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Heart rate control during treadmill exercise using input-sensitivity shaping for disturbance rejection of very-low-frequency heart rate variability

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ABSTRACT

Background: Automatic and accurate control of heart rate (HR) during treadmill exercise is important for prescription and implementation of training protocols. The principal design issue for feedback control of HR is to achieve disturbance rejection of very-low-frequency heart rate variability (VLF-HRV) with a level of control signal activity (treadmill speed) which is sufficiently smooth and acceptable to the runner. This work aimed to develop a new method for feedback control of heart rate during treadmill exercise based on shaping of the input sensitivity function, and to empirically evaluate quantitative performance outcomes in an experimental study.
Methods: Thirty healthy male subjects participated. 20 subjects were included in a preceding study to determine an approximate, average nominal model of heart rate dynamics, and 10 were not. The design method guarantees that the input sensitivity function gain monotonically decreases with frequency, is therefore devoid of peaking, and has a pre-specified value at a chosen critical frequency, thus avoiding unwanted amplification of HRV disturbances in the very-low-frequency band. Controllers were designed using the existing approximate nominal plant model which was not specific to any of the subjects tested.
Results: Accurate, stable and robust overall performance was observed for all 30 subjects, with a mean RMS tracking error of 2.96 beats/min and a smooth, low-power control signal. There were no significant differences in tracking accuracy or control signal power between the 10 subjects who were not in the preceding identification study and a matched subgroup of subjects who were (respectively: mean RMSE 2.69 vs. 3.28 beats/min, $p = 0.24$; mean control signal power 15.62 vs. 16.31×10^{-4} m^2/s^2, $p = 0.37$). Substantial and significant reductions over time in RMS tracking error and average control signal power were observed.
Conclusions: The input-sensitivity-shaping method provides a direct way to address the principal design challenge for HR control, namely disturbance rejection in relation to VLF-HRV, and delivered robust and accurate tracking with a smooth, low-power control signal. Issues of parametric and structural plant uncertainty are secondary because a simple approximate plant model, not specific to any of the subjects tested, was sufficient to achieve accurate, stable and robust heart rate control performance.

1. Introduction

The ability to automatically and accurately control heart rate (HR) during treadmill exercise would bring important benefits for the prescription and implementation of exercise training protocols. Heart rate is used to delineate the exercise intensity regimes which form part of current recommendations for development and maintenance of cardiorespiratory fitness [1]; these recommendations are given in terms of frequency, duration and intensity, the latter typically lying in the range of "moderate" to "vigorous" exercise. Exercise intensity, in turn, is described as a percentage of either maximal heart rate (HR_{max}) or of heart rate reserve (HRR), which is the difference between maximal and resting heart rates: $HRR \triangleq HR_{max} - HR_{rest}$. Using HRR, moderate and vigorous intensities correspond respectively to the ranges 40–59% and 60–89% of HRR [2].

High-intensity interval training (HIT), which combines periods of vigorous to high-intensity exercise with low or moderate-intensity recovery periods, has been shown to provide additional

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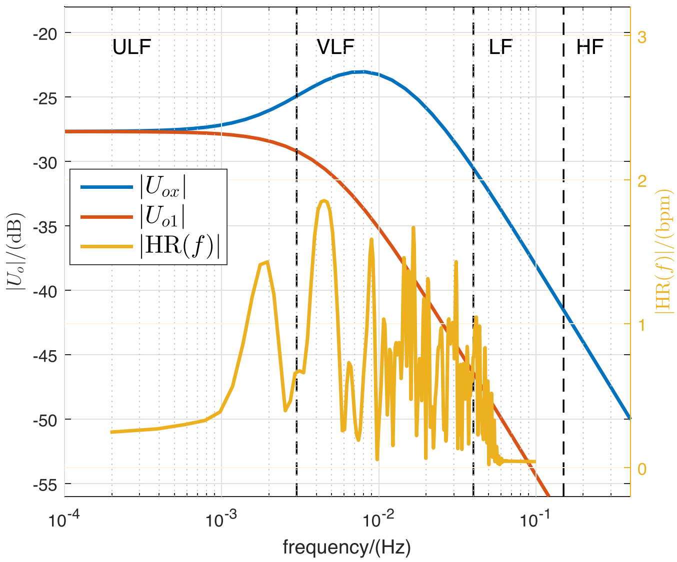

Fig. 1. Four principal frequency bands for heart rate variability analysis: ultra-low frequency (ULF), very-low frequency (VLF), low frequency (LF) and high frequency (HF). Amplitude spectrum of HR for subject S02 (orange trace, right-hand y-axis). Input sensitivity function magnitudes $|U_o(j\omega)|$ (left-hand y-axis) for naive feedback design (blue trace $|U_{ox}|$) and for shaped controller C_1 (red trace $|U_{o1}|$; Eqs. (33) and (34)). (For interpretation of the references to colour in this legend, the reader is referred to the web version of the article.)

benefits for cardiorespiratory fitness and cardiovascular function when compared to constant-intensity training (systematic reviews: [3,4]). There is considerable flexibility in setting the durations and intensity levels of the different regimes within HIT in healthy adults [3] and in various patient groups, e.g. in cardiac rehabilitation [5]. This motivates the development of accurate and robust feedback approaches for automatic control of arbitrary heart rate reference profiles. For treadmill-based training, the feedback controller would automatically adjust the treadmill speed based on continuous observation of the reference and actual HR values.

The primary design challenge for feedback control of heart rate is to ensure that the control system maintains acceptable performance in the face of disturbances to the heart rate caused by physiological heart rate variability (HRV) [6]; this concept is supported by data presented in the preliminary observational case study below. Performance of heart rate control systems should always be quantified in terms of both tracking accuracy (e.g. root-mean-square heart-rate tracking error, RMSE) and the level of activity of the control signal (e.g. average power of the control signal, i.e. the treadmill speed reference). For the HR control application, the classical trade-off between tracking accuracy and control signal power – higher accuracy is usually achieved at the cost of increased control signal activity – is particularly pronounced and important: the HRV disturbance entering the system will be rejected to a degree defined by the frequency-response of the sensitivity function (S_o, Eq. (11)), with a higher level of disturbance rejection leading generally to lower tracking error but requiring higher control signal power. Since the control signal in this case is the treadmill speed reference, changes in this variable directly impact on the human subject running on the treadmill, so these changes must be kept within acceptable limits, even if some degree of tracking accuracy has to be sacrificed; hence the importance of the input sensitivity function (U_o, Eq. (12)), which links the HRV disturbance to the control signal.

Current standards for measurement and interpretation of HRV identify four principal frequency bands for analysis [7,8] (cf. Fig. 1):

- ultra-low frequency (ULF), with frequency $f < 0.003$ Hz;
- very-low frequency (VLF), where $0.003 \leq f < 0.04$ Hz;
- low frequency (LF), $0.04 \leq f < 0.15$ Hz;
- high frequency (HF), $0.15 \leq f \leq 0.4$ Hz.

For design of heart rate controllers, the VLF component is of primary importance because this band usually incorporates the crossover region of the feedback loop; peaking of the sensitivity functions can occur in the crossover region, potentially leading to unwanted power in the control signal in the VLF frequency band, which manifests as changes in the treadmill speed which would be strongly perceptible to the runner. HRV in the ULF band, in contrast, represents a very slow disturbance which can readily be fully rejected by having high gain in the controller in this range (e.g. by using integral action); the resulting very-slow changes in the control signal would not be perceived as unpleasant or undesirable by the runner – the upper-frequency bound of the ULF range, 0.003 Hz, corresponds to an oscillation period of just over 5 min (333.3 s). HRV in the LF and HF frequency bands, on the other hand, will typically lie outwith the bandwidth of the feedback loop and will have little effect on the control signal if the controller's frequency response is appropriately designed; one way to do this is to prescribe a strictly-proper controller transfer function so that the loop gain rolls off towards zero above the crossover region. This makes the control signal insensitive to HRV disturbances in the LF and HF bands.

These considerations emphasize that the feedback loop properties in the VLF band are paramount and that disturbance rejection behaviour is the key design issue; these concepts are further elucidated in the case presented in Section 2. To directly address these challenges, a novel design approach is derived and tested in the present work which is based on shaping the frequency response of the input sensitivity function (U_o, Eq. (12): the transfer function between the HRV disturbance and the control signal) so that it has a pre-specified gain at a selected critical frequency in the crossover region within the VLF band. Moreover, the design approach is constrained to make the gain of the input sensitivity function monotonically decreasing with frequency, so that peaking of this gain cannot occur. Finally, the requirements of the ULF and LF/HF bands are addressed respectively, as alluded to above, by including integral action in the feedback compensator and by making it strictly proper (i.e. low pass).

Previous work on treadmill HR control has focused not on the key issues of HRV and disturbance rejection, but rather on parametric and structural plant uncertainty [9–12]. A further novel element of the present work is the assumption of a very simple and approximate model of heart rate dynamics, which was the outcome of a companion identification study [13]. The control design approach detailed here uses this single approximate nominal plant model, and does not require any information on, or identification of, heart rate dynamics for individual runners. A similar nominal model strategy was taken in related reports of heart rate control during outdoor running [14] and in a comparison of linear and nonlinear heart rate controllers [15].

The aim of the present work was twofold: to set out the input-sensitivity-shaping method for feedback control of heart rate during treadmill exercise; and to empirically evaluate quantitative performance outcomes with the proposed method in an experimental study with a number of subjects sufficient to allow statistically valid conclusions to be drawn.

2. HRV – preliminary observational case study

The introductory discussion highlighted the importance of the VLF band of HRV for the design of HR control systems, and that disturbance rejection is the principal design issue. These concepts can be exemplified by considering data recorded from one