Robust PPG-exclusive Heart Rate Estimation during Maximal Exercise Using Population-Based Priors

Elisabetta De Giovanni, Iñigo Urteaga, Matteo Croci, Tomas Teijeiro

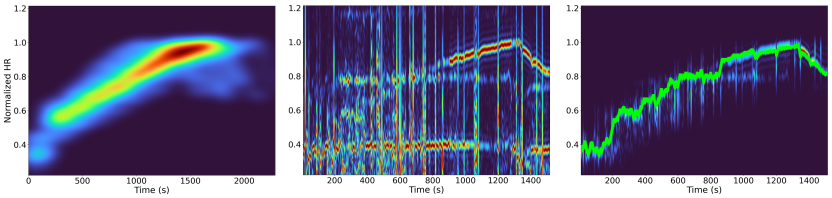
Basque Center for Applied Mathematics (BCAM), Bilbao, Spain

Aims: PPG remains the prevailing technology for wearable heart rate (HR) monitoring. However, motion artifacts compromise its reliability because their frequency components overlap with the cardiac signal during demanding physical activities. This study investigates whether heavily contaminated PPG signals can still yield reliable HR estimations without the need for auxiliary sensors (e.g., accelerometers), by leveraging prior knowledge of HR dynamics.

Methods: We analyzed a dataset comprising 21 subjects undergoing a maximal exercise test on a cycloergometer. Simultaneous PPG and ECG signals were acquired, with the latter serving as the ground-truth reference. We applied a Leave-One-Subject-Out cross-validation methodology to build HR evolution priors from the training population. We used Dynamic Time Warping (DTW) to align normalized HR curves and quantify morphological similarities across subjects. For each test subject, we combined the Power Spectral Density (PSD) of the PPG with the population-based prior distribution to generate a per-subject "posterior PSD". We leverage this posterior to identify candidate HR trajectories via heuristic search, with the final selection determined by the minimum DTW distance to the learned priors' barycenter.

Results: We observed that DTW aligns the normalized HR curves with minimal error across all subjects, validating the applicability of robust population-based priors. For the test subjects, the approach achieved a median MAE reduction of 68.7% (IQR: 47.0 – 84.2 %) relative to a benchmark algorithm employing PPG and accelerometer data, with both methods evaluated against ground-truth ECG. These results demonstrate satisfactory performance despite severe signal degradation artifacts induced by intense physical activity.

Conclusion: Physiological empirical priors and DTW-based path selection enable robust HR estimation where traditional processing fails, demonstrating the feasibility of PPG-exclusive monitoring for high-intensity exercise.



(left) Population-based Prior; (center) PPG PSD of example subject; (right) Posterior HR estimation.