Alignment of Multi-Sensor Data:
Adjustment of Sampling Frequencies and Time Shifts

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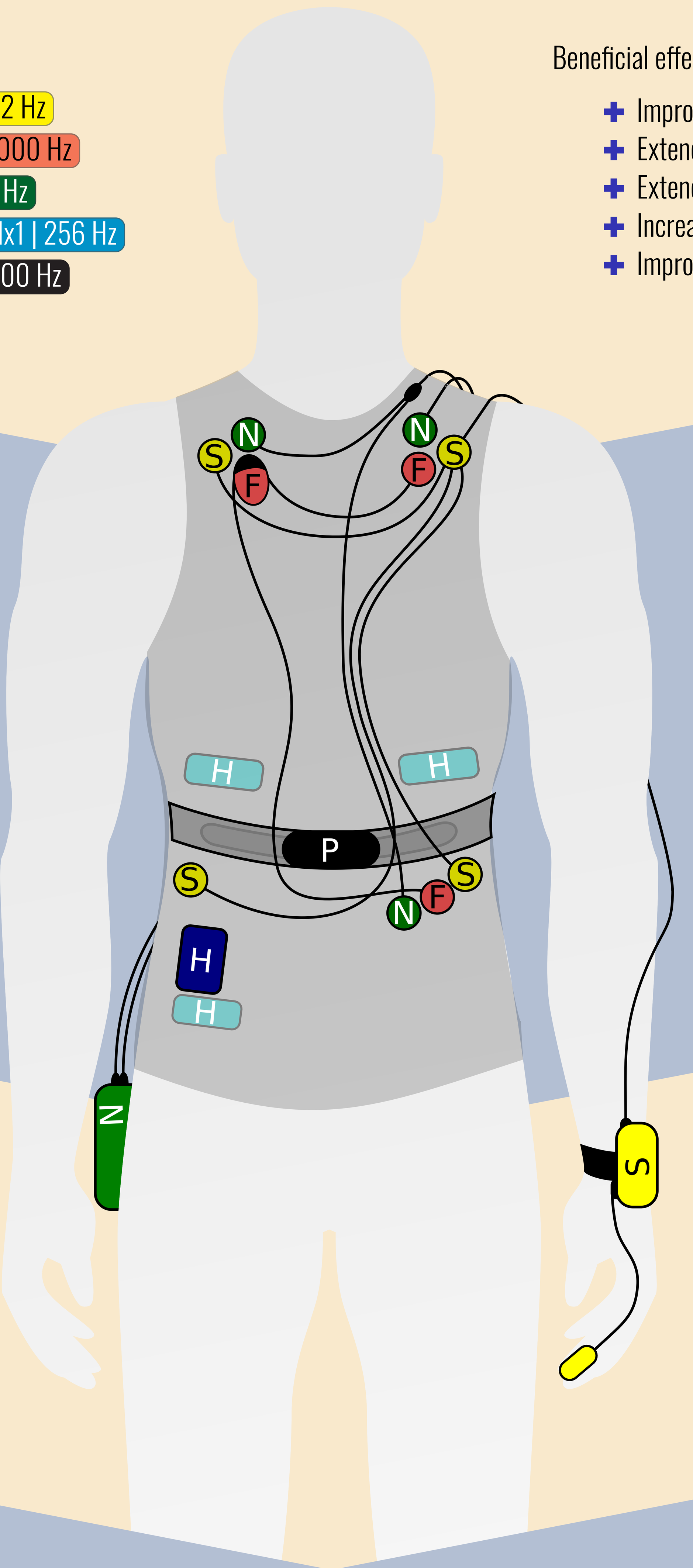
"Multisensor data fusion refers to the acquisition, processing and synergistic combination of information gathered by various knowledge sources and sensors to provide a better understanding of a phenomenon."
Varshney, P. K. (1997). Multisensor data fusion. Electronics & Communication Engineering Journal, 9(6), 245-253.

Our aim is to establish a robust method for correcting sampling frequencies and time shifts in order to align non-synchronized sensors from multiple devices. Our approach is based on RR intervals from multiple ECG measurements.

Equipped devices

- S SOMNOtouch NIBP | 512 Hz
- F EMotion Faros 360° | 1000 Hz
- N NeXus-10 MKII | 8000 Hz
- H Hexoskin Smart Shirt Hx1 | 256 Hz
- P Polar RS800 Multi | 1000 Hz



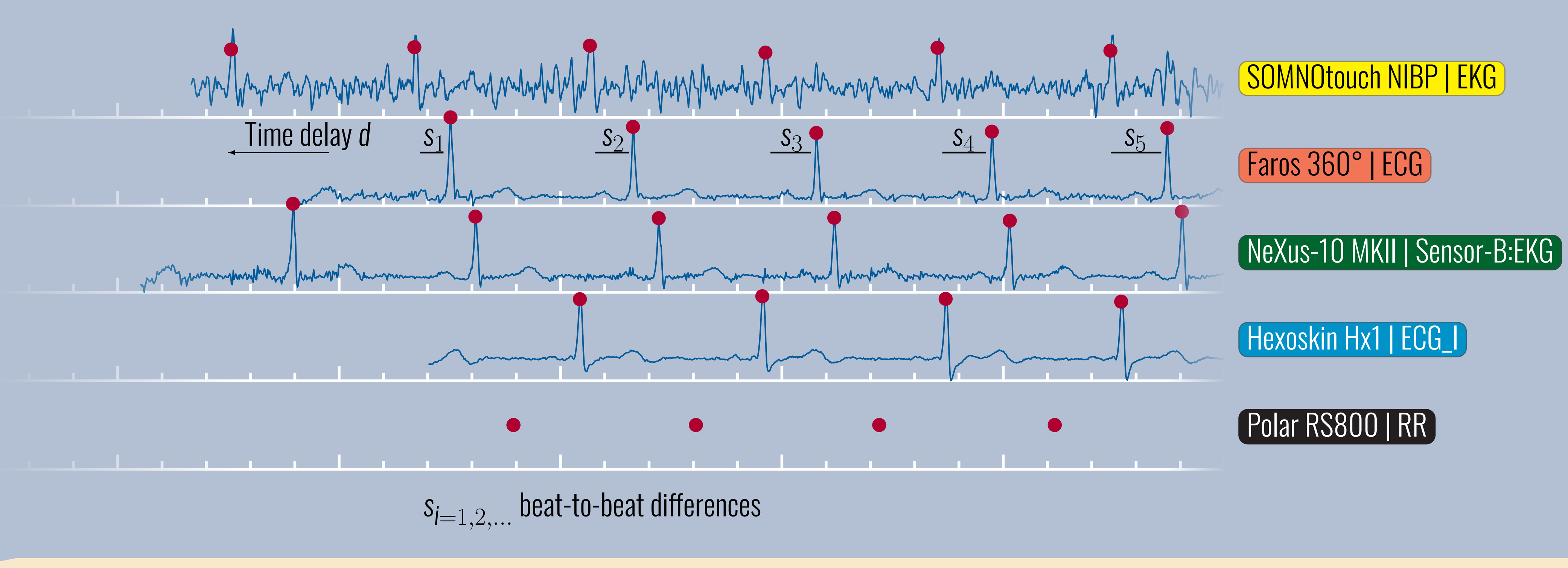
Beneficial effects:

- Improved system reliability and robustness
- Extended coverage (spatial, temporal)
- Extended sensor variety
- Increased confidence
- Improved resolution

Experimental data collected from 13 subjects

- 5 min standing rest
- 5 min walking on treadmill (1.2 m/s)
- cognitive task (2-back audio test)
- 5 min walking on treadmill (1.2 m/s, 15% gradient)
- In between: NASA Task Load Index to measure individual strain

Raw data
Condition before multi-sensor adjustments.



Why should I adjust for sampling frequencies?

In 24h-ECG measurement sampled at 1000 Hz we assume to collect 1000*24*60*60 = 86,400,000 samples
Actually given the impreciseness of the clock signal (quartz crystal) +0.01% we observe 86,408,640 samples

8,640/1000 Hz = 8.64 s divergence

Identical signals are not aligned anymore. Without frequency adjustment wrong conclusions can be reached:

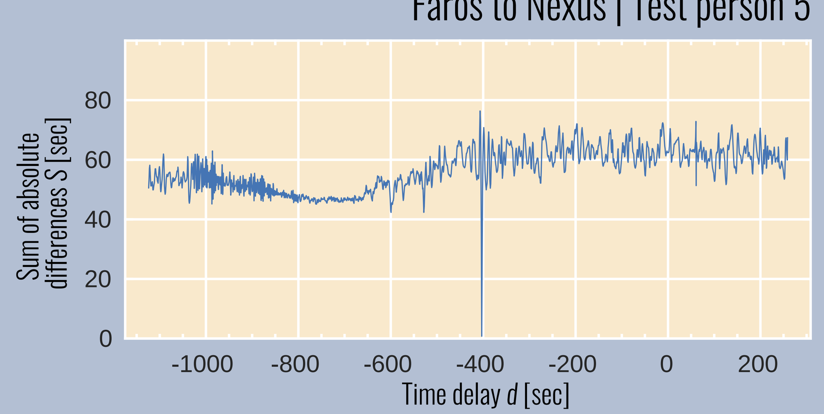
The heart rate increased subsequent to the accident.
The heart rate increased just before the accident.

1 We aligned the sensors locally using a **short and clean segment** of 300 beats from a resting state period. The time shift d was determined by searching for a time shift d for which S, the **sum of absolute differences to the reference sensor**, reached the minimum value. We took into account that some of the heartbeats could be misplaced due to noise, or could not be identified at all. Therefore, S is based only on matched beats which differ not more than 750 ms.

2 Linear adjustment of sampling frequencies was performed by computing a **robust linear regression** from the 300 matched beats of the resting period using iteratively reweighted least squares with a bisquare weighting function. Next, we **transformed the resulting slope into a factor for sampling frequency correction**:

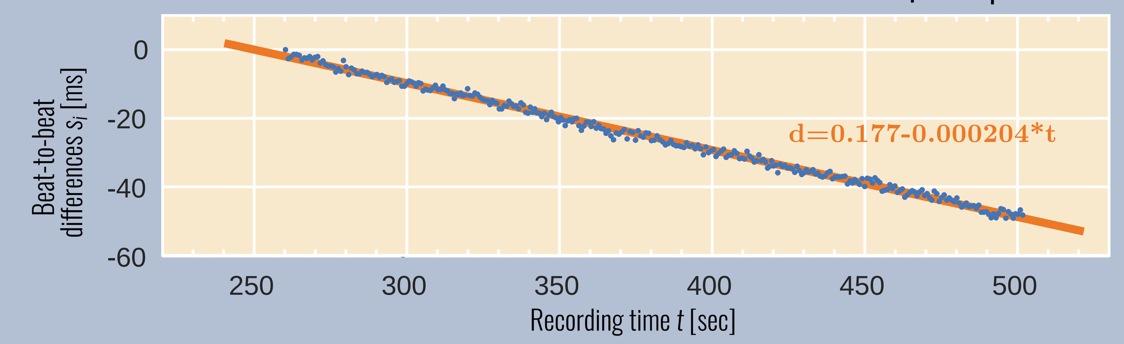
$$Fs_{\text{correct}} = Fs \cdot (1 - \text{Slope of robust regression fit})$$

Correction of time shift
Faros to Nexus | Test person 5



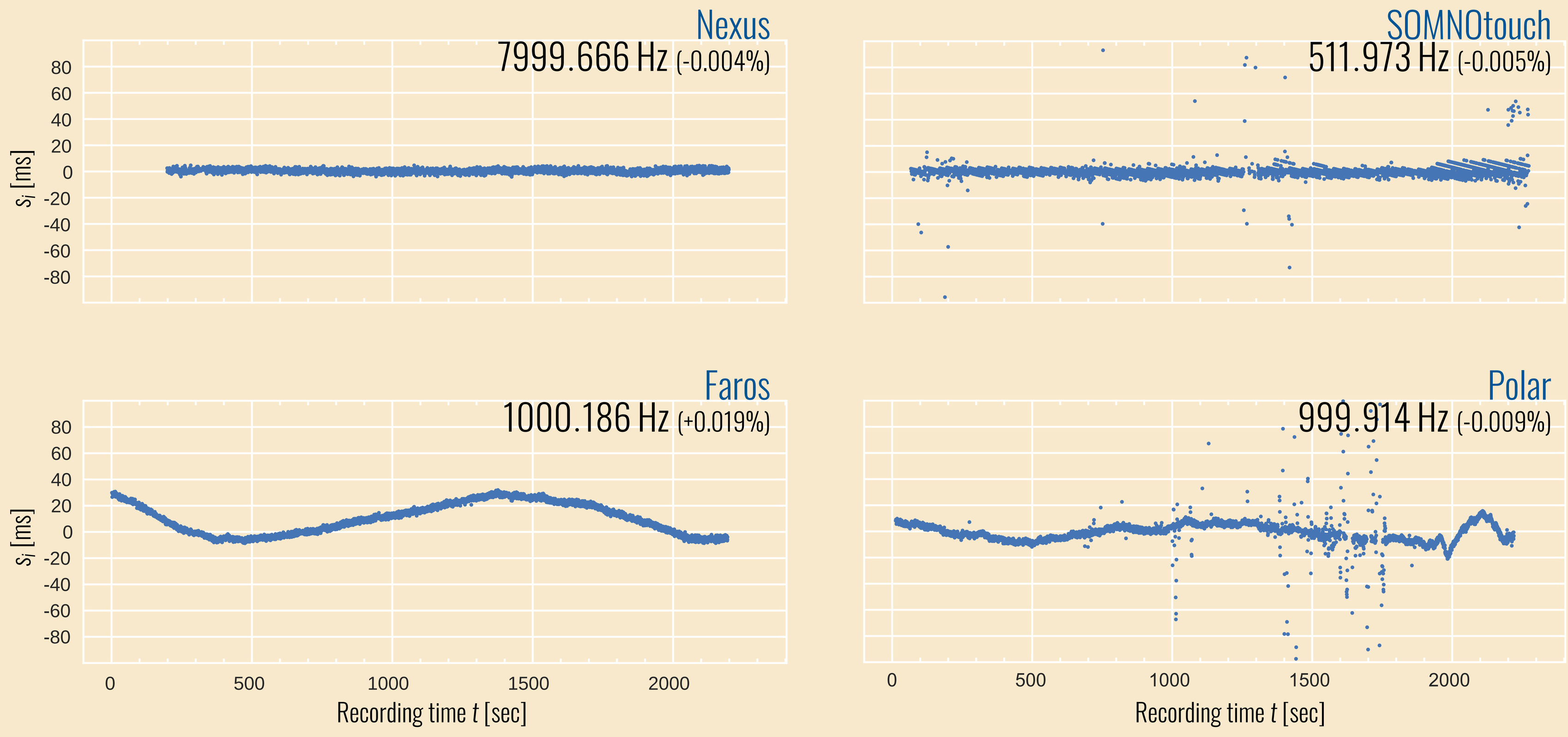
The sum of absolute differences of mismatched beats $S = \sum_i |s_i|$ are randomly distributed at a constant high value.

Adjustment of sampling frequency
Faros to Nexus | Test person 5



Non-conformance in the sampling frequency result in linear drifts of pairwise differences of aligned heartbeats. Some differences d rise or fall over time linearly.

Hexoskin as the reference



Recording Device	Factory specification (Hz)	Measured mean (min to max in Hz)	Linear adjustable
SOMNOtouch NIBP	512	511.97 (511.97 to 511.97)	✔
eMotion Faros 360°	1000	1000.23 (1000.15 to 1000.36)	✗
NeXus-10 MKII	8000	7999.60 (7999.37 to 7999.68)	✔
Polar RS800 Multi	1000	999.91 (999.87 to 999.95)	✗

Adjusted sampling frequencies
13 independent measurements, Hexoskin as reference

We observed changes in the sampling frequencies of Faros and Polar devices. Non-linear adjustments can be carried out by resampling and the use of a robust non-linear fit.

- It was possible to increase the integrity and accuracy of the experimental data by conducting a simple method specifically for alignment of multiple ECG signals.
- Results are currently under review by mimicking a cardiac signal at a given exact heart frequency using an arbitrary waveform generator.

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