



Welcome!

Experimental heart rate variability characterization

Lars Brockmann

About me

- ▶ Bachelor in Mechanical Engineering (2017 – 2020)
 - ▶ BFH
- ▶ Master in Biomedical Engineering (2020 – now)
 - ▶ BFH, University of Bern
- ▶ Assistant (2020 – now)
 - ▶ The Laboratory for Rehabilitation Engineering (rehaLab)



Lars Brockmann
Tel: +41 34 426 41 97
Email: lars.brockmann@bfh.ch

Project Grant

Title: Heart Rate Variability, Dynamics and Control During Exercise

Funded by: Swiss National Science Foundation (SNSF)

Investigator: Prof. Kenneth J. Hunt

Duration: 01.11.2019 to 31.10.2023 (4 years)

Amount: CHF 472'768

Outline

- ▶ Background
 - ▶ Heart rate (HR)
 - ▶ Heart rate variability (HRV)
- ▶ Experimental HRV characterization
 - ▶ Motivation
 - ▶ Methods
 - ▶ Results
 - ▶ Conclusion
- ▶ Outlook
 - ▶ Future Project

Background

What is heart rate? Pulse rate? How is it calculated? How can we measure it?

Background | Heart rate

$$\text{HR} = \frac{\text{\#heart beats}}{1 \text{ min.}} \rightarrow 80 \text{ bpm}$$



Background | Heart rate | Instruments/Wearables

ECG



Pulse oximeter



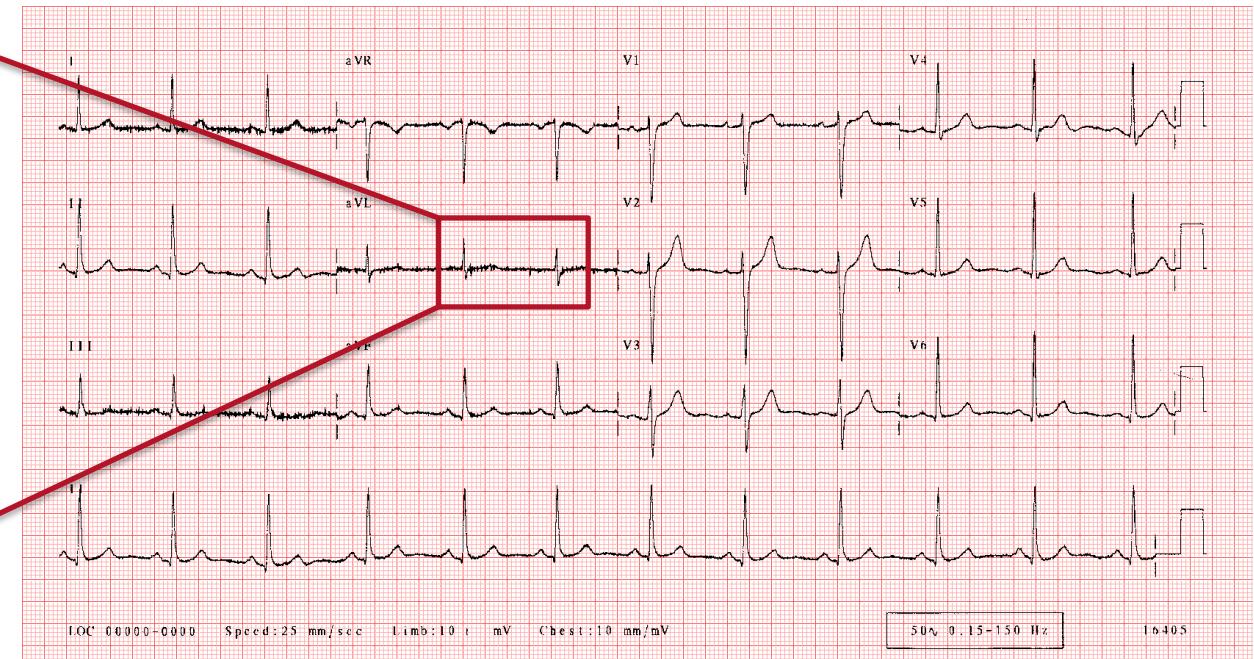
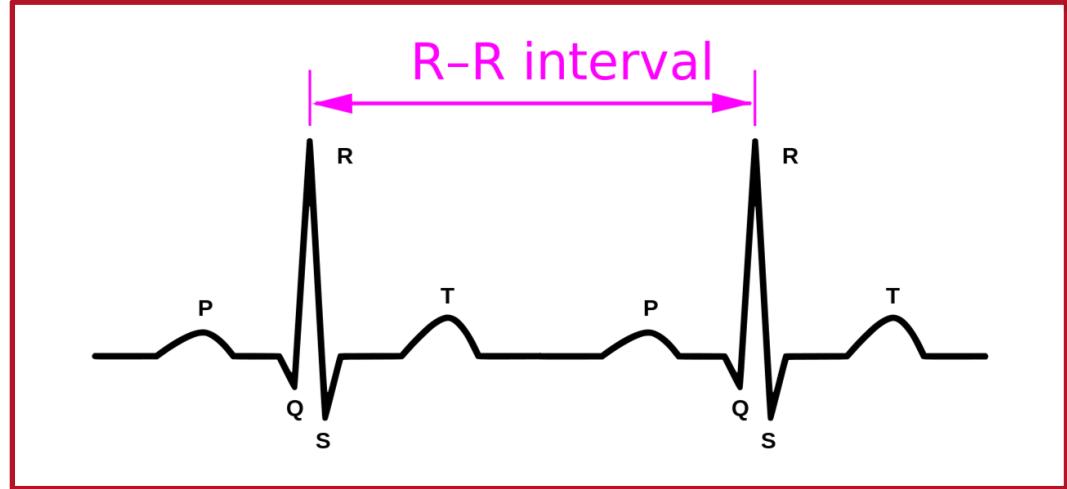
Chest belt



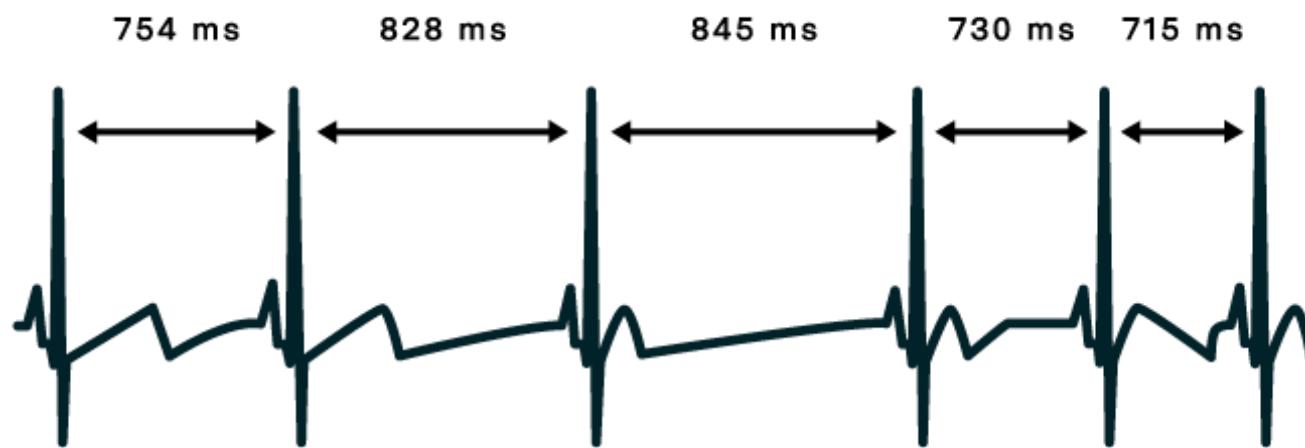
Wrist Watch



Background | Heart rate | Electrical activity



Background | Heart rate variability (HRV)



Background | Heart rate variability (HRV) | Metrics

Time-domain:

Parameter	Unit	Description	NN-Intervals: RR-Intervals with artifacts removed
SDNN	ms	Standard deviation of NN intervals	
RMSSTD	ms	Root mean square of successive RR interval differences	

Frequency-domain:

Parameter	Unit	Description
ULF power	ms ²	Absolute power of the ultra-low-frequency band (≤ 0.003 Hz)
VLF power	ms ²	Absolute power of the very-low-frequency band (0.0033–0.04 Hz)
LF power	ms ²	Absolute power of the low-frequency band (0.04–0.15 Hz)
HF power	ms ²	Absolute power of the high-frequency band (0.15–0.4 Hz)
LF/HF	%	Ratio of LF-to-HF power

Background | Fields of Application

Clinical applications

- ▶ As a predictor of risk of arrhythmic events or sudden cardiac death
- ▶ HRV as a clinical marker (a range of diseases have been associated with modified HRV)

Psychological aspects

- ▶ PTSD, depression, anxiety and stress

Sports and exercise sciences

- ▶ Determine a recovery status -> Avoid overtraining

Overall lifestyle metric (quantify well-being)

Background | General Knowledge

Low HRV	High HRV
Fight or Flight	Rest
Stress	greater cardiovascular health
Low adaptability	High adaptability
Decreased cognition	Improved cognition

→ a higher HRV is generally a good thing

Experimental heart rate variability characterization

Motivation, Methods, Results and Discussion

Focus/Motivation

Heart rate variability during exercise

- ▶ How does **exercise intensity** affect HRV?
- ▶ How does **time** affect HRV?

Goal:

- ▶ Gain new knowledge
- ▶ Contribute to the field

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Berner Fachhochschule | Haute école spécialisée bernoise | Bern University of Applied Sciences

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Literature Review | Knowledge Gap

Michael et al. (2017) [doi: 10.3389/fphys.2017.00301](https://doi.org/10.3389/fphys.2017.00301)

- ▶ “**HRV measures demonstrate a curvilinear decay as a function of exercise intensity**”

Hunt et al. (2018) [doi: 10.1186/s12938-018-0561-x](https://doi.org/10.1186/s12938-018-0561-x)

- ▶ ULF and VLF power was found to decrease with increasing intensity of exercise
- ▶ “*remains to clarify whether these changes are due to time itself or to increases in HR related to cardiovascular drift*”

The image displays two side-by-side academic articles. The left article is from 'frontiers in Physiology' (published 28 May 2017, doi: 10.3389/fphys.2017.00301). It is titled 'Cardiac Autonomic Responses during Exercise and Post-exercise Recovery Using Heart Rate Variability and Systolic Time Intervals—A Review'. The right article is from 'BioMedical Engineering Online' (published 28 May 2017, doi: 10.1186/s12938-018-0561-x). It is titled 'Changes in heart rate variability with respect to exercise intensity and time during treadmill running'.

frontiers in Physiology
published: 28 May 2017
doi: 10.3389/fphys.2017.00301
REVIEW
published: 28 May 2017
doi: 10.3389/fphys.2017.00301
frontiersin.org

Cardiac Autonomic Responses during Exercise and Post-exercise Recovery Using Heart Rate Variability and Systolic Time Intervals—A Review

BioMedical Engineering Online
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RESEARCH
published: 28 May 2017
doi: 10.1186/s12938-018-0561-x
frontiersin.org

Changes in heart rate variability with respect to exercise intensity and time during treadmill running

Kenneth J. Hunt¹ and Jittima Saengsuwan^{2,3*}
Full author information is available at the end of the article

Abstract
Background: Heart rate variability (HRV) arises from the complex interplay of sympathetic and parasympathetic regulation of heart rate. Ultra-low-frequency (ULF) and very-low-frequency (VLF) components of HRV play a significant role in autonomic HR controllers, but these frequency bands have hitherto largely been neglected in HRV studies. The aim of this work was to investigate changes in ULF and VLF heart rate variability over time during exercise and recovery.

Methods: RR intervals were determined by ECG in 21 healthy male participants at rest, and during moderate and vigorous-intensity treadmill running; each of these three tests had a duration of 45 min. Time dependence of HRV was investigated for moderate and vigorous exercise. Changes in HRV over time were assessed by calculating mean power in three consecutive windows of equal duration (~ 14 min), denoted w_1 , w_2 and w_3 . ULF and VLF power were computed using Lomb-Scargle power spectral density estimates.

Results: For both the ULF and VLF frequency bands, mean power was significantly lower for moderate vs. rest ($p < 0.001$) and for vigorous vs. rest ($p < 0.001$). Overall $p < 0.001$: mean power was lower for moderate vs. rest ($p < 0.001$), for vigorous vs. rest ($p < 0.001$), and for vigorous vs. moderate ($p < 0.001$). For both ULF and VLF and moderate exercise, mean power was significantly lower for w_1 vs. w_2 ($p < 0.001$) and for w_2 vs. w_3 ($p < 0.001$). For vigorous exercise, mean power was lower for w_1 vs. w_3 ($p = 0.019$) and for w_1 vs. w_2 ($p = 0.005$). For VLF, mean power was lower for w_2 vs. w_3 ($p = 0.001$). For all comparisons, there was no significant difference in mean power between the three time windows ($\text{overall } p = 0.12$). For VLF and vigorous intensity, mean power was significantly different between w_1 and w_3 ($\text{overall } p < 0.001$): mean power was lower for w_1 vs. w_3 ($p = 0.001$) and for w_1 vs. w_3 ($p < 0.001$).

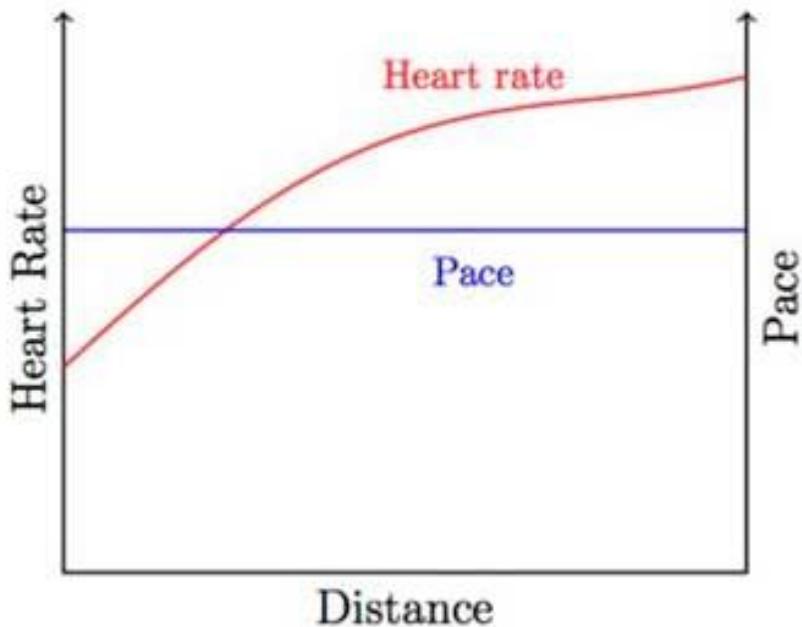
Conclusions: The degree of HRV in terms of ULF and VLF power was found to decrease with increasing intensity of exercise. HRV was also observed to change over time, but it remains to clarify whether these changes are due to time itself or to increases in HR related to cardiovascular drift. For feedback control applications, attention should be focused on meeting performance targets at low intensity and during the early stages of exercise.

Keywords: Heart rate control, Heart rate variability, Spectral analysis, Treadmills

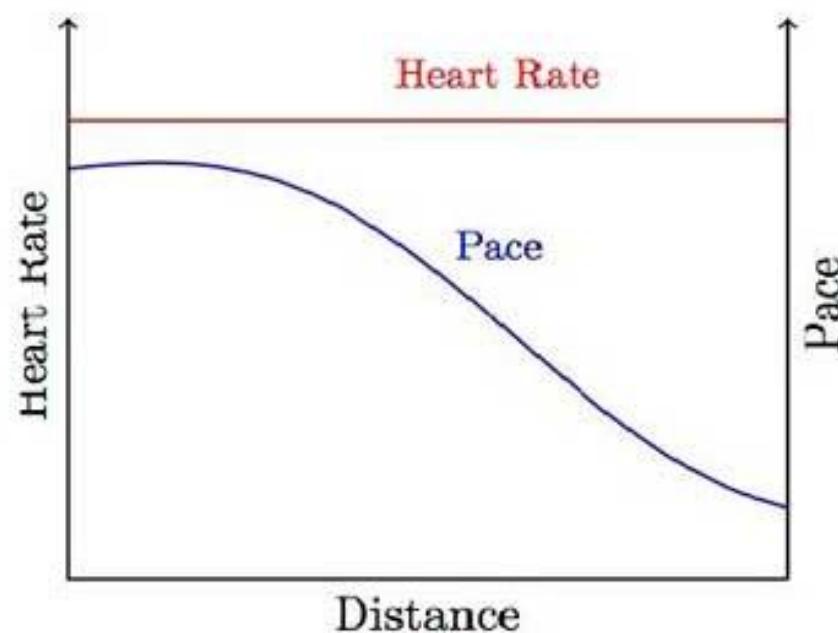
BMC
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Cardiovascular drift

constant pace

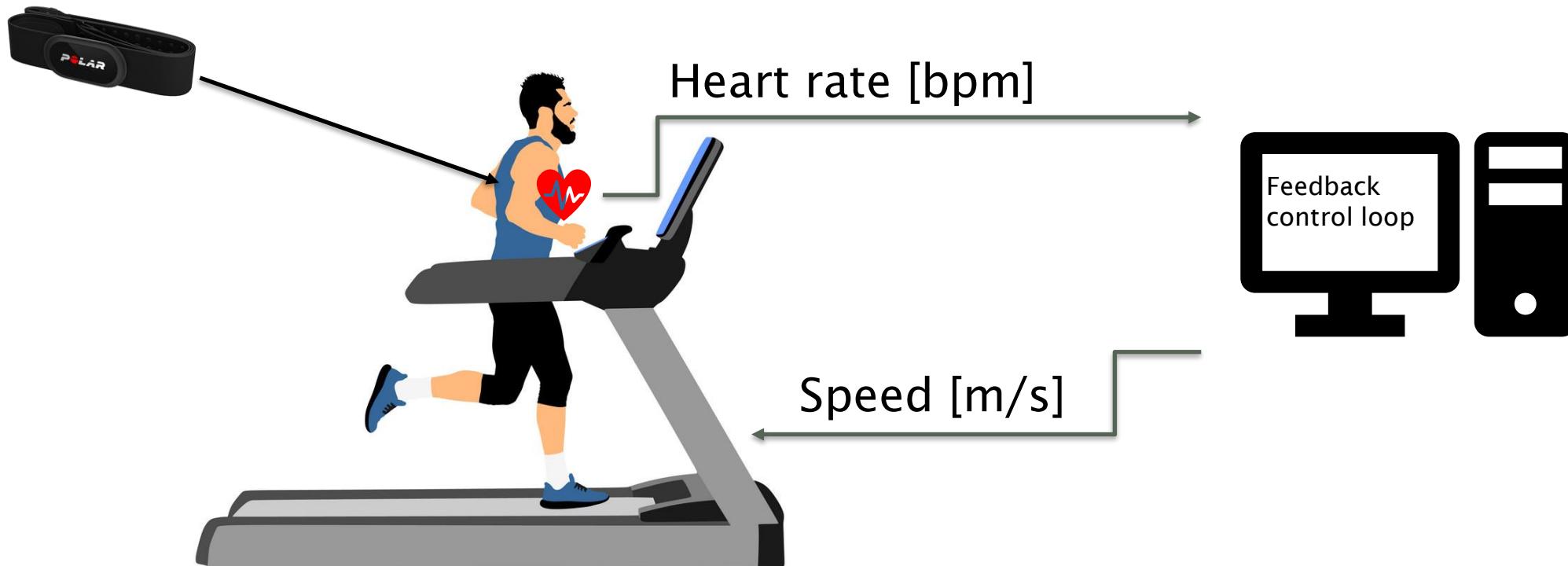


constant heart rate



Setup and HR Control

HRV is a disturbance in this control loop. If HRV would not exist an equilibrium could be found where HR and TM speed are constant.



Pilot Study

Brockmann et al. (2022) [doi: 10.1080/21642583.2022.2068166](https://doi.org/10.1080/21642583.2022.2068166)

Dataset:

- ▶ 8 Participants - 2 measurements each -> 16 samples

Conclusion:

- ▶ Results provide evidence of a **decrease** in HRV over time during treadmill running
- ▶ **Larger sample size** is needed to improve the statistical power
- ▶ (Experimental design can be optimized)

Time dependence of heart rate variability during treadmill running

Lars Brockmann, Hanjie Wang, Kenneth J. Hunt

Institute for Rehabilitation and Performance Technology, Bern University of Applied Sciences, Burgdorf, Switzerland

ABSTRACT
To investigate the time dependence of the heart rate variability (HRV) during treadmill running, a feedback control loop was implemented to eliminate the potentially confounding influence of cardiovascular drift. Without cardiovascular drift, observed changes in HRV can be directly attributed to the exercise intensity. Eight participants were included. The outcome measures showed a decrease of HRV, standard HRV metrics for two consecutive windows of equal duration (12.5 min) were computed and compared. Eight participants were included. The outcome measures showed an overall decrease of HRV over time. The decrease was significant ($p < 0.05$) for all three HRV metrics ($p < 0.05$). Three HRV metrics showed moderate evidence of decrease over time, viz. average con- tinuous power (AC), low frequency power (LF) and very low frequency power (VLF). The decrease of LF and VLF was significant ($p < 0.05$). The decrease of AC was not significant ($p = 0.12$). Taken together, these results provide evidence of a decrease of HRV over time during moderate-intensity treadmill running. The decrease of HRV is important as cardiovascular drift was eliminated. Further work is required to optimise the experimental design and to use a larger sample size to improve the statistical power of the results.

ARTICLE HISTORY
Received 11 January 2022
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KEYWORDS
Heart rate variability, feedback control, spectral analysis

Ginsberg, 2017). The exclusion of abnormalities is a crucial step in a sophisticated HRV analysis (Choi & Shin, 2018). Heart rate variability (HRV) is an important physiological index reflecting interactions between the sympathetic and parasympathetic divisions of the autonomic nervous system (Acharya et al., 2005; Kim et al., 2018). Decreases in HRV can be used as a strong predictor of cardiac and arrhythmic mortality (Stein et al., 2005; Szajdel, 2006). Furthermore, HRV has become an established, non-invasive tool for providing insights into the activity of the autonomic nervous system (Catalozel, 2004). Along with the medical field, the field of sports and exercise sciences has shown increased interest in the analysis of frequency-domain measures of HRV (Dempsey & Hagberg, 2016).

HRV is defined as the variation of the time interval between two successive heartbeats (Shaffer & Ginsberg, 2017). To quantify the RR-interval, it is necessary to identify the R-waves in the time series of recorded heart beats, calculated for every R-wave of a QRS-complex (Malik et al., 1996). If unreliable RR-intervals (caused by undetected beats, artefacts or arrhythmia) are excluded by prior processing, the signal is commonly referred to as NN-interval (normal-to-normal) (Shaffer & Ginsberg, 2017). The exclusion of abnormalities is a crucial step in a sophisticated HRV analysis (Choi & Shin, 2018). Standards for HRV outcome measures in time and frequency domains have been proposed (Ingram et al., 2021; Malik et al., 1996). Commonly used time-domain measures are the standard deviation of the NN-intervals (SDNN) and the root mean square of the successive differences (RMSSD). For the analysis of HRV in the frequency domain, there are usually four distinct frequency bands to consider (Malik et al., 1996):

- Ultra-low frequency (ULF), with $f < 0.003$ Hz;
- Very low frequency (VLF), with $0.003 \leq f < 0.04$ Hz;
- Low frequency (LF), with $0.04 \leq f < 0.15$ Hz;
- High frequency (HF), with $0.15 \leq f < 0.4$ Hz.

The frequency-domain measures estimate the mean power in those four frequency bands (Paganini et al., 1984; Shaffer & Ginsberg, 2017). The power is generally calculated by integrating the power density spectrum.

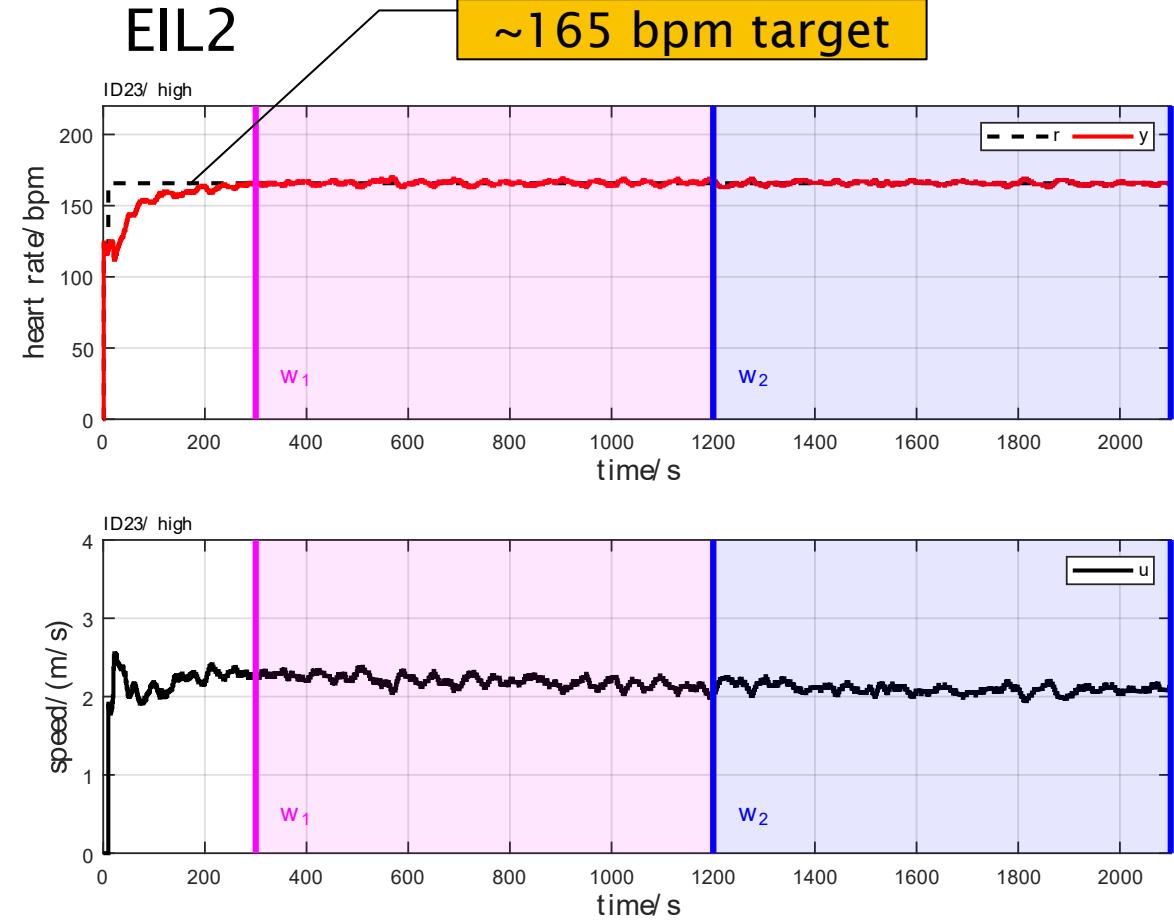
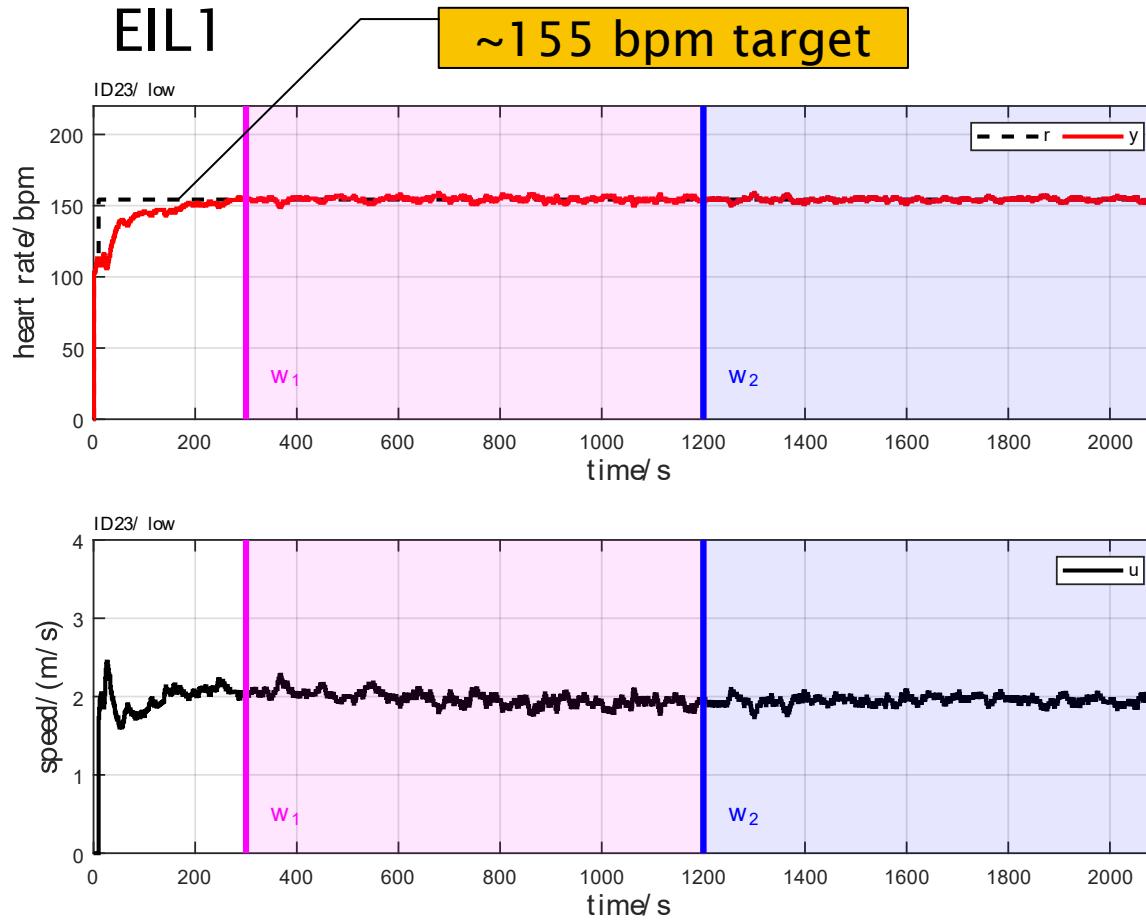
The focus of the present work is on changes in heart rate over time during moderate-intensity treadmill running. A recent review systematically analysed evidence relating to changes in HRV with respect to intensity, duration and modality (Michael et al., 2017). The two principal

CONTACT Lars Brockmann (✉) lars.brockmann@haw-hochschule.ch
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Protocol

- ▶ 32 healthy regular exercising adults
- ▶ Participants were required to avoid
 - ▶ strenuous exercise (24h),
 - ▶ caffeine (12h),
 - ▶ and heavy meals (4h) before each test.
- ▶ Every participant performed a treadmill running exercise at **two** distinct HR levels (exercise intensity level (EIL) 1 and 2).

Results | Data records for a single participant



Analysis

Time dependence

- EIL1w1 vs EIL1w2
- EIL2w1 vs EIL2w2

	w1	w2
EIL1		
EIL2		

EIL1/EIL2: Exercise Intensity level 1/2; w1/w2: window 1/2

Exercise intensity dependence

- EIL1w1 vs EIL2w1
- EIL1w2 vs EIL2w2

	w1w2
EIL1	
EIL2	

EIL1/EIL2: Exercise Intensity level 1/2; w1w2: window 1 and 2

Results

time dependence

Exercise intensity
dependence

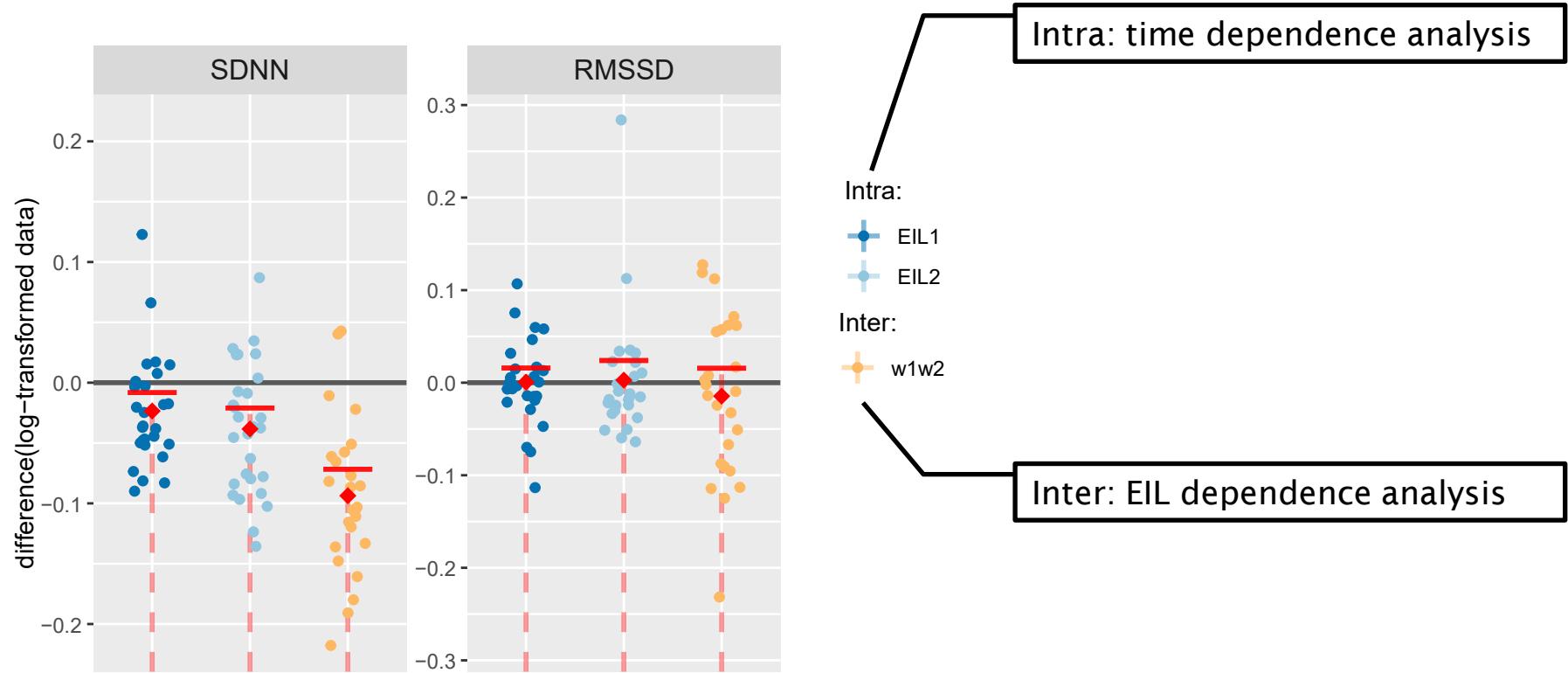
7 metrics; 3 comparisons -> 21 outcomes

		Time domain HRV metrics		IR-interval frequency domain HRV metrics				
		SDNN	RMSD	RRULF	RRVLF	RRLF	RRHF	RRtotal
intra	EIL1	mean w_1	7.79e-01	4.93e-01	3.31e-01	1.37e+00	6.30e-01	8.27e-02
		sd w_1	1.19e-01	1.41e-01	4.42e-01	2.59e-01	3.31e-01	3.95e-01
		mean w_2	7.55e-01	4.93e-01	1.57e-01	1.31e+00	5.91e-01	5.97e-02
		sd w_2	1.26e-01	1.34e-01	4.35e-01	3.11e-01	3.47e-01	4.18e-01
		MD	-2.35e-02	6.04e-04	-1.74e-01	-6.12e-02	-3.89e-02	-2.30e-02
		CI	-8.20e-03	1.58e-02	-5.67e-02	-1.30e-02	8.66e-03	3.69e-02
		p-value	7.20e-03	5.27e-01	8.88e-03	1.99e-02	8.74e-02	2.59e-01
inter	EIL2	mean w_1	6.97e-01	4.83e-01	1.13e-01	1.20e+00	3.39e-01	-5.57e-02
		sd w_1	1.36e-01	1.28e-01	4.59e-01	3.32e-01	4.29e-01	3.25e-01
		mean w_2	6.59e-01	4.86e-01	-4.30e-02	1.07e+00	2.96e-01	-5.74e-02
		sd w_2	1.28e-01	1.37e-01	5.25e-01	3.44e-01	4.83e-01	3.59e-01
		MD	-3.84e-02	2.77e-03	-1.56e-01	-1.24e-01	-4.32e-02	-1.76e-03
		CI	-2.09e-02	2.40e-02	2.04e-02	-8.04e-02	-1.62e-04	6.75e-02
		p-value	4.24e-04	5.87e-01	7.19e-02	2.33e-05	4.94e-02	4.83e-01
inter	$w_1 w_2$	mean EIL1	7.73e-01	5.00e-01	3.13e-01	1.34e+00	6.36e-01	8.53e-02
		sd EIL1	1.21e-01	1.35e-01	4.14e-01	2.75e-01	3.34e-01	3.95e-01
		mean EIL2	6.79e-01	4.86e-01	8.03e-02	1.14e+00	3.21e-01	-6.77e-02
		sd EIL2	1.29e-01	1.30e-01	4.34e-01	3.35e-01	4.54e-01	2.92e-01
		MD	-9.37e-02	-1.45e-02	-2.33e-01	-2.06e-01	-3.15e-01	-1.53e-01
		CI	-7.17e-02	1.56e-02	-1.02e-01	-1.54e-01	-2.26e-01	-2.63e-02
		p-value	7.78e-08	2.09e-01	2.76e-03	2.79e-07	1.41e-06	2.49e-02

Results for outcomes
that have not been
introduced in this
presentation.

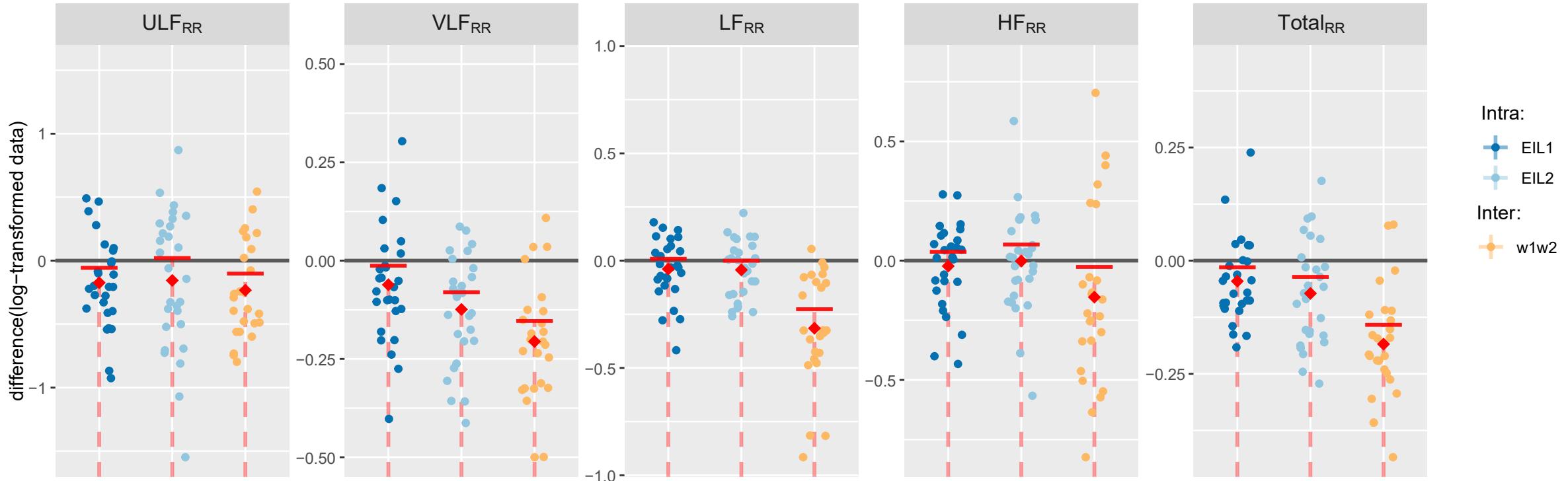
TABLE II: Outcomes: Numerical values (all outcomes are log-transformed, thus dimensionless; MD: mean difference (intra-group comparison: $w_2 - w_1$; inter-group comparison: EIL2 - EIL1); CI: upper 95% confidence interval boundary; p-value: derived from a single-sided t-test performed on the log-transformed data of the respective comparison groups. The p-values were conditionally colored: p-value $< \alpha = 0.05 \rightarrow$ green else orange)

Results | Time-domain



Time domain outcomes (A categorical scatter plot visualization of each comparison group for every time domain HRV metric. Intra-EIL₁: EIL₁w₁ vs. EIL₁w₂; Intra-EIL₂: EIL₂w₁ vs. EIL₂w₂; Inter-w₁w₂: EIL₁w₁w₂ vs. EIL₂w₁w₂. The red lines mark the 95% confidence intervals for a single-sided t-test with null hypothesis $H_0: m \geq 0$ and alternative hypothesis $H_0: m < 0$; m represents the sample mean is marked by a ◊ symbol.)

Results | Frequency-domain



Frequency domain outcomes (A categorical scatter plot visualization of each comparison group for every frequency domain HRV metric. Intra-EIL₁: EIL₁*w*₁ vs. EIL₁*w*₂; Intra-EIL₂: EIL₂*w*₁ vs. EIL₂*w*₂; Inter-*w*₁*w*₂: EIL₁*w*₁*w*₂ vs. EIL₂*w*₁*w*₂. The red lines mark the 95% confidence intervals for a single-sided t-test with null hypothesis $H_0: m \geq 0$ and alternative hypothesis $H_0: m < 0$; m represents the sample mean is marked by a \diamond symbol.)

Results | Summary

- ▶ Many HRV metrics were found to **decrease with time and with exercise intensity.**
- ▶ The **intensity-related** reductions were found to be greater in value and significance compared to the **time-related** reductions.
- ▶ Outcomes from RMSSD and HF stand out! **No or only a minimal decrease was found.**
- ▶ These parameters (RMSSD and HF) have been reported to reach a near-zero minimum early (between low and moderate intensity).

Conclusion

- ▶ **Heart rate control was successfully employed** in treadmill running exercises to allow for an unobstructed HRV time-dependence analysis (**removing the confounding effect of cardiovascular drift**).
- ▶ The results highlight that many HRV metrics **decrease with time and with exercise intensity**.
- ▶ The results indicate that HRV metrics appear to **only be able to decrease** with time or exercise intensity **as long as** their metric-specific near-zero **minimum has not been reached yet**.

Next step

- ▶ What now? One theory worth investigating would be to:
 - ▶ Design a heart rate controller that expects the HRV to decrease with time so control responsiveness could be adaptively increased with time -> improving control performance without disturbing the control variable (speed for TM exercise).
- ▶ What about people with disabilities/impairments? Do we expect similar results?
- ▶ Feasibility study with stroke patient @Reha Rheinfelden.
 - ▶ Up to 12 patients
 - ▶ Evaluate the feasibility of employing heart rate control in rehabilitation exercises
 - ▶ HRV (do we find similar trends? are there differences?)



Image sources

- p6 <https://www.gefro.de/blog/coca-test/>
- p7 <https://www.usamedical surgical.com/blog/ekg-ecg-machine-buyers-guide/>
<https://www.nurnatur.ch/pulse-oximeter-1-stueck>
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- p17 <https://www.vectorstock.com/royalty-free-vector/sport-man-running-on-treadmill-in-gym-vector-28905737>

Next seminars

Biel/Bienne

Quellgasse 21, Aula

09.12.22 Parylene-based encapsulation technology for wearable or implantable electronic devices Dr. Andreas Hogg, CEO, Coat-X AG, La Chaux-de-Fonds

13.01.23 Care@Home mit technischer Unterstützung Prof. Dr. Sang-II Kim, Professor, Institute for Medical Informatics I4MI, BFH-TI

Burgdorf/Berthoud

Pestalozzistrasse 20, E 013

02.12.22 Wie gefährlich ist ein Unfall mit einem Cabriolet? Prof. Raphael Murri, Institutsleiter IEM, Institut für Energie- und Mobilitätsforschung IEM, BFH-TI

16.12.22 Systemtechnologie für die Mikrobearbeitung mit Hochleistungs-UKP-Lasern Prof. Dr. Beat Neuenschwander, Institutsleiter ALPS, Institute for Applied Laser, Photonics and Surface Technologies ALPS, BFH-TI