

Supplementary Materials

Supplementary Tables

Table S1 summarizes best results across Study 1/2/3 tasks (Ring 1/2). Tables S2–S3 report Study 3 treadmill HR/RR benchmarks using IR-only inputs (avg-5folds), while Tables S4–S14 and all Supplementary Figures correspond to Study 1/2 experiments.

Task	Ring 1 (Reflective)						Ring 2 (Transmissive)					
	Best Model	MAE	RMSE	NRMSE	MAPE	Pearson	Best Model	MAE	RMSE	NRMSE	MAPE	Pearson
HR	resnet (ir)	5.33 ± 0.17	9.25 ± 0.21	0.29	6.87	0.71	resnet (irred)	7.32 ± 0.17	10.44 ± 0.24	0.49	9.02	0.48
RR	peak (ir)	2.98 ± 0.06	4.03 ± 0.09	0.29	18.38	0.45	inception-time (ir)	3.28 ± 0.07	4.25 ± 0.10	0.28	20.40	0.22
SpO ₂	transformer (irred)	1.72 ± 0.04	2.62 ± 0.06	0.29	3.58	0.19	transformer (irred)	1.48 ± 0.04	2.28 ± 0.05	0.35	4.20	0.03
SBP	transformer (irred)	12.98 ± 0.74	15.58 ± 1.33	0.25	12.21	0.28	resnet (irred)	14.81 ± 1.07	18.18 ± 1.83	0.26	14.36	0.15
DBP	transformer (irred)	7.64 ± 0.51	9.70 ± 0.83	0.15	12.03	−0.06	transformer (ir)	8.11 ± 0.72	10.79 ± 1.09	0.16	12.60	−0.12

MAE: mean absolute error; RMSE: root mean square error; NRMSE: subject-wise normalized RMSE; MAPE: mean absolute percentage error (%); Pearson denotes Pearson correlation. Values are mean ± standard error (SEM); best model and channel shown for each ring.

For NRMSE, each subject's label range ($y_{\max,s} - y_{\min,s}$) is computed from that subject's test windows; for BP we normalize by the task's global label range due to sparse labels per subject. Channel notation: ir (infrared), irimu (infrared+IMU), irred (infrared+red), irredimu (infrared+red+IMU).

Table S1. Best results on HR, RR, SpO₂, and BP tasks (All scenarios).

Method	Study 1/2 Pretrained (Zero-shot)						Treadmill Fine-tune (Init: Study 1/2)					
	Input	MAE	RMSE	NRMSE	MAPE	Pearson	Input	MAE	RMSE	NRMSE	MAPE	Pearson
ResNet	IR	39.07 ± 1.17	47.67 ± 1.84	0.38	28.79	−0.10	IR	35.18 ± 2.65	43.34 ± 3.03	0.31	26.03	0.08
InceptionTime	IR	39.68 ± 1.92	47.67 ± 2.36	0.38	29.32	0.12	IR	39.14 ± 3.31	46.66 ± 3.58	0.33	29.30	0.28
Transformer	IR	38.10 ± 1.75	46.34 ± 2.30	0.37	28.10	−0.01	IR	23.99 ± 0.61	29.80 ± 0.83	0.21	19.93	0.12
Mamba2	IR	36.91 ± 2.16	45.13 ± 2.37	0.36	27.26	0.02	IR	26.95 ± 2.98	33.21 ± 3.66	0.24	22.08	0.04

Values are mean ± SEM. Zero-shot uses the five Study 1/2 cross-validation folds evaluated on treadmill data without adaptation.

Fine-tune results are averaged over five fine-tune rotations (one fold fine-tuned, four folds tested per rotation).

NRMSE is RMSE normalized by the label range.

MAPE is mean absolute percentage error (%).

Table S2. Treadmill running HR benchmarks comparing Study 1/2 zero-shot evaluation vs. treadmill fine-tuning (Study 3), using IR-only inputs (avg-5folds).

Method	Study 1/2 Pretrained (Zero-shot)						Treadmill Fine-tune (Init: Study 1/2)					
	Input	MAE	RMSE	NRMSE	MAPE	Pearson	Input	MAE	RMSE	NRMSE	MAPE	Pearson
ResNet	IR	5.65 ± 0.36	6.65 ± 0.40	0.26	26.29	0.03	IR	5.44 ± 0.25	6.48 ± 0.27	0.23	25.64	0.03
InceptionTime	IR	5.87 ± 0.47	6.89 ± 0.52	0.27	27.01	0.01	IR	5.64 ± 0.29	6.68 ± 0.31	0.24	26.27	0.02
Transformer	IR	5.87 ± 0.43	6.90 ± 0.48	0.27	26.98	−0.07	IR	4.61 ± 0.20	5.65 ± 0.22	0.21	23.88	−0.08
Mamba2	IR	5.44 ± 0.26	6.45 ± 0.29	0.25	25.36	0.02	IR	5.46 ± 0.15	6.50 ± 0.17	0.24	25.45	0.01

Values are mean ± SEM. Zero-shot uses the five Study 1/2 cross-validation folds evaluated on treadmill data without adaptation.

Fine-tune results are averaged over five fine-tune rotations (one fold fine-tuned, four folds tested per rotation).

NRMSE is RMSE normalized by the label range.

MAPE is mean absolute percentage error (%).

Table S3. Treadmill running RR benchmarks comparing Study 1/2 zero-shot evaluation vs. treadmill fine-tuning (Study 3), using IR-only inputs (avg-5folds).

HR Stationary	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Physics-based	Peak	6.27 ± 0.26	12.22 ± 0.29	0.18	7.74	0.59	13.70 ± 0.37	20.18 ± 0.48	0.36	17.44	0.18
	FFT	6.01 ± 0.31	14.07 ± 0.32	0.21	7.28	0.56	12.39 ± 0.42	20.95 ± 0.47	0.38	15.18	0.23
Supervised	ResNet	4.14 ± 0.13	6.75 ± 0.16	0.10	5.28	0.83	6.59 ± 0.16	9.15 ± 0.23	0.16	8.51	0.50
	InceptionTime	5.60 ± 0.14	8.05 ± 0.19	0.12	7.16	0.74	7.00 ± 0.14	9.14 ± 0.22	0.16	9.02	0.45
	Transformer	6.76 ± 0.13	8.80 ± 0.21	0.13	8.45	0.66	8.09 ± 0.16	10.31 ± 0.25	0.18	10.46	−0.02
	Mamba	7.00 ± 0.16	9.56 ± 0.22	0.14	9.08	0.66	8.52 ± 0.16	10.82 ± 0.26	0.19	11.22	0.07

MAE = Mean Absolute Error in HR estimation (Beats/Min), RMSE = Root Mean Square Error in HR estimation (Beats/Min), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in HR estimation.
Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.

Table S4. Benchmark results of different methods on HR task in stationary scenarios.

HR Motion	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Physics-based	Peak	31.99 ± 1.56	38.15 ± 1.94	0.44	35.69	−0.05	36.17 ± 1.78	42.97 ± 2.26	0.51	40.31	−0.16
	FFT	40.49 ± 1.62	45.97 ± 1.69	0.54	43.91	0.09	40.56 ± 1.62	45.83 ± 1.85	0.54	43.72	−0.06
Supervised	ResNet	16.83 ± 0.98	21.39 ± 1.56	0.25	21.11	−0.03	14.22 ± 0.91	18.63 ± 1.38	0.22	16.79	0.12
	InceptionTime	17.09 ± 1.00	21.71 ± 1.53	0.25	20.62	0.01	14.53 ± 0.92	18.98 ± 1.35	0.22	16.79	0.07
	Transformer	16.00 ± 0.95	20.45 ± 1.51	0.24	20.59	0.01	14.79 ± 0.94	19.28 ± 1.35	0.23	16.99	−0.06
	Mamba	15.85 ± 0.96	20.44 ± 1.50	0.24	20.07	0.03	14.83 ± 0.91	19.10 ± 1.33	0.23	16.95	0.04

MAE = Mean Absolute Error in HR estimation (Beats/Min), RMSE = Root Mean Square Error in HR estimation (Beats/Min), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in HR estimation.
Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.

Table S5. Benchmark results of different methods on HR task in motion scenarios.

HR Motion	In-Channel(s)	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Mamba	IR	17.32 ± 1.00	21.94 ± 1.60	0.26	21.77	−0.06	15.92 ± 0.91	19.96 ± 1.35	0.23	18.19	0.02
	IR+RED	18.55 ± 1.00	22.94 ± 1.67	0.27	22.71	−0.06	14.83 ± 0.91	19.10 ± 1.33	0.23	16.95	0.04
	IR+RED+IMU	15.85 ± 0.96	20.44 ± 1.50	0.24	20.07	0.03	15.66 ± 1.01	20.61 ± 1.43	0.24	17.84	−0.22

MAE = Mean Absolute Error in HR estimation (Beats/Min), RMSE = Root Mean Square Error in HR estimation (Beats/Min), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in HR estimation.
Values are mean ± standard error (SEM). Best results in bold.
IR: infrared channel, RED: red light channel, IMU: inertial measurement unit (accelerometer).

Table S6. Ablation study of multi-channel fusion on HR estimation in motion scenarios with Mamba model.

RR All	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Physics-based	Peak	2.98 ± 0.06	4.03 ± 0.09	0.17	18.38	0.44	3.84 ± 0.08	5.09 ± 0.12	0.22	24.74	0.21
	FFT	4.80 ± 0.08	5.78 ± 0.09	0.25	26.28	0.29	4.95 ± 0.09	6.07 ± 0.11	0.26	26.81	0.16
Supervised	ResNet	3.12 ± 0.06	4.05 ± 0.09	0.18	20.15	0.32	3.33 ± 0.07	4.30 ± 0.10	0.19	20.60	0.18
	InceptionTime	3.21 ± 0.06	4.15 ± 0.10	0.18	20.56	0.25	3.28 ± 0.07	4.25 ± 0.10	0.18	20.40	0.22
	Transformer	3.33 ± 0.06	4.30 ± 0.10	0.19	21.52	0.05	3.34 ± 0.07	4.34 ± 0.10	0.19	20.77	0.09
	Mamba	3.23 ± 0.06	4.22 ± 0.10	0.18	21.68	0.15	3.36 ± 0.07	4.35 ± 0.10	0.19	22.01	0.03

MAE = Mean Absolute Error in RR estimation (Breaths/Min), RMSE = Root Mean Square Error in RR estimation (Breaths/Min), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in RR estimation.
Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.
IR: infrared channel; RED: red light channel; IMU: inertial measurement unit. “–” indicates the correlation is undefined (nan).

Table S7. Benchmark results of different methods on RR estimation.

RR Stationary	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Physics-based	Peak	2.84 ± 0.06	3.87 ± 0.09	0.17	18.19	0.46	3.72 ± 0.09	4.97 ± 0.13	0.22	24.38	0.21
	FFT	4.52 ± 0.08	5.44 ± 0.09	0.24	25.68	0.31	4.76 ± 0.09	5.82 ± 0.11	0.25	26.42	0.16
Supervised	ResNet	2.92 ± 0.06	3.78 ± 0.09	0.17	19.92	0.23	3.16 ± 0.06	4.06 ± 0.10	0.18	20.20	0.07
	InceptionTime	2.99 ± 0.06	3.84 ± 0.09	0.17	20.25	0.15	3.11 ± 0.06	4.01 ± 0.10	0.17	19.96	0.11
	Transformer	3.07 ± 0.06	3.96 ± 0.10	0.17	21.17	−0.05	3.12 ± 0.07	4.04 ± 0.10	0.18	20.18	0.01
	Mamba	3.03 ± 0.06	3.96 ± 0.09	0.17	21.65	0.05	3.18 ± 0.07	4.09 ± 0.10	0.18	21.63	0.05

MAE = Mean Absolute Error in RR estimation (Breaths/Min), RMSE = Root Mean Square Error in RR estimation (Breaths/Min), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in RR estimation.
Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.
IR: infrared channel; RED: red light channel; IMU: inertial measurement unit.

Table S8. Benchmark results of different methods on RR estimation in stationary scenarios.

RR Motion	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Physics-based	Peak	4.22 ± 0.26	5.49 ± 0.36	0.24	20.06	0.34	4.99 ± 0.29	6.19 ± 0.48	0.27	28.19	0.14
	FFT	7.42 ± 0.35	8.80 ± 0.39	0.38	31.80	0.10	6.70 ± 0.40	8.46 ± 0.46	0.37	30.47	0.17
Supervised	ResNet	4.83 ± 0.24	5.87 ± 0.38	0.26	22.16	0.06	4.87 ± 0.28	6.07 ± 0.41	0.26	24.22	0.21
	InceptionTime	5.10 ± 0.25	6.19 ± 0.39	0.27	23.19	0.07	4.83 ± 0.27	5.95 ± 0.41	0.26	24.27	0.23
	Transformer	5.53 ± 0.25	6.55 ± 0.37	0.28	24.51	−0.02	5.30 ± 0.28	6.41 ± 0.42	0.28	26.04	0.08
	Mamba	4.89 ± 0.25	6.05 ± 0.36	0.26	21.97	0.04	5.04 ± 0.27	6.17 ± 0.42	0.27	25.38	−0.01

MAE = Mean Absolute Error in RR estimation (Breaths/Min), RMSE = Root Mean Square Error in RR estimation (Breaths/Min), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in RR estimation.
Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.
IR: infrared channel; RED: red light channel; IMU: inertial measurement unit. “−” indicates the correlation is undefined (nan).

Table S9. Benchmark results of different methods on RR estimation in motion scenarios.

HR Comparison	Method	Ring 1 (Reflective)		Samsung		Ring 2 (Transmissive)		Samsung	
		MAE	MAPE	MAE	MAPE	MAE	MAPE	MAE	MAPE
Physics-based	Peak	8.68 ± 0.27	10.36	9.90 ± 1.25	13.94	15.79 ± 0.37	19.56	9.94 ± 1.57	13.32
	FFT	9.24 ± 0.32	10.70			15.06 ± 0.41	17.88		
Supervised	ResNet	5.33 ± 0.10	6.83			7.32 ± 0.08	9.31		
	InceptionTime	6.70 ± 0.10	8.47			7.80 ± 0.08	9.83		
	Transformer	7.68 ± 0.08	9.62			8.81 ± 0.08	11.14		
	Mamba2	8.09 ± 0.12	10.37			9.23 ± 0.09	11.89		

MAE = Mean Absolute Error in HR estimation (Beats/Min), MAPE = Mean Absolute Percentage Error (%).
Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.
Samsung columns report the built-in HR estimation performance of Samsung Galaxy Ring compared to medical-grade ground truth.

Table S10. Benchmark results of different methods on HR task compared with Samsung Ring.

HR Comparison	Method	Ring 1 (Reflective)		Oura		Ring 2 (Transmissive)		Oura	
		MAE	MAPE	MAE	MAPE	MAE	MAPE	MAE	MAPE
Physics-based	Peak	10.94 ± 0.74	13.54	10.09 ± 1.13	14.67	15.85 ± 1.33	18.60	10.56 ± 1.43	14.38
	FFT	10.88 ± 0.90	12.43			17.20 ± 1.51	19.67		
Supervised	ResNet	5.32 ± 0.12	6.87			7.05 ± 0.09	9.02		
	InceptionTime	6.71 ± 0.11	8.59			7.57 ± 0.10	9.76		
	Transformer	7.67 ± 0.09	9.67			8.92 ± 0.09	11.49		
	Mamba2	8.31 ± 0.14	10.73			9.61 ± 0.12	12.32		

MAE = Mean Absolute Error in HR estimation (Beats/Min), MAPE = Mean Absolute Percentage Error (%). Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE; best results are in bold.
Oura columns report the built-in HR estimation performance of the Oura Gen 3 Ring on the same segments (deepsquat, sitting, SpO₂) used for these comparisons.

Table S11. Benchmark results of different methods on HR task compared with Oura Ring.

SpO2 Low Oxygen	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Physics-based	Ratio	3.57 ± 0.14	4.65 ± 0.21	0.23	3.86	0.30	3.30 ± 0.13	3.93 ± 0.24	0.22	3.57	0.28
Supervised	ResNet	3.53 ± 0.45	4.72 ± 0.62	0.24	3.91	0.06	3.89 ± 0.39	5.10 ± 0.61	0.28	4.35	0.06
	InceptionTime	3.35 ± 0.40	4.41 ± 0.55	0.22	3.70	0.16	3.70 ± 0.36	4.94 ± 0.50	0.28	4.13	0.13
	Transformer	3.22 ± 0.28	4.46 ± 0.44	0.22	3.58	0.03	3.73 ± 0.48	5.16 ± 0.65	0.29	4.20	−0.05
	Mamba	5.87 ± 1.03	6.84 ± 0.99	0.34	6.40	0.11	5.37 ± 1.15	6.31 ± 1.28	0.35	5.92	−0.09

MAE = Mean Absolute Error in SpO2 estimation, RMSE = Root Mean Square Error in SpO2 estimation, NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in SpO2 estimation.

Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.

Table S12. Benchmark results of different methods on SpO2 estimation in low oxygen simulation scenario.

SBP All	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Supervised	ResNet	14.21 ± 0.88	17.49 ± 1.46	0.27	13.88	0.08	14.81 ± 1.07	18.18 ± 1.83	0.28	14.36	0.15
	InceptionTime	14.01 ± 0.85	17.14 ± 1.45	0.27	12.94	−0.01	16.69 ± 1.01	19.41 ± 1.93	0.30	15.60	0.06
	Transformer	12.98 ± 0.74	15.58 ± 1.33	0.24	12.21	0.28	15.44 ± 0.93	17.94 ± 1.82	0.28	14.80	0.02
	Mamba	13.33 ± 0.84	16.52 ± 1.42	0.26	12.75	−0.01	15.06 ± 1.02	18.10 ± 1.80	0.28	14.88	0.04

MAE = Mean Absolute Error in SBP estimation (mmHg), RMSE = Root Mean Square Error in SBP estimation (mmHg), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in SBP estimation.

Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.

Table S13. Benchmark results of different methods on SBP estimation.

DBP All	Method	Ring 1 (Reflective)					Ring 2 (Transmissive)				
		MAE	RMSE	NRMSE	MAPE	Pearson	MAE	RMSE	NRMSE	MAPE	Pearson
Supervised	ResNet	8.47 ± 0.59	10.94 ± 0.94	0.21	13.30	−0.20	8.46 ± 0.76	11.30 ± 1.12	0.21	13.72	−0.16
	InceptionTime	8.77 ± 0.54	10.80 ± 0.91	0.20	13.36	−0.28	8.58 ± 0.68	10.90 ± 1.09	0.21	13.17	−0.06
	Transformer	7.64 ± 0.51	9.70 ± 0.83	0.18	12.03	−0.06	8.11 ± 0.72	10.79 ± 1.09	0.20	12.60	−0.12
	Mamba	7.84 ± 0.53	10.01 ± 0.86	0.19	12.23	−0.17	8.58 ± 0.71	11.07 ± 1.12	0.21	13.73	−0.17

MAE = Mean Absolute Error in DBP estimation (mmHg), RMSE = Root Mean Square Error in DBP estimation (mmHg), NRMSE = Normalized RMSE, MAPE = Mean Absolute Percentage Error (%), Pearson = Pearson Correlation in DBP estimation.

Values are mean ± standard error (SEM). Best channel selected for each model based on lowest MAE. Best results in bold.

Table S14. Benchmark results of different methods on DBP estimation.

Supplementary Figures

All Supplementary Figures correspond to Study 1/2 experiments.

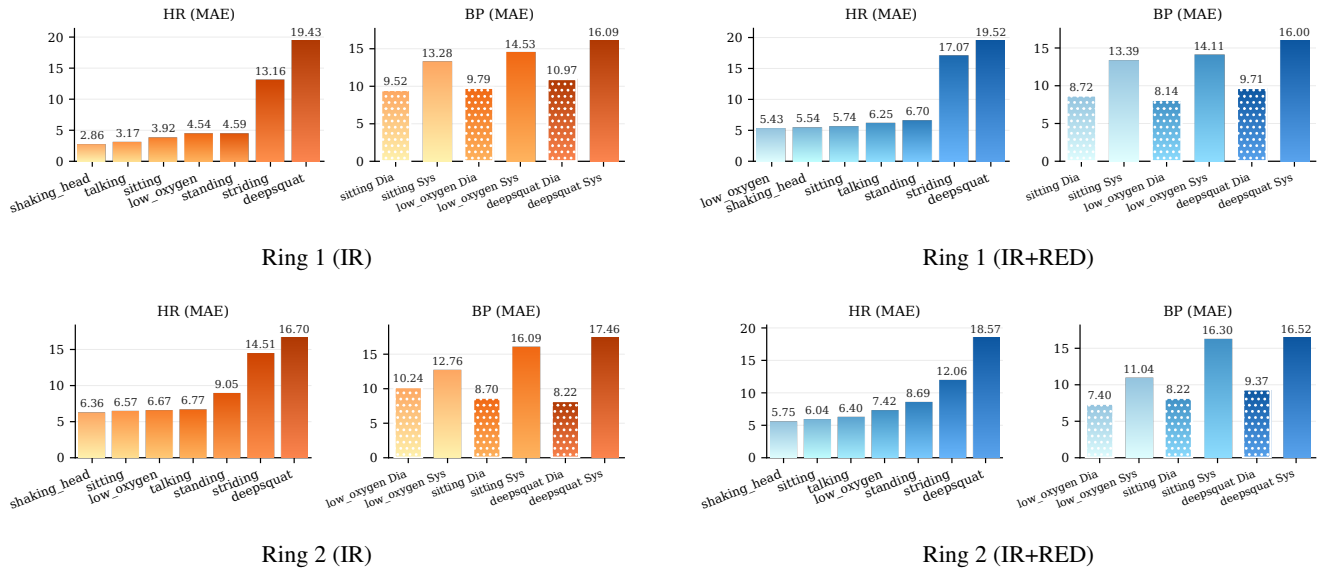


Figure S1. ResNet HR/BP MAE across scenarios. Each panel summarises the four-task scenario analysis (HR, RR, SpO₂, BP); HR appears in the top-left subplot and BP in the bottom row, enabling comparison of IR versus IR+RED channels for both rings.

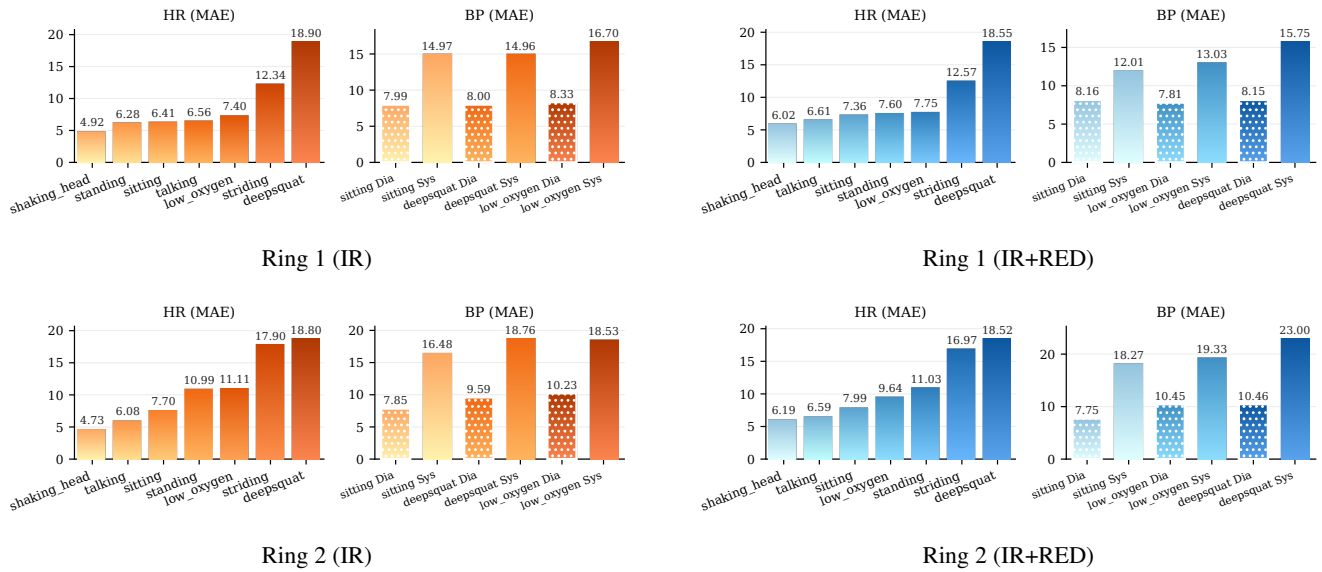


Figure S2. Transformer HR/BP MAE across scenarios. HR top-left and BP bottom-row panels allow side-by-side assessment of channel choices for both rings.

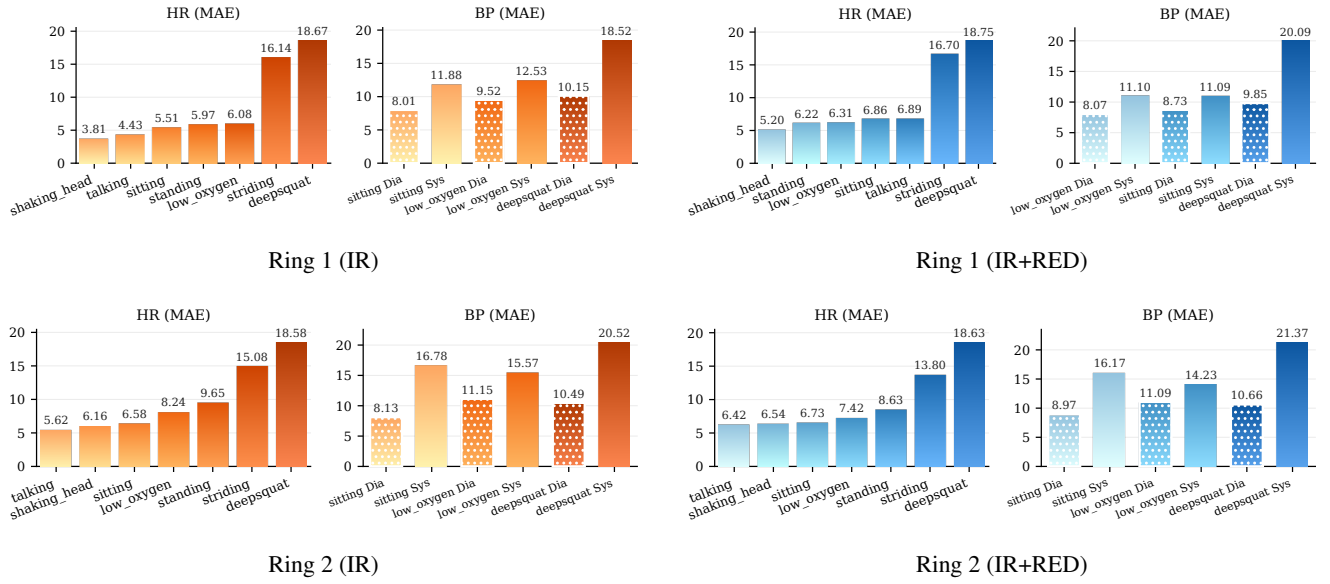


Figure S3. InceptionTime HR/BP MAE across scenarios. Four panels capture the 16 scenario combinations covering ring and channel variations.

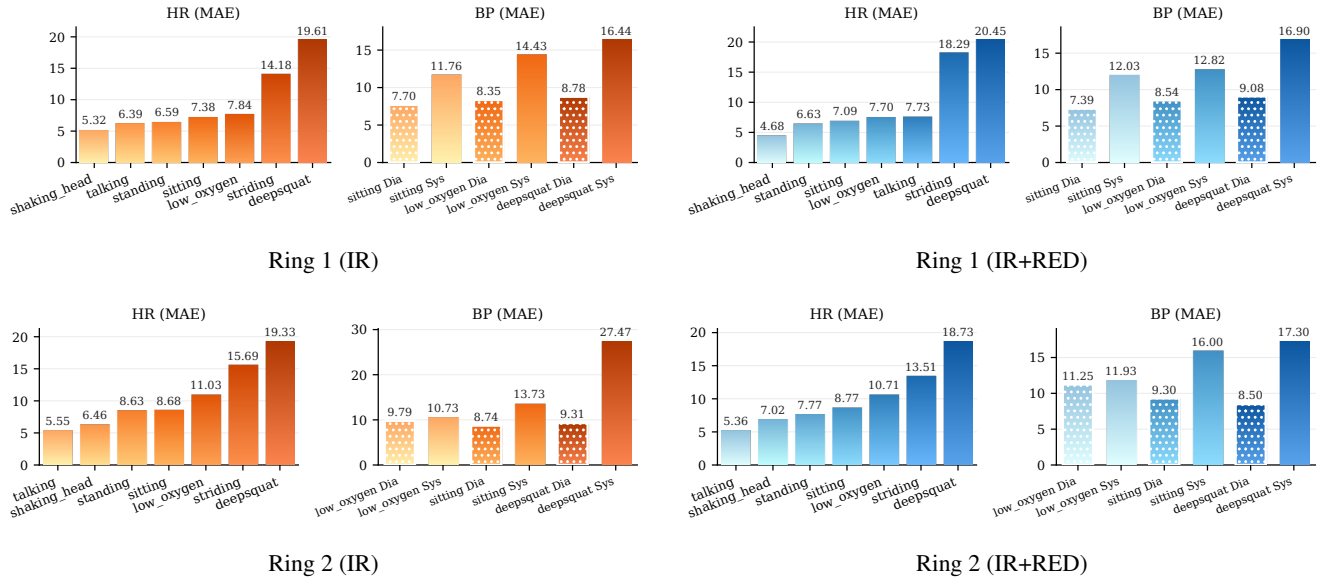


Figure S4. Mamba HR/BP MAE across scenarios. The four panels complete the 4 models $\times$ 2 rings $\times$ 2 channel combinations requested; HR is shown in the top-left subplot and BP in the bottom row of each panel.