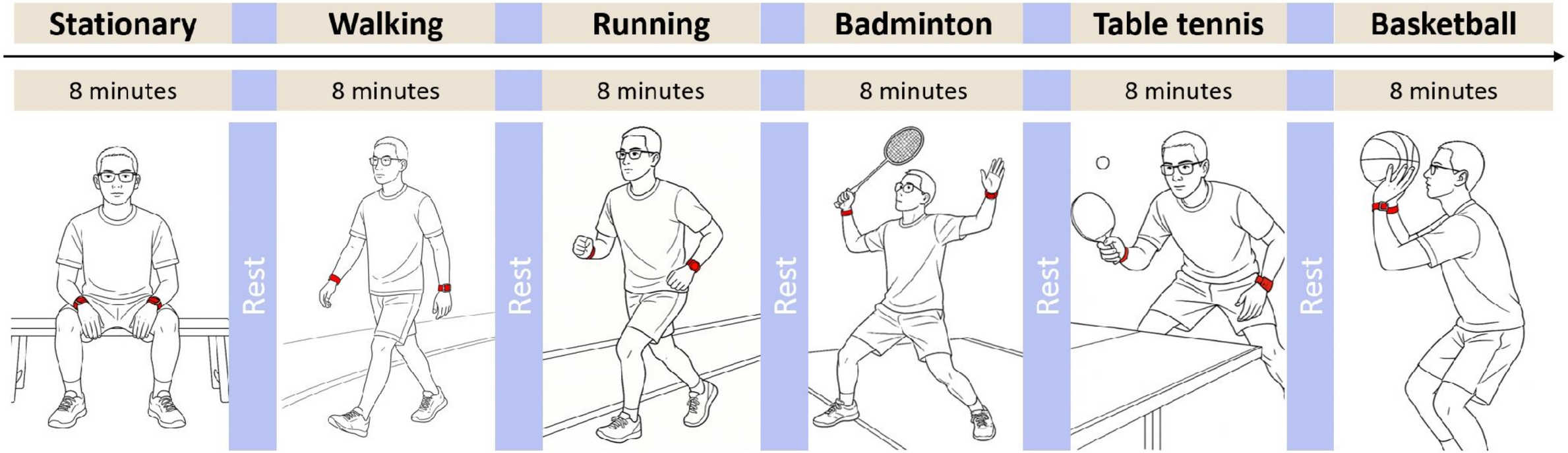
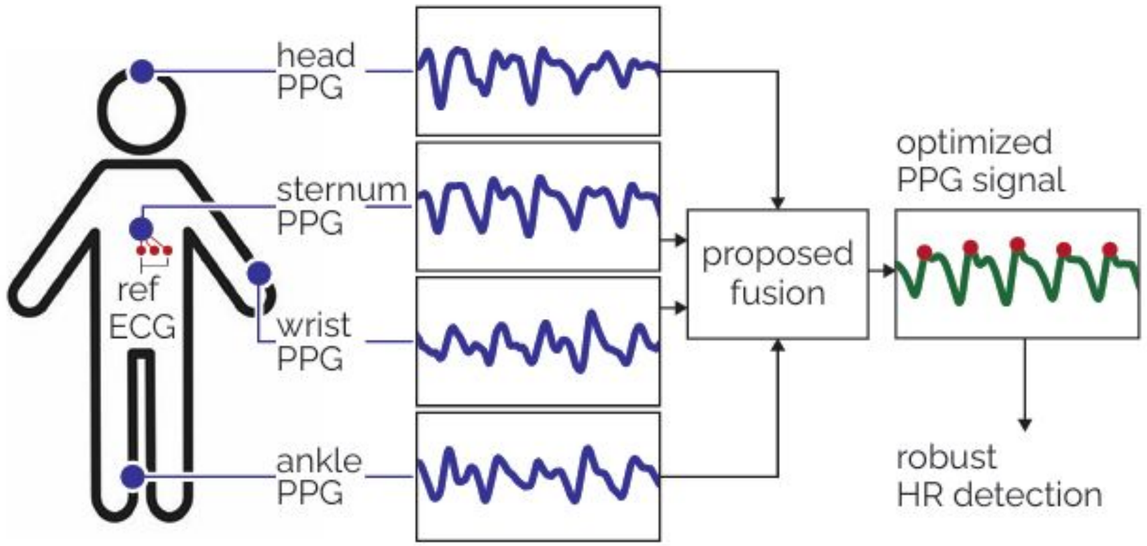
Learning from Bilateral PPG via Cross-Site Attention and Knowledge Distillation

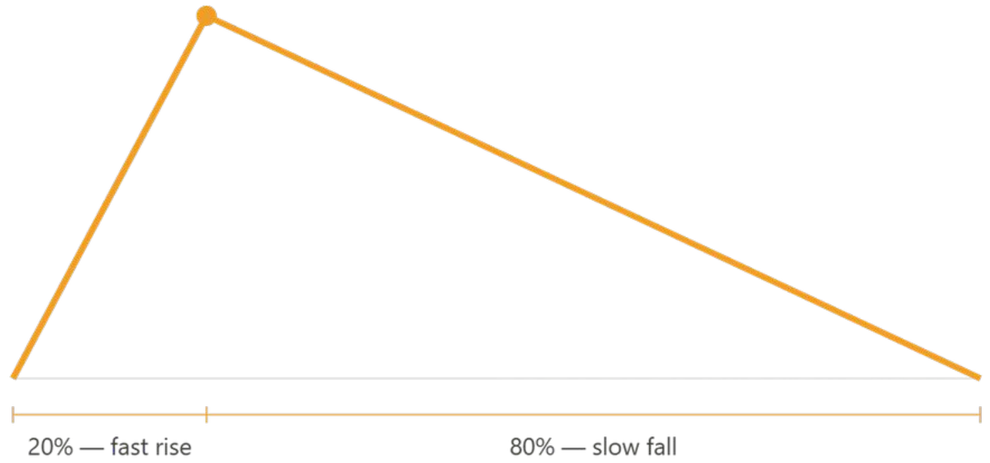
Thamilezai Ananthakumar, Hung Manh Pham, Dong Ma,
Archan Misra, Thivya Kandappu

Introduction and Motivation



Prior Work (WildPPG)





Template : Leaning triangle wave

- **Method** : template-based multi-site fusion that dynamically weights signals from different body locations.

- **Disadvantage** : require all sensing sites at inference.

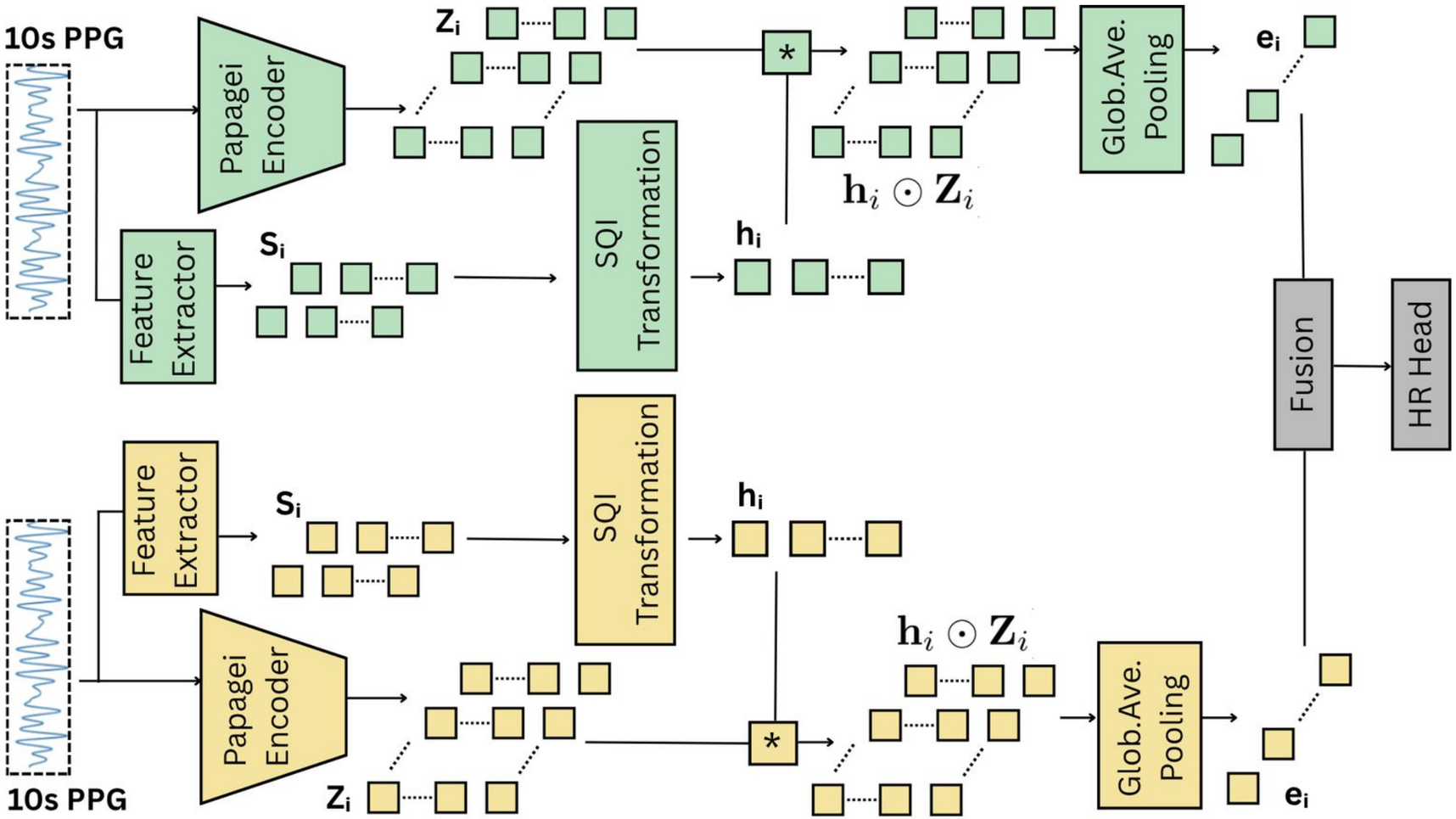
Overall Goals

1. **PPG-only** end-to-end motion artefact removal pipeline using bilateral PPG signals.

- Goal 1: Extract PPG morphology-related features → Papgei Foundation Model Encoder
- Goal2: Extract Signal Quality features as a proxy for motion artefacts → SQI Encoder

2. Attention-based fusion of bilateral morphology and SQI
3. Bilateral to unilateral knowledge distillation

Our Method : Bilateral Teacher



[Papagei]

1. Bilateral Outperforms Unilateral Sensing

Model	Stat	Walk	Run	Badmin	T.Tennis	Basket	Comb
Papagei-s(Frz, ND)	9.27	19.93	40.62	16.35	18.66	7.11	18.66
Papagei-s(Frz, Dom)	10.69	13.88	38.26	20.75	20.41	7.52	18.59
Papagei-s(FT, ND)	2.04	2.89	1.67	7.93	2.97	2.38	3.32
Papagei-s(FT, Dom)	2.62	3.98	5.05	10.65	3.63	6.81	5.86
PulsePPG(FT, ND)	1.85	4.87	2.12	7.98	2.97	2.12	3.65
PulsePPG(FT,Dom)	1.88	2.78	6.43	9.20	5.93	5.73	5.32
ReseNet18(ND)	1.61	9.76	2.29	8.90	6.35	4.41	5.57
Efficientnet(ND)	1.52	4.08	1.77	8.19	1.90	2.85	3.39
Bilateral	**1.26**	**2.76**	**1.23**	7.99	**1.86**	**2.02**	**2.85**

- **Key Takeaway 1:** **Across various models, we show that by carefully fusing morphology and SQ features,bilateral outperforms unilateral PPG sensing in hear rate estimation**

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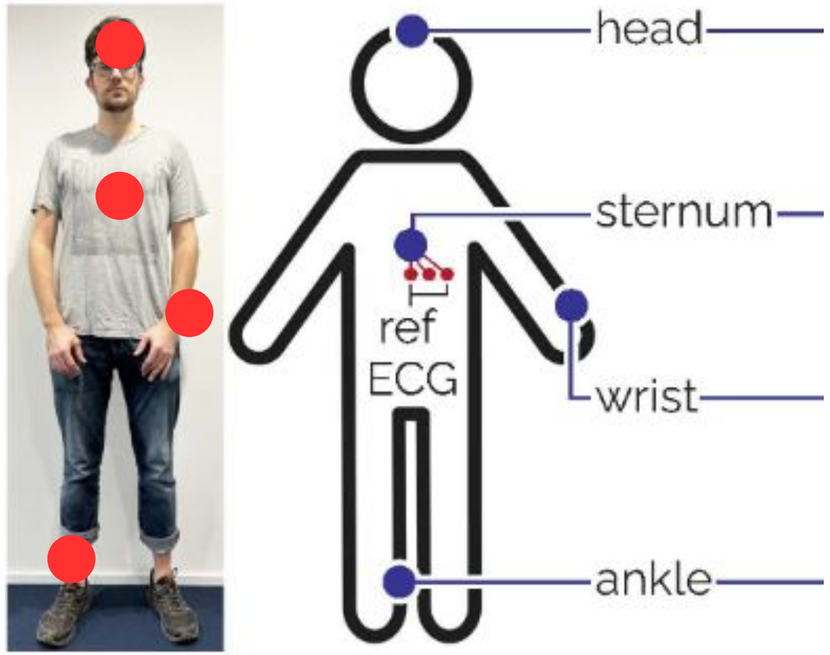
1. Ablation Study

Model Variant	MAE (bpm)
Without SQI	3.20
Non-dominant Only	3.35
Dominant Only	6.25
Without Attention	3.52
Ours	**2.85**

- **Key Takeaway 2: Each Part of the bilateral models has its own advantage**

1. Multi-site Bilateral Sensing



Configuration	MAE (bpm)
Ankle Only	3.48
Head Only	5.44
Wrist Only	8.42
Ankle-Wrist Pair	**3.32**
Head-Wrist Pair	**4.43**
Head-Ankle Pair	**2.63**

- **Key Takeaway 3:** **The model generalizes across various body locations, not just the two wrists (Location-agnostic model).**

1. Hardware-agnostic Performance

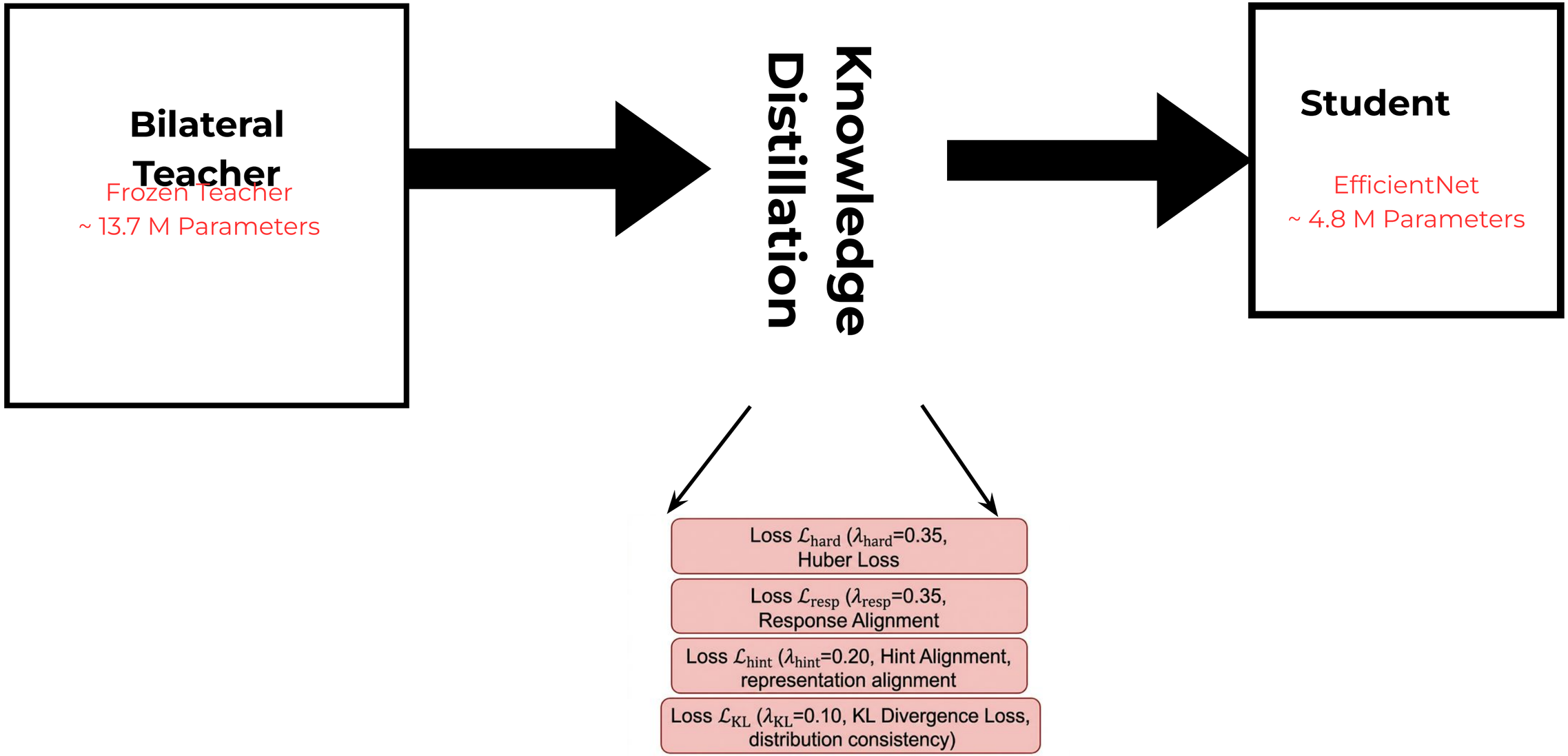
Empatica E4
Sampling frequency : 64Hz

Galaxy 5
Sampling frequency : 25Hz

Configuration	MAE (bpm)
Left Wrist (Empatica E4)	5.24
Right Wrist (Galaxy Watch)	6.56
Bilateral	**4.71**

- **Key Takeaway 4: The model generalizes across various devices with different sampling frequencies (Device-agnostic Model)**

Practical Concern on Bilateral Availability



1. Impact of Knowledge Distillation

Model	stat	walk	Run	Bad	T.Tennis	Basket	Comb.
ND Baseline	2.04	2.89	1.67	7.93	2.97	2.38	3.32
Dom Baseline	2.62	3.98	5.05	10.65	5.63	6.81	5.86
KD Student (ND)	**1.32**	**2.75**	**1.67**	**8.14**	**1.39**	**1.46**	**2.79**
KD Student (Dom)	**1.50**	**1.83**	**4.03**	**8.77**	**2.38**	**3.83**	**3.72**

- **Key Takeaway 5: Knowledge distillation outperforms unilateral PPG, and bilateral knowledge is successfully transferred to the unilateral student model.**

1. Impact of Knowledge Distillation

Model	MAE (bpm)
Unilateral Ankle	3.48
Unilateral Head	5.44
KD: Ankle Student	**3.19**
KD: Head Student	**4.38**

WildPPG

Model	MAE (bpm)
Unilateral Left	5.24
Unilateral Right	6.56
KD : Left Student	**5.06**
KD : Right Student	**6.36**

GalaxyPPG

Conclusion

- **Bilateral sensing** improves accuracy by combining heart rate signals from both wrists, allowing the system to dynamically focus on whichever signal is less affected by motion artifacts.

- **Knowledge distillation** transfers this "motion-compensation" expertise from the dual-wrist system to a single-wrist wearable, enabling highly accurate heart rate tracking using just one sensor

THANK YOU