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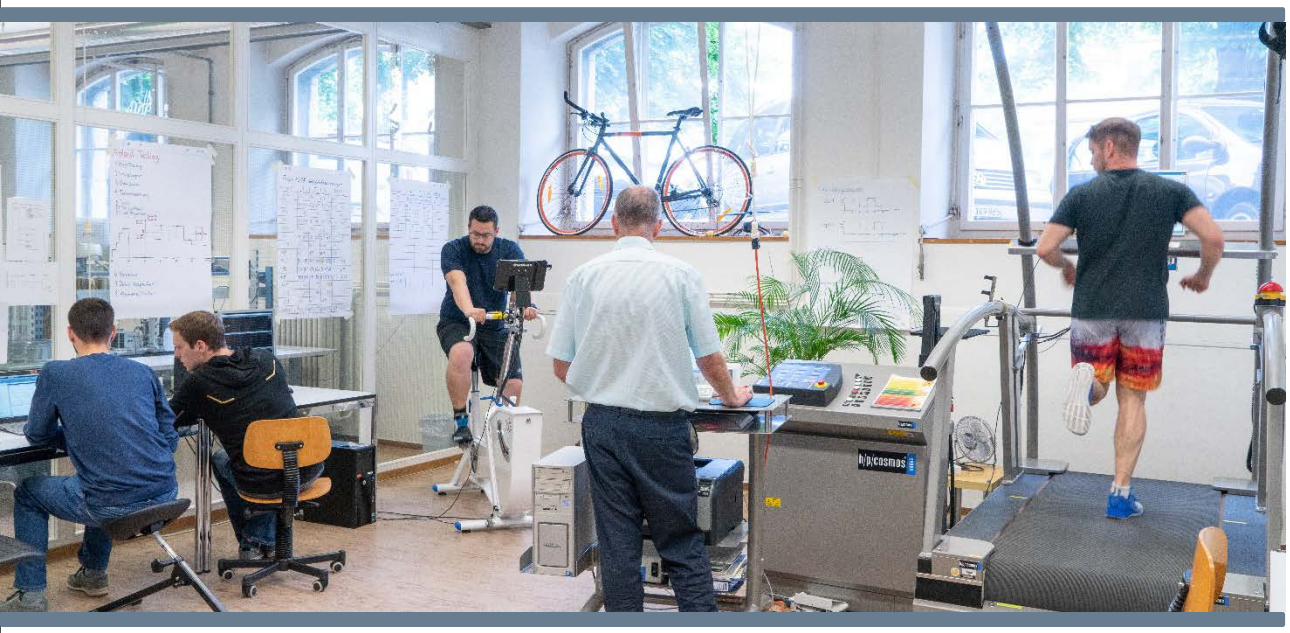


Automatic Heart Rate Control During Treadmill Exercise

Hanjie WANG, PhD student, hanjie.wang@bfh.ch

Outline

- Introduction
- Identification Tests
- Feedback Tests
- Results
- Conclusions

1. Introduction

1. Introduction

Overall Project grant.

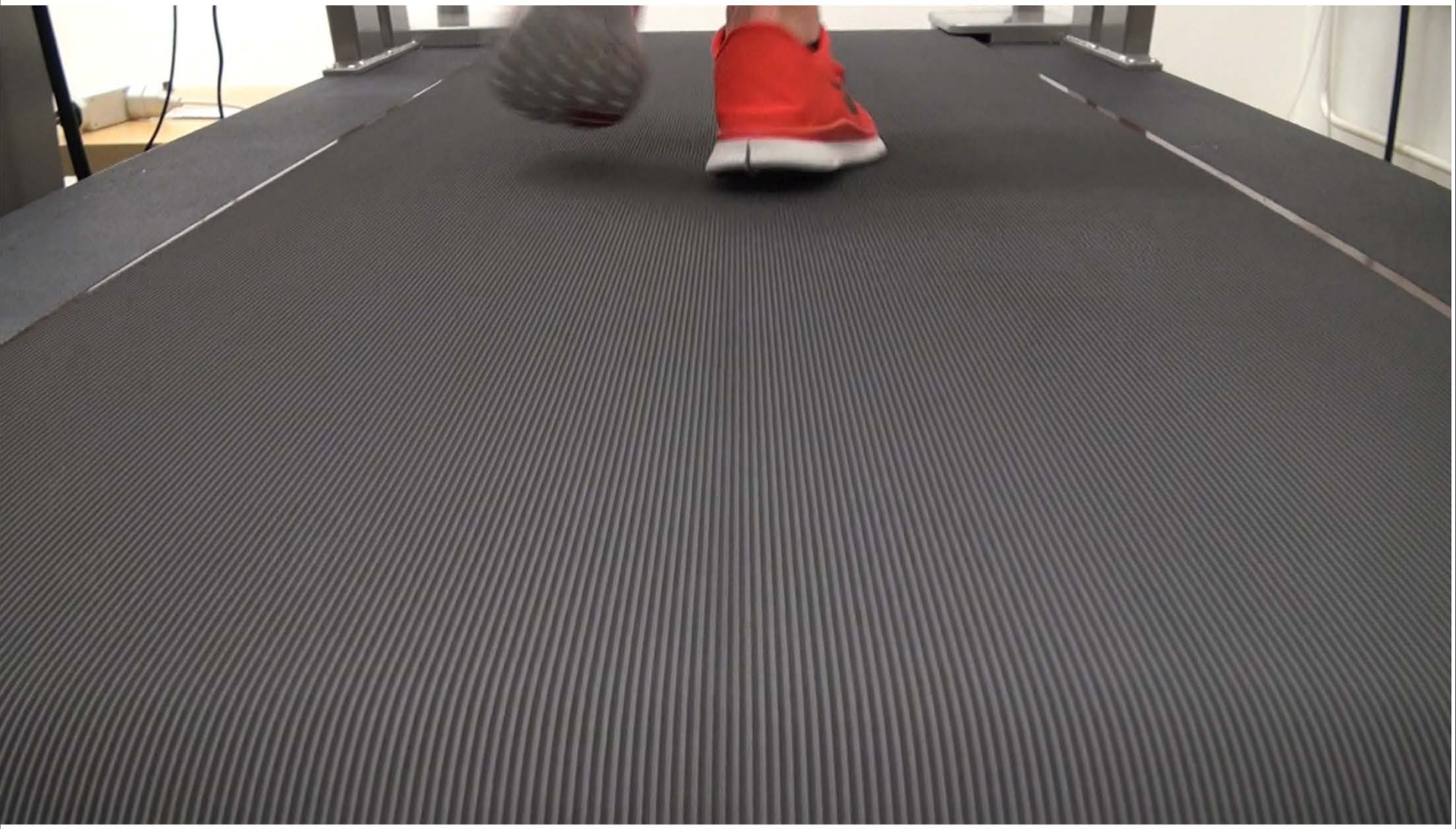
Title	Heart Rate Variability, Dynamics and Control During Exercise
Funded	Swiss National Science Foundation (SNSF)
Principal Investigator	Prof. Kenneth J. Hunt
Duration	01.11.2019 to 31.10.2023 (4 years)*
Amount	CHF 472'768

1. Introduction

Aims of Overall Project.

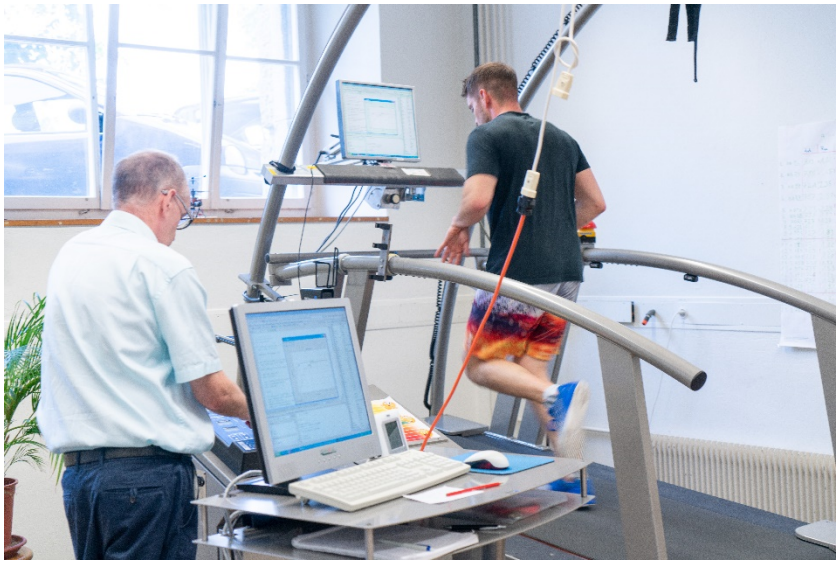
- Investigate changes in Heart Rate Variability (HRV) in relation to exercise intensity and duration;
- Identify models for the rapid cardio-dynamic HR response to exercise;
- Develop novel HR control strategies which account for HRV disturbances and rapid HR dynamics ;
- Carry out a clinical feasibility study of HR control in neurologically-impaired participants.

1. Introduction



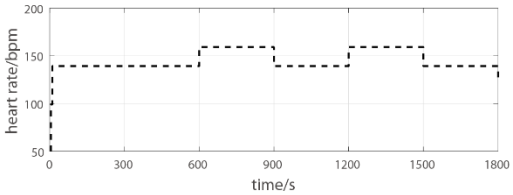
1. Introduction

PhD Project introduction.



1. Introduction

How to control the HR?



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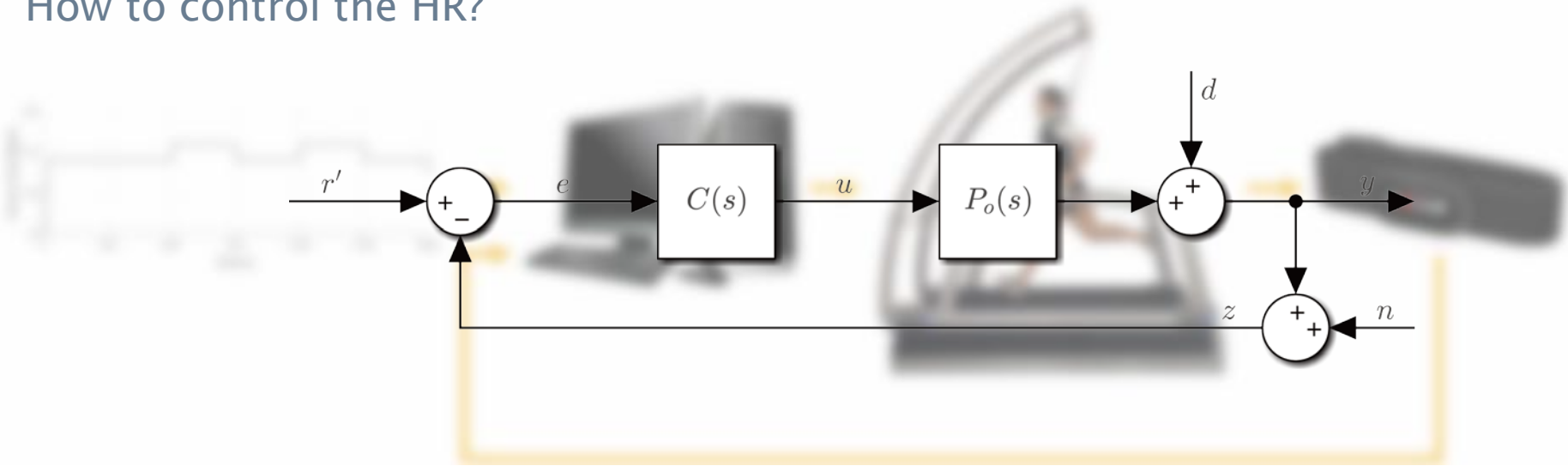

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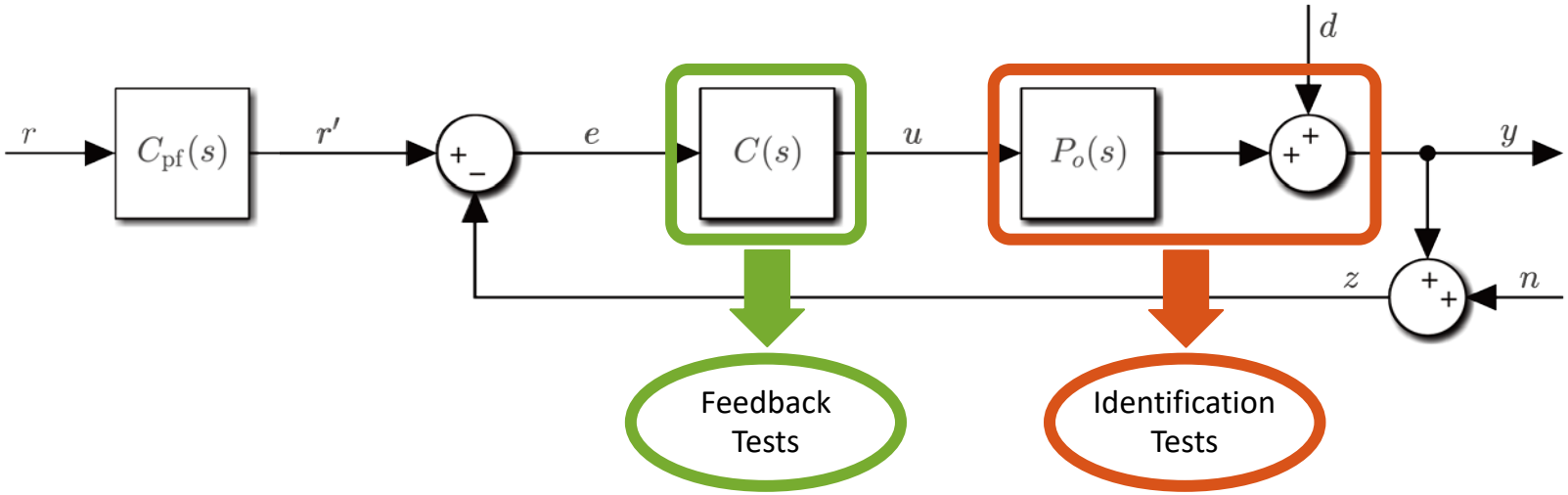
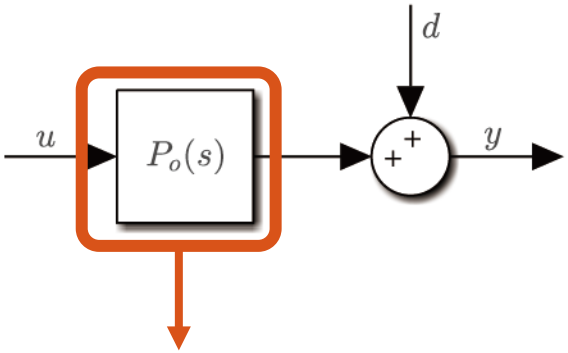


1. Introduction

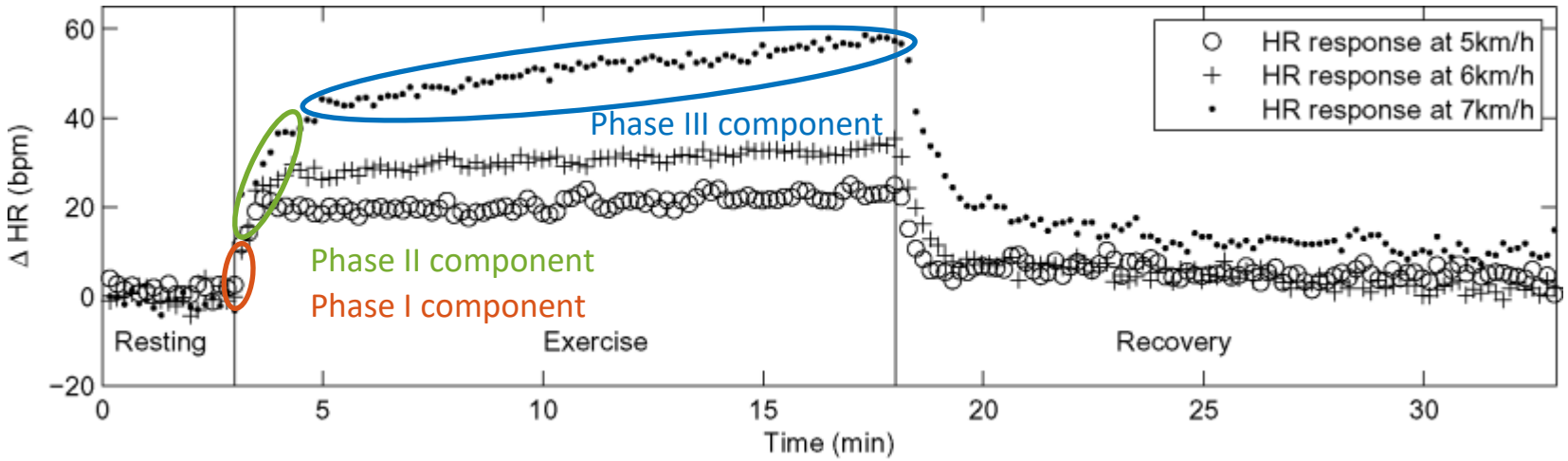
Plant Model



Transfer function that describe
the HR dynamic to different speed

1. Introduction

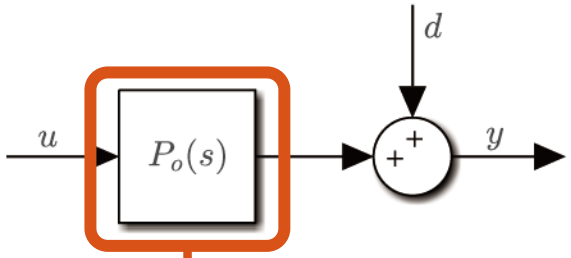
HR dynamic to different TM speed.



Typical HR responses to walking exercise with speed: 5 km/h (circle), 6 km/h (plus), and 7 km/h (dot).
T. M. Cheng, A. V. Savkin, B. G. Celler, S. W. Su and L. Wang, ”Nonlinear Modeling and Control of Human Heart Rate Response During Exercise With Vaious Work Load Intensities,”, *IEEE Transactions on Biomedical Engineering*, vol. 55, no. 11, 2008.

1. Introduction

Plant Model



$$P_1(s) = \frac{k_1}{\tau_1 s + 1},$$

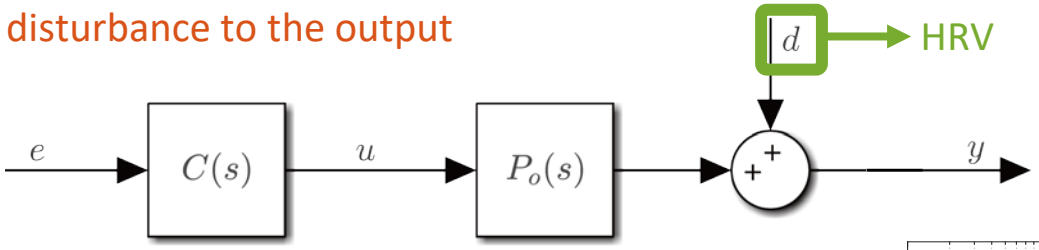
$$P_2(s) = \frac{k_2}{(\tau_{21} s + 1)(\tau_{22} s + 1)}.$$

Which model is more accurate ?

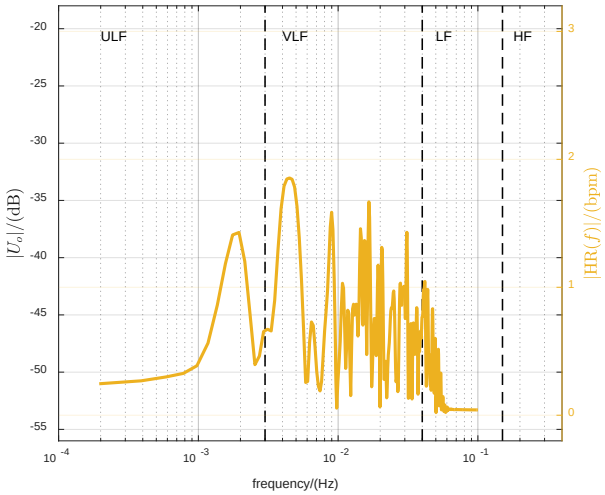
1. Introduction

Controller Design.

To reduce the effect of disturbance to the output

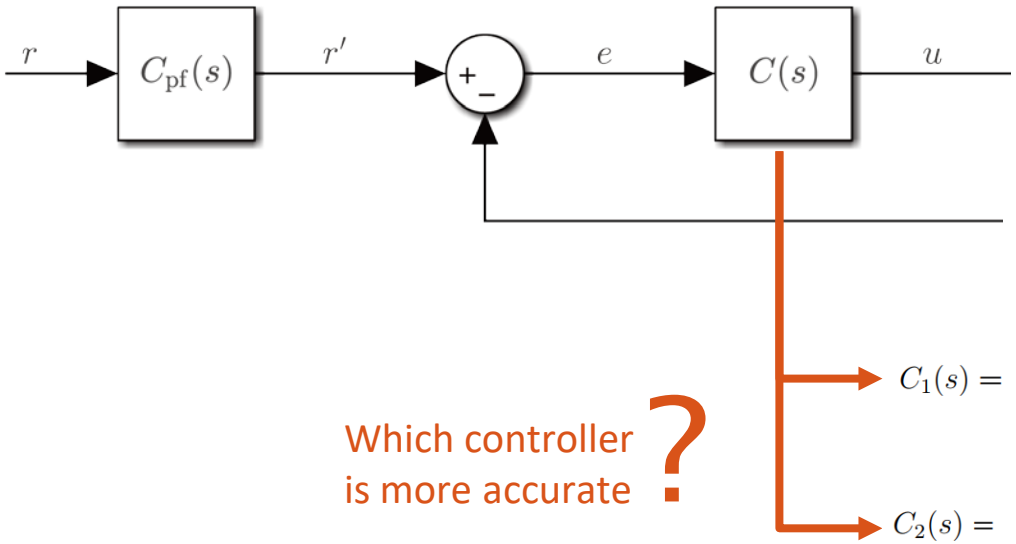


- ultra-low frequency (ULF): $\leq 0.00\overline{3}$ Hz,
- very-low frequency (VLF): $0.00\overline{3}$ Hz-0.04 Hz,
- low frequency (LF): 0.04 Hz-0.15 Hz,
- high frequency (HF): 0.15 Hz-0.4 Hz.

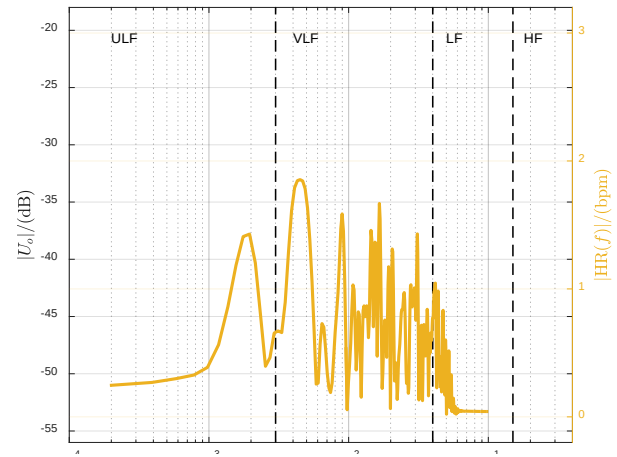


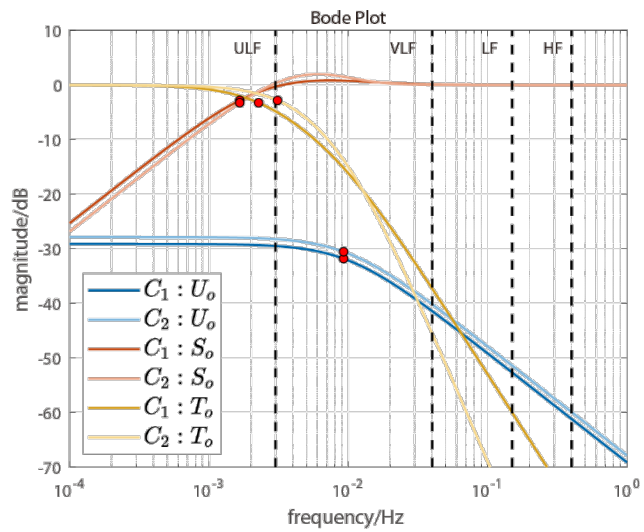
1. Introduction

Controller Design.



Which controller is more accurate ?





1. Introduction

Aims of PhD Project.

- Investigate whether second-order models with separate Phase I and Phase II components of HR response can achieve better fitting performance compared to first-order models that do not delineate the two phases.
- Investigate whether heart rate control design based on second-order models can achieve better tracking accuracy as a consequence of a more dynamic control signal when compared to controllers designed from first-order models.

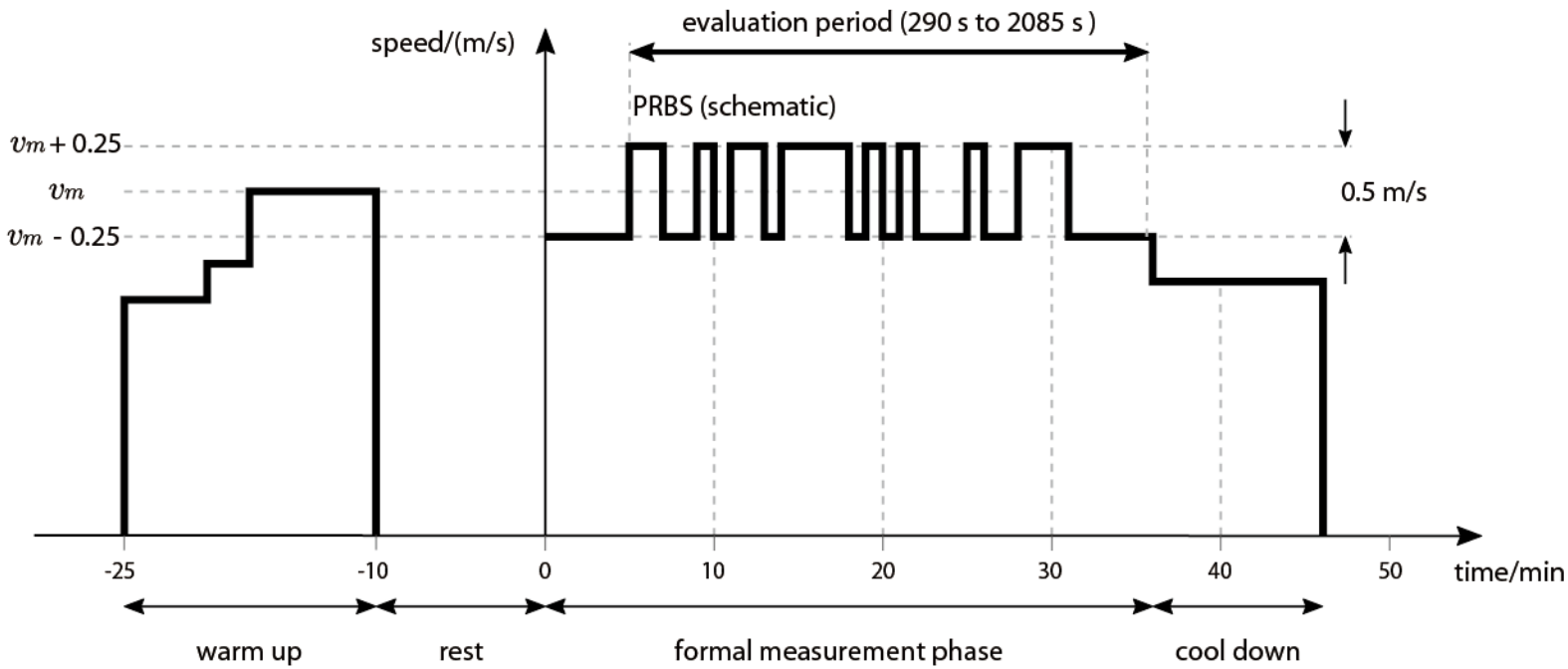
2. Identification Tests

2. Identification Tests

Test protocol.

2. Identification Tests

Formal test protocol.



2. Identification Tests

Evaluation of model accuracy.

$$\text{fit (NRMSE) [\%]} = \left(1 - \sqrt{\frac{\sum_{i=1}^{N}(\text{HR}(i) - \text{HR}_{\text{sim}}(i))^2}{\sum_{i=1}^{N}(\text{HR}(i) - \overline{\text{HR}})^2}}\right) \times 100\ \%,$$

$$\text{RMSE [bpm]} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\text{HR}_{\text{sim}}(i) - \text{HR}(i))^2}.$$

- HR_{sim} is the simulated HR response. HR is the measured HR from the validation data. $\overline{HR}$ is the mean value of HR. **i** is the discrete time index and **N** is the number of discrete samples considered.

3. Feedback Tests

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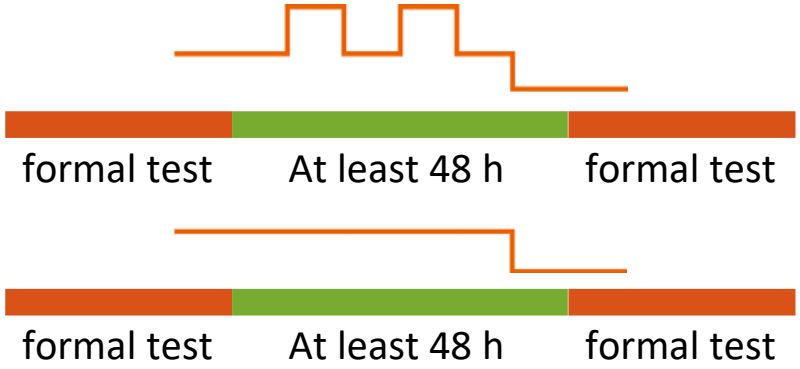
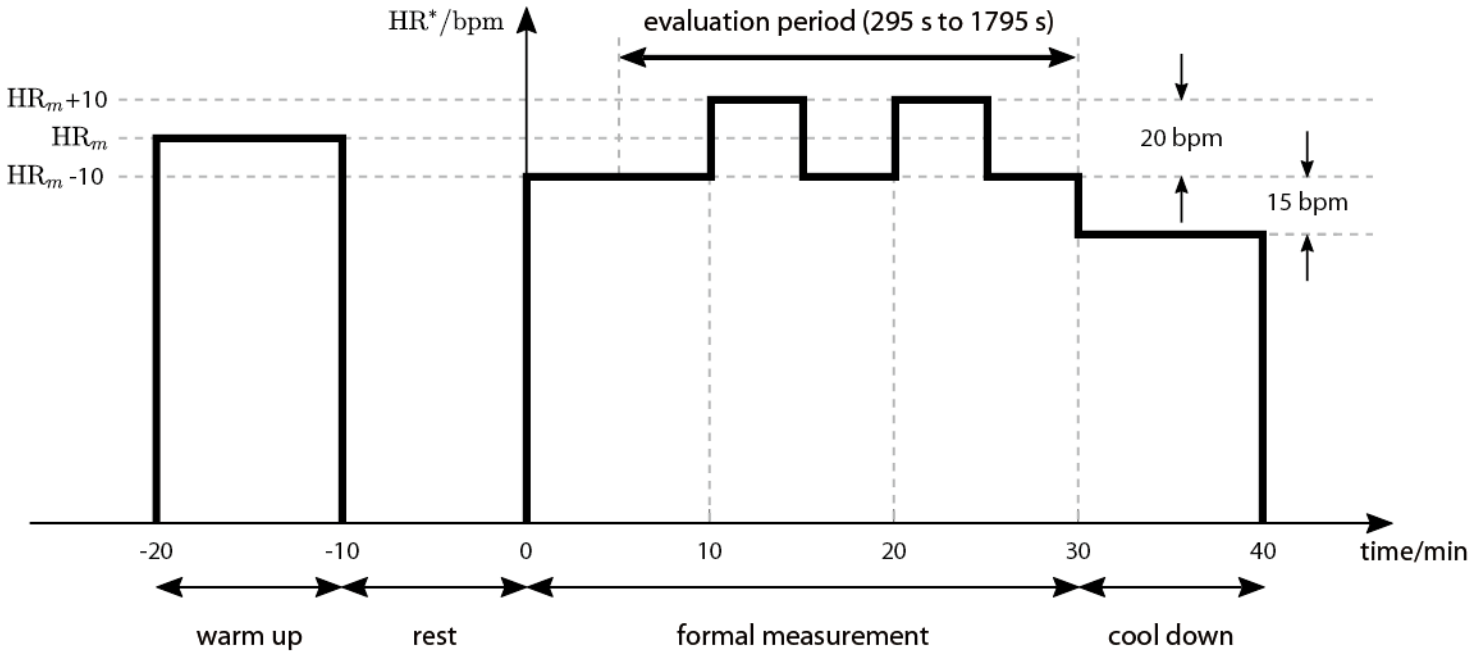
Test protocol.



3. Feedback Tests

Formal test protocol.



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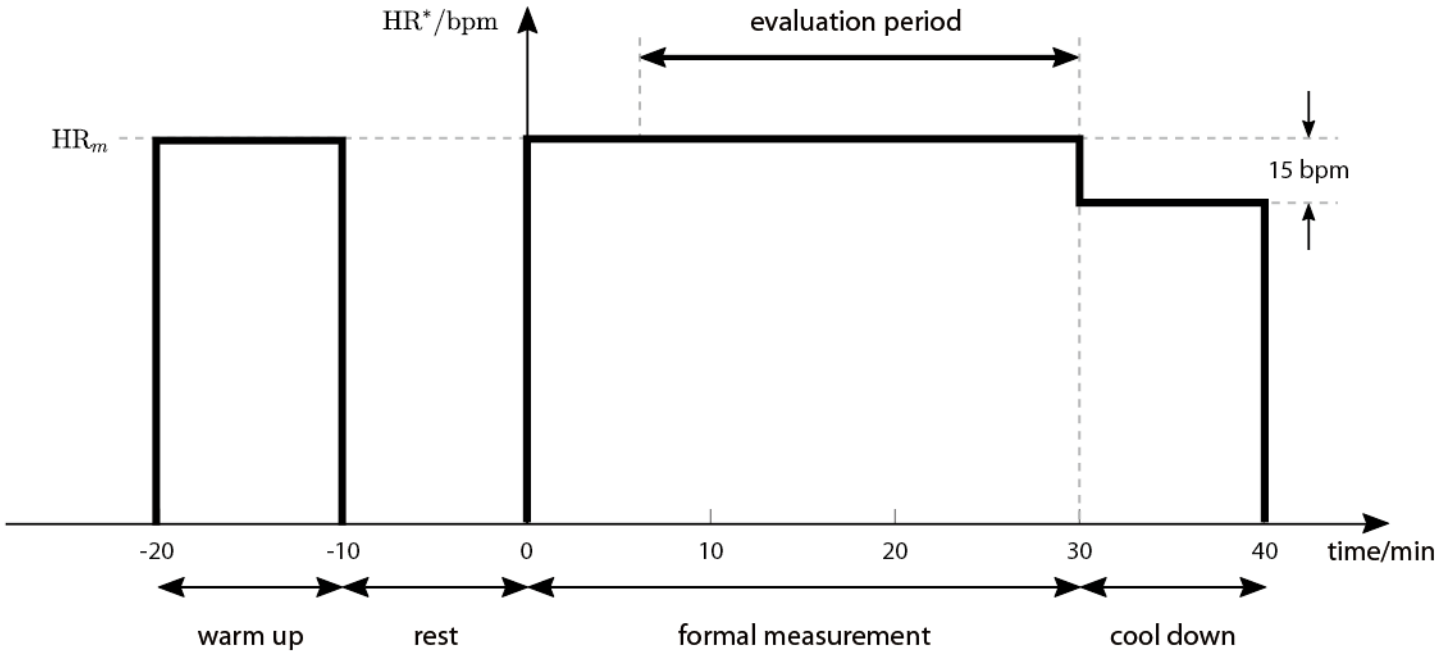
Formal test protocol.



3. Feedback Tests

Evaluation of controller performance.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{HR}_{\mathrm{nom}}(i) - \mathrm{HR}(i))^2},$$

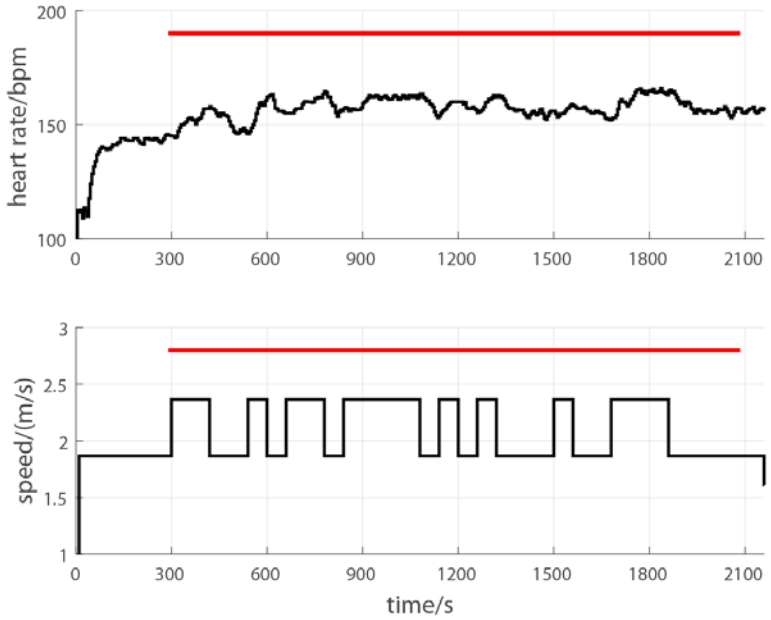
$$P_{\nabla u} = \frac{1}{N-1}\sum_{i=2}^{N}(u(i) - u(i-1))^2.$$

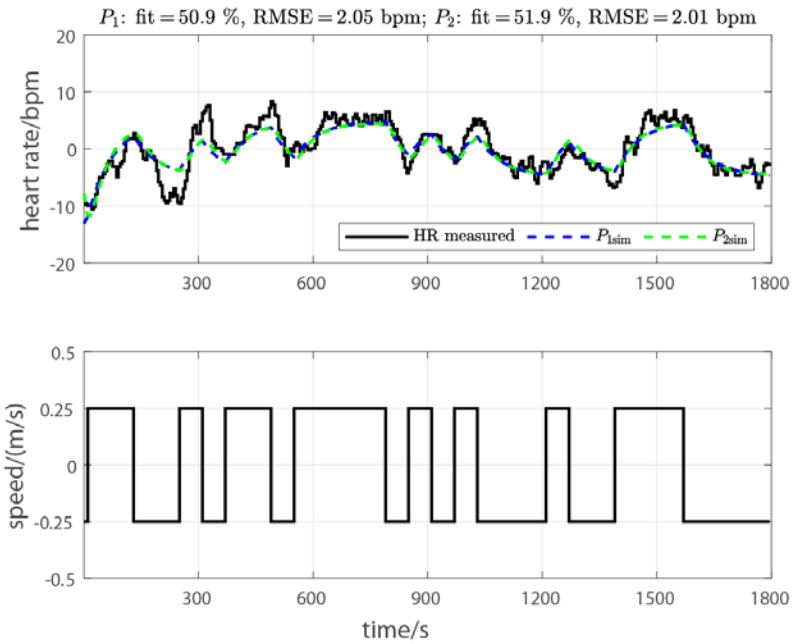
- HR_{nom} is the simulated closed-loop HR response. HR is the measured HR. **u** is the treadmill speed. **i** is the discrete time index and **N** is the number of discrete sample instants over the evaluation period.

4. Results

4. Results

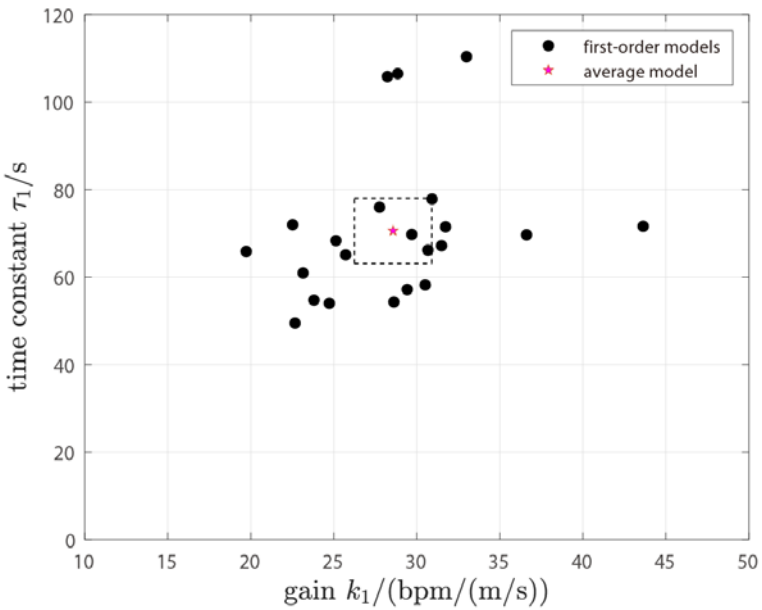
Sample Measurement for Identification tests.

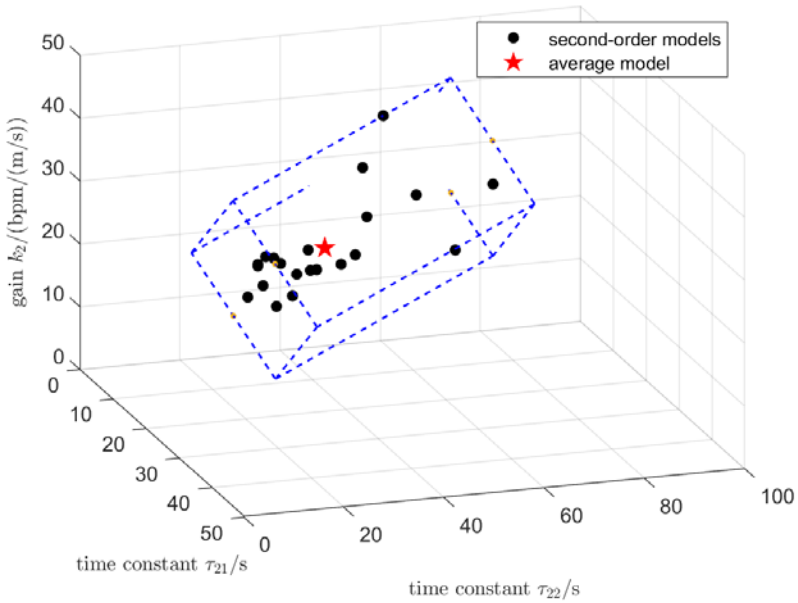




4. Results

Dispersion of estimated model parameters.





First-order average model

k_1	τ_1
28.57	70.56

Second-order average model

k_1	τ_{21}	τ_{22}
24.70	18.60	37.95

4. Results

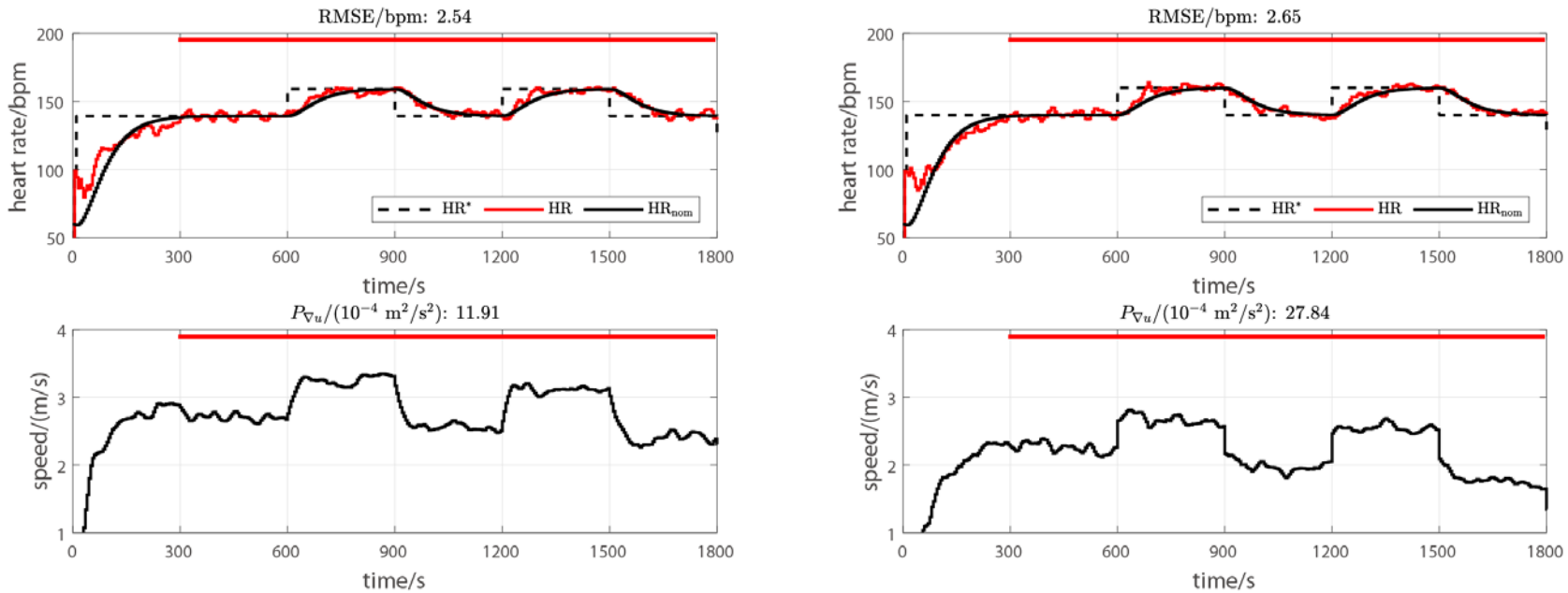
Overall outcomes for Identification tests.

	$Mean \pm SD$		MD (%95 CI)	$p - value$
	P_1	P_2	P_2 - P_1	
RMSE/bmp	2.27±0.36	2.07±0.36	-0.19 (-∞ , -0.16)	2.8×10^{-10}
fit/%	50.2±4.8	54.5±5.2	4.3 (3.6 , ∞)	6.8×10^{-10}

n = 22
P_1: first-order models
P_2: second-order models
SD: standard deviation
MD: mean difference
95% CI: confidence interval for the mean difference
$p - value$: paired one-sided t-tests
RMSE: root-mean-square error
fit: normalised root-mean-square error
bpm: beats per minute

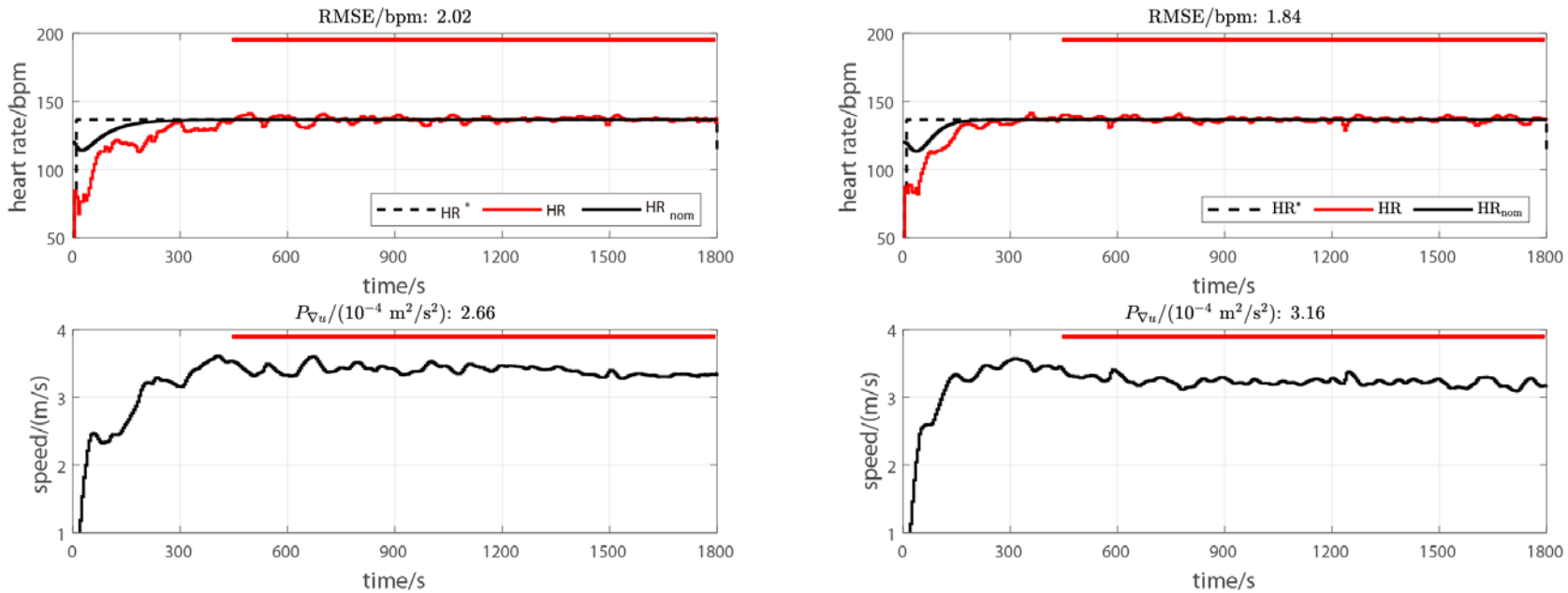
4. Results

Sample Measurement for Feedback tests.



4. Results

Sample Measurement for Feedback tests.



4. Results

Overall outcomes for Feedback tests.

	$Mean \pm SD$		MD (%95 CI)	$p - value$
	C_1	C_2	C_2 - C_1	
RMSE/bmp	2.59±0.50	2.69 ±0.34	0.10 (-∞ , 0.32)	0.79
$P_{\nabla u}/(10^{-4}\ m^2/s^2)$	11.29 ±1.65	27.91±0.95	16.62 (15.49 , ∞)	3.1×10^{-10}

n = 10
C_1: compensator C_1
C_2: compensator C_2
SD: standard deviation
MD: mean difference
95% CI: confidence interval for the mean difference
$p - value$: paired one-sided t-tests
RMSE: root-mean-square error
$P_{\nabla u}$: average control signal power
bpm: beats per minute

4. Results

Overall outcomes for Feedback tests.

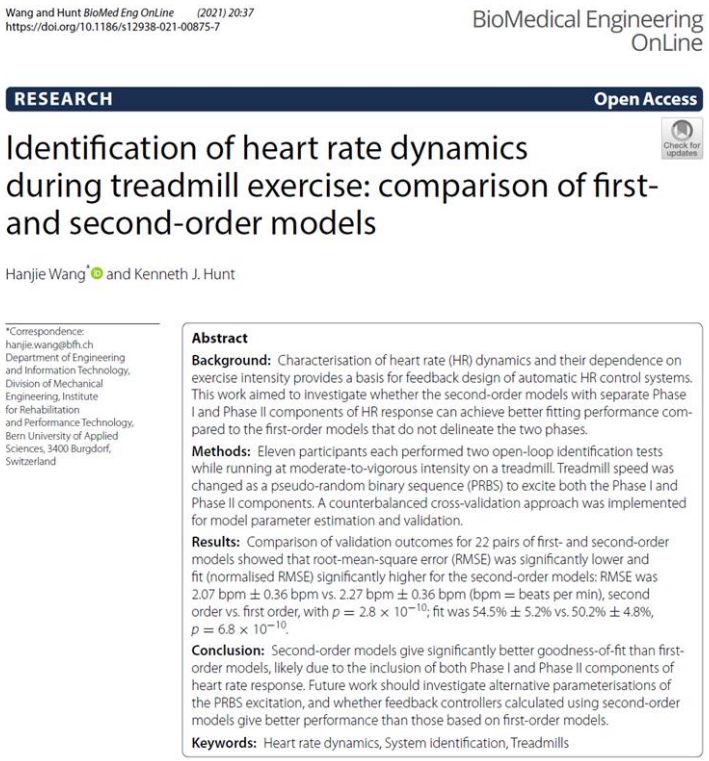
	$Mean \pm SD$		MD (%95 CI)	$p - value$
	C_1	C_2	C_2 - C_1	
RMSE/bmp	1.99±0.45	1.94 ±0.50	-0.05 (-∞ , 0.27)	0.39
$P_{\nabla u}/(10^{-4}\ m^2/s^2)$	2.20 ±0.93	2.78 ± 1.30	0.58 (0.02 , ∞)	0.045

n = 8
C_1: compensator C_1
C_2: compensator C_2
SD: standard deviation
MD: mean difference
95% CI: confidence interval for the mean difference
$p - value$: paired one-sided t-tests
RMSE: root-mean-square error
$P_{\nabla u}$: average control signal power
bpm: beats per minute

4. Results

Publications of project results.

- ‘Identification of heart rate dynamics during treadmill exercise: comparison of first- and second-order models ’, *BioMedical Engineering OnLine*, Published: 21 April 2021.
- ‘Heart rate control using first- and second-order models during treadmill exercise‘, *Systems Science & Control Engineering*, Reviewing.



Wang and Hunt *BioMed Eng OnLine* (2021) 20:37
https://doi.org/10.1186/s12938-021-00875-7

BioMedical Engineering OnLine

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Identification of heart rate dynamics during treadmill exercise: comparison of first- and second-order models

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Abstract

Background: Characterisation of heart rate (HR) dynamics and their dependence on exercise intensity provides a basis for feedback design of automatic HR control systems. This work aimed to investigate whether the second-order models with separate Phase I and Phase II components of HR response can achieve better fitting performance compared to the first-order models that do not delineate the two phases.

Methods: Eleven participants each performed two open-loop identification tests while running at moderate-to-vigorous intensity on a treadmill. Treadmill speed was changed as a pseudo-random binary sequence (PRBS) to excite both the Phase I and Phase II components. A counterbalanced cross-validation approach was implemented for model parameter estimation and validation.

Results: Comparison of validation outcomes for 22 pairs of first- and second-order models showed that root-mean-square error (RMSE) was significantly lower and fit (normalised RMSE) significantly higher for the second-order models: RMSE was 2.07 bpm ± 0.36 bpm vs. 2.27 bpm ± 0.36 bpm (bpm = beats per min), second order vs. first order, with $p = 2.8 \times 10^{-10}$; fit was 54.5% ± 5.2% vs. 50.2% ± 4.8%, $p = 6.8 \times 10^{-10}$.

Conclusion: Second-order models give significantly better goodness-of-fit than first-order models, likely due to the inclusion of both Phase I and Phase II components of heart rate response. Future work should investigate alternative parameterisations of the PRBS excitation, and whether feedback controllers calculated using second-order models give better performance than those based on first-order models.

Keywords: Heart rate dynamics, System identification, Treadmills

5. Conclusions & Future Work

5. Conclusions & Future Work

Conclusions.

- Second-order models give significantly better goodness-of-fit than first-order models, likely due to the inclusion of both Phase I and Phase II components of heart-rate response.
- No evidence that controllers based on second-order models lead to better tracking accuracy, despite the finding that they are significantly more dynamic.

5. Conclusions & Future Work

Future work.

- New feedback tests with larger participant number will be organized.
- New controller which has a sensitivity function with lower peak will be implemented for the future feedback tests .

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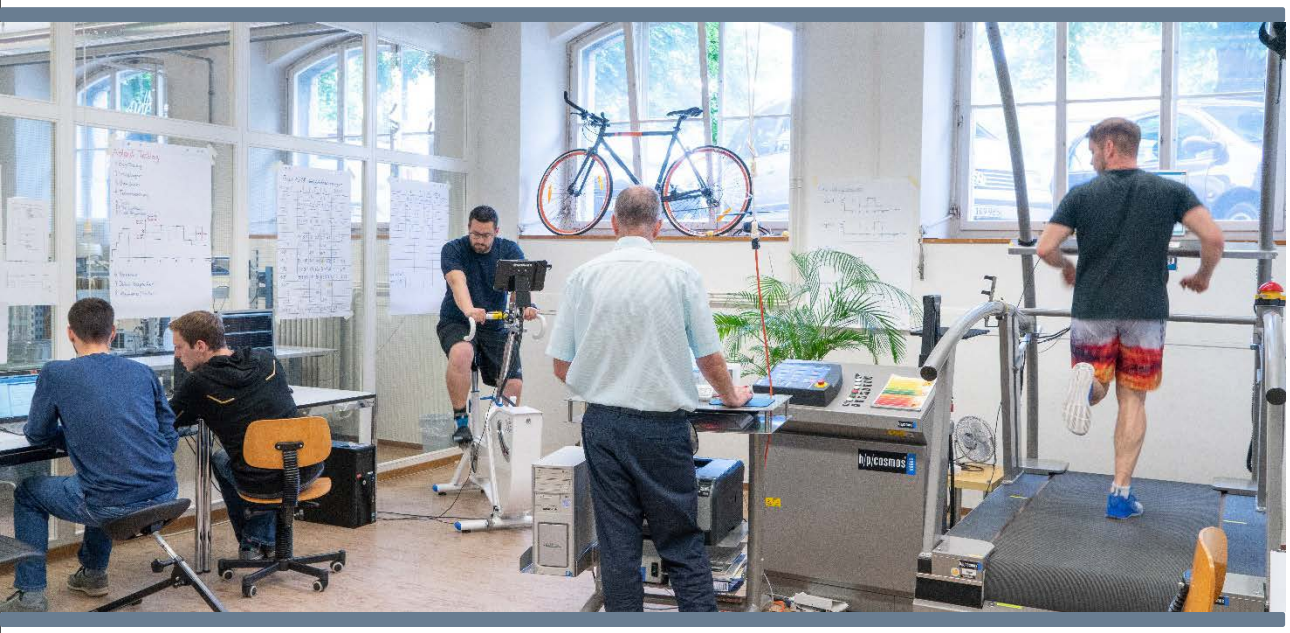

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