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Prototypical clustered federated learning for heart rate prediction

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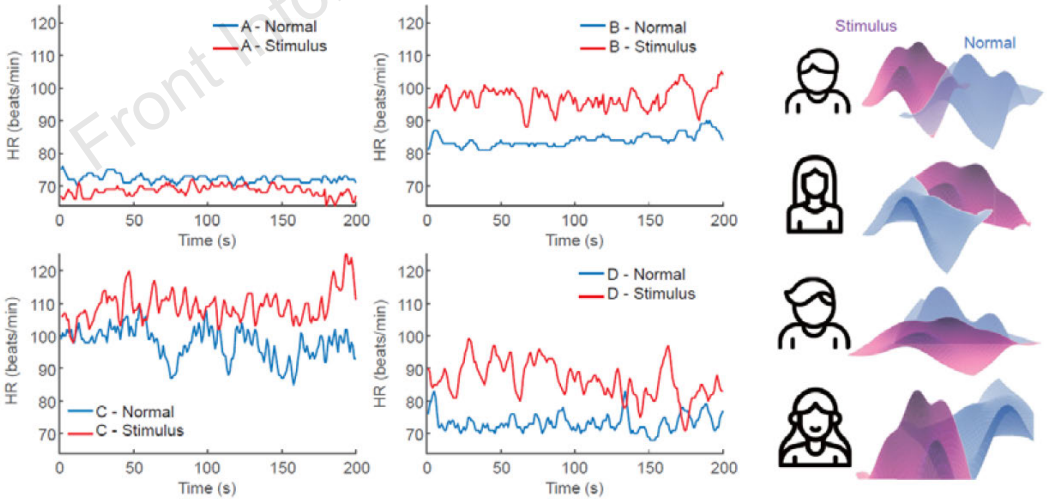
Key words: Federated learning; Heart rate prediction; Prototypical contrastive learning

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Motivation

- **Privacy Risk of Heart Rate Prediction**: Centralized heart rate training exposes sensitive physiological HR data, compromising data privacy and highlighting the need for federated learning (FL).
- **Data Heterogeneity and Client Disconnection:** Existing methods suffer performance degradation due to the inherent heterogeneity of heart rate data and temporary client disconnections to the central server.
- **Need for an Effective Methods**: There is an urgent demand for robust and privacy-preserving solutions to enhance personalized heart rate prediction.

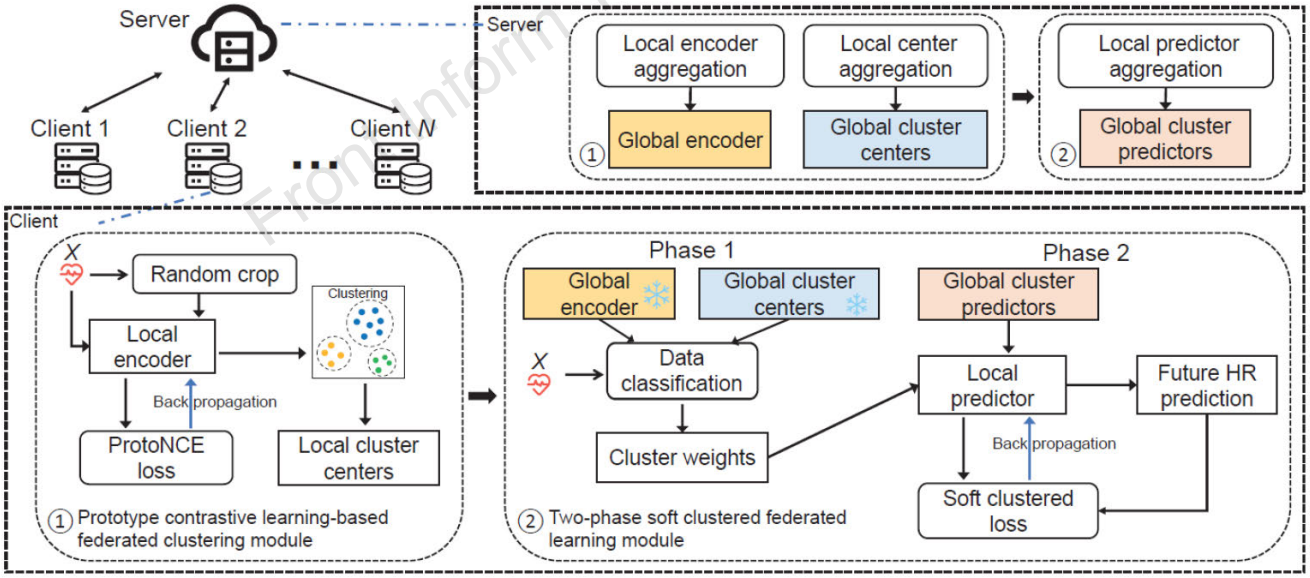
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Heart rate patterns of different individuals under varying conditions

Method

- We propose a federated learning-based approach named PCFedH, which provides personalized and applicable heart rate prediction.
- The prototypical contrastive learning-based federated clustering module is designed to extract representations from heterogeneous heart rate data, achieving privacy-preserving and accurate clustering across clients.
- The two-phase soft clustered federated learning module trains personalized FL models for heart rate prediction, effectively mitigating data heterogeneity.



Architecture of the PCFedH model

Major Results

Prediction results

- PCFedH outperforms all the baselines, across both datasets, achieving average reductions of 3.1% in MSE, 1.6% in MAE, and 1.7% in MAPE compared with the second-best results.
- PCFedH can effectively recognize and use inter-client differences, enhancing the model's personalized adaptability.

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Table 2 Performance comparison of PCFedH and baseline methods on the datasets of PPG-DaLiA and Distracted

Method	PPG-DaLiA			Distracted		
	MSE	MAE	MAPE (%)	MSE	MAE	MAPE (%)
FedAvg	2.621±2.060	1.121±0.398	1.445±0.583	20.242±153.889	1.466±4.076	1.486±1.804
FedProx	2.597±1.784	1.126±0.388	1.441±0.553	1.665±1.209	0.929±0.393	1.202±0.519
FedALA	2.615±2.029	1.121±0.396	1.445±0.581	46.470±13.783	6.610±0.898	8.819±2.525
IFCA	2.624±2.008	1.125±0.393	1.449±0.575	19.868±151.646	1.404±4.018	1.402±1.773
FedSoft	2.737±1.861	1.155±0.394	1.478±0.556	1.671±1.214	0.930±0.395	1.205±0.522
FedCE	2.610±1.987	1.121±0.391	1.443±0.573	18.649±140.433	1.473±3.870	1.532±1.716
FedProto	23.133±19.097	3.559±1.552	4.445±1.658	99.373±450.702	4.503±7.050	4.715±3.565
FedPCL	11.239±24.140	2.410±2.330	3.028±2.996	38.898±244.490	3.532±5.141	4.144±3.996
PCFedH	**2.549±1.736**	**1.117±0.383**	**1.431±0.549**	**1.593±1.175**	**0.903±0.398**	**1.170±0.526**

MAE: mean absolute error; MAPE: mean absolute percentage error; MSE: mean squared error. The best result is highlighted in boldface, and the second-best result is underlined. It shows PCFedH's superior results in reducing MSE, MAE, and MAPE on the PPG-DaLiA and Distracted datasets

Major Results

Ablation study

- All modules in our model contribute to improving the performance of heart rate prediction.
- The marked decline after removing the soft clustered FL module suggests that different data types still mutually benefit each other, highlighting the necessity of soft clustering.

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Table 3 Ablation study: SoftCluster is the most important design

Method	MSE	MAE	MAPE (%)
PCFedH (w/o PCL)	2.553±1.729	1.118±0.381	**1.431±0.542**
PCFedH (w/o CRE)	2.565±1.762	1.119±0.381	1.432±0.543
PCFedH (w/o DCP)	2.737±1.861	1.155±0.394	1.478±0.556
PCFedH (w/o SC)	2.785±1.957	1.165±0.379	1.490±0.546
PCFedH	**2.549±1.736**	**1.117±0.383**	1.431±0.549

MAE: mean absolute error; MAPE: mean absolute percentage error; MSE: mean squared error; w/o: without; PCL: prototypical contrastive learning; CRE: cluster representation encoder; DCP: data classification phase; SC: soft clustered. The best result is highlighted in boldface, and the second-best result is underlined

Major Results

Hyperparameter sensitivity analysis

- When the learning round R_{pcl} is set to 10 in the two-phase soft clustered FL module, PCFedH achieves satisfactory performance, maintaining efficiency without significant sacrifice in accuracy.

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Table 4 Performance of PCFedH at varying PCL rounds

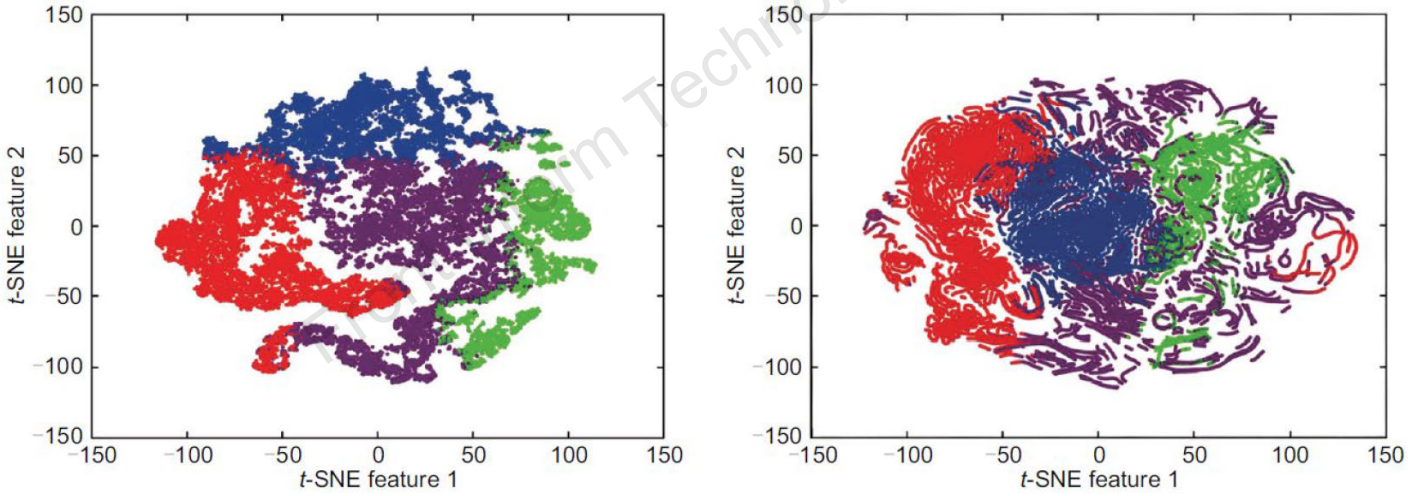
Round	MSE	MAE	MAPE (%)
$R_{pcl} = 1$	2.562±1.730	1.122±0.385	1.437±0.552
$R_{pcl} = 5$	2.548±1.745	1.119±0.389	1.433±0.560
$R_{pcl} = 10$	2.549±1.736	1.117±0.383	1.431±0.549
$R_{pcl} = 50$	2.565±1.762	1.118±0.381	1.430±0.542
$R_{pcl} = 100$	2.549±1.740	1.116±0.381	1.428±0.544

MAE: mean absolute error; MAPE: mean absolute percentage error; MSE: mean squared error; PCL: prototypical contrastive learning

Major Results

Visualization results

- The application of prototypical cluster learning significantly improves cluster separability, as illustrated by the *t*-SNE visualization after dimensionality reduction.



Visualizations of PPG-DaLiA dataset representations
Left: the enhanced representation by PCFedH; Right: the original representation

Conclusions

- We propose PCFedH, a novel federated learning framework that addresses privacy concerns and handles the heterogeneity of heart rate data to achieve personalized and accurate heart rate prediction.
- By combining prototypical contrastive learning with clustered FL, PCFedH enhances clustering stability and improves model personalization under heterogeneous data distributions.
- Extensive experiments show a 3.1% reduction in MSE compared to suboptimal results, demonstrating significant improvement over state-of-the-art methods.

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Author Biography



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