Combined Time-Frequency Calculation of pNN50 Metric From Noisy Heart Rate Measurement [1]

Problem Definition
- pNN50 is a metric derived from heart rate (HR) measurements
- Conventionally, it is calculated from successive time periods in peak-to-peak occurrences in HR.
- In the case of noisy measurements of HR, however, peak-to-peak detection may not be reliable.

Objective
- A combined time-frequency domain analysis (Short Time Fourier Transform) is presented.
- Goal: To more accurately extract pNN50 metric from noisy HR data.
- Test: An experimental measurement with added noise is used as a benchmark to demonstrate the effectiveness of the approach with noticeable improvement over the conventional time domain peak-to-peak detection algorithm.

Why Heart Rate (HR), and Heart Rate Variability (HRV)?
- Autonomic Nervous System (ANS) responds to stress and mental workload changes [4,7].
- Stress and Mental Workload changes affect Heart Rate (HR) and hence Inter-Beat Interval (IBI).
- HR, and heart rate variability (HRV) affects affective states of human, and mental workload [4-7].

Heart Rate (HR), Heart Rate Variability (HRV) Measurement

1. Estimating the IBI:
   (a) Peak finding algorithm
   (b) Calculating the time differences between consecutive peaks

2. HR, HRV Analysis [7]:
   (a) Frequency Domain: FFT of IBI.
   (b) Time Domain: IBI related metrics: HR, RMSSD, pNN50, etc.

Calculating pNN50 (Conventional Method in time domain) [7]
- Temporal changes of the normal-to-normal (NN) heartbeat intervals.
- pNN50 decreases when mental workload (or stress) level increases.

\[ \text{pNN50} = \frac{\#\text{NN} - \#\text{NN}}{\#\text{NN}} \]

where \( \text{NN} \) is the number of \( \Delta N > 50 \text{ms} \), and
\[ \text{IBI}_{6} = \text{NN}_{6} = t_{6} - t_{6-1} \rightarrow T_{6} = \Delta N_{6} = \text{NN}_{6} - \text{NN}_{6-1} \]

Correct Estimation IBIs

<table>
<thead>
<tr>
<th>Incorrect IBI Estimation</th>
<th>Suggested Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR Sensor and Movement</td>
<td>Restrict Human Motion</td>
</tr>
<tr>
<td>Data Acquisition Error</td>
<td>Reduce Noise (Filtering HR Signal)</td>
</tr>
<tr>
<td>Peak Detection Error (Noise)</td>
<td>Design Better Peak Detection Algorithm</td>
</tr>
</tbody>
</table>

Error in Estimating IBI [3-7]

The suggested solution are:
- Post-processing methods.
- The entire HR data is required.
- Are not universal.

pNN50 using Combined Time-Frequency (STFT)

(a) Average IBI:
\[ \bar{f}_{\text{IBI}} = \frac{1}{\text{IBI}} \]
where \( \bar{f}_{\text{IBI}} \) is weighted average of dominant component with threshold \( C_{1} \), and
\[ \text{IBI} = \frac{1}{\bar{f}_{\text{IBI}}} \]

(b) Assuming:
Window shape: Rectangular, Hamming, and Chebyshev.
Window size \( (\delta) \) = 2 * IBI (minimum size to calculate pNN50).
Window overlap (\( \delta \)) = \( C_{2} \), IBI \( (C_{2} = 1 : 50\% \) window size).

(c) Calculating Short Time Fourier Transform (STFT)
\[ |X(t, f)|^2 \] (time and frequency)

(d) Extract the instantaneous frequency:
\[ f_{1}(t) = \max\left|X(t, f)\right|^2 \]

(f) Estimate the variations of NN intervals:
\[ \Delta N = \frac{1}{|G(\Delta t)|^2} \Delta t \]

(g) Calculate pNN50 using:
\[ \text{pNN50} = \frac{\#\text{NN} - \#\text{NN}}{\#\text{NN}} \]

Validating Our Method in Calculating pNN50

- pNN50 is calculated for each segment of the game, i.e., Rest 1, Easy 1, Difficult, Rest 2, and Easy 2.

Conclusion
- Highest amount error in time domain - not reliable on noisy signals
- Best setting \( C_{1} = 0.8 \) & \( C_{2} = 1.0 \) in time-frequency domain (STFT Algorithm)
- Across all subjects (12), error in Time Domain is significantly higher than STFT regardless of window shape \( (P < 0.01) \).
- STFT algorithm outperforms the conventional pNN50 calculation across all the subjects.

References

Acknowledgment
The work of R. Sipahi is supported by DARPA N66001-13-1-4021 (Grant # 13-12-14). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agency.