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Feedback control of heart rate during outdoor running: A smartphone implementation

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ABSTRACT

The aim was to develop and to investigate the technical feasibility of a novel smartphone-based mobile system for feedback control of heart rate during outdoor running. Accurate control is important because heart rate can be used for prescription of exercise intensity for development and maintenance of cardiorespiratory fitness.

An Android smartphone was employed together with wearable, wireless sensors for heart rate and running speed. A simple feedback design algorithm appropriate for embedded mobile applications was developed. Controller synthesis uses a low-order, physiologically-validated plant model and requires a single bandwidth-related tuning parameter.

Twenty real time controller tests demonstrated highly accurate tracking of target heart rate with a mean root-mean-square tracking error (RMSE) of less than 2 beats per minute (bpm); a sufficient level of robustness was demonstrated within the range of conditions tested. Adjustment of the tuning parameter towards lower closed-loop bandwidth gave markedly lower control signal power (0.0008 vs. 0.0030 m^2/s^2, $p < 0.0001$, low vs. high bandwidth), but at the cost of a significantly lower heart rate tracking accuracy (RMSE 1.99 vs. 1.67 bpm, $p < 0.01$).

The precision achieved suggests that the system might be applicable for accurate achievement of prescribed exercise intensity for development and maintenance of cardiorespiratory fitness. High-accuracy feedback control of heart rate during outdoor running using smartphone technology is deemed feasible.

1. Introduction

The prescription of exercise intensity for development and maintenance of cardiorespiratory fitness in adults is based on either heart rate (HR) or oxygen uptake [1,2]. With heart rate, intensity can be expressed as a percentage of either maximum heart rate or of heart rate reserve (HRR), the latter being defined as the difference between an individual's maximum and resting heart rates, i.e. $HRR \triangleq HR_{max} - HR_{rest}$. For most adults, training is recommended for 20–60 min on 3–5 d/week at a moderate to vigorous intensity; using heart rate reserve, moderate intensity is defined as 40–59% of HRR and vigorous intensity as 60–89% of HRR [1]. It is therefore of high interest to investigate feedback methods for accurate control of heart rate during exercise.

Because of the convenience of measuring heart rate, automated heart rate control has been implemented in different exercise devices including treadmills [3,4] and cycle ergometers [5], both within commercial devices and in the scientific research literature. Feedback controllers within commercial products seem to be based mainly on conservatively-tuned proportional-integral (PI) controllers and give very poor heart rate tracking performance. Controllers described in the literature tend, on the other hand, to be based on sophisticated non-linear modelling/identification [6] and control design techniques (e.g. [7–10]); to the best of our knowledge, no data have been presented which compare such methods with well-designed robust linear-time-invariant (LTI) controllers.

The primary contribution of this work is the development of a system which enables feedback control of heart rate during free-running outdoor exercise. Hitherto, no system with this capability has been demonstrated, but state-of-the-art smartphone and wearable sensor technologies present the potential to address this lack: smartphones are now available with appropriate open-source programming and operating system environments (e.g. Java, Android) and wireless communication systems (e.g. ANT+); simple, accurate and cost-effective sensors are available for real-time measurement and wireless transmission of heart rate and running speed.

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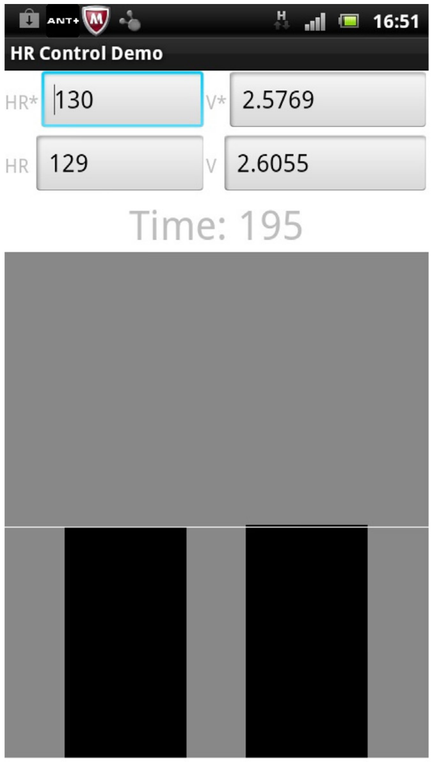

(a) App screenshot.

(b) Foot Pod running-speed sensor.

(c) Outdoor HR control.

Fig. 1. The HR control App screenshot, (a), shows the user interface for identification and feedback control. The left bar is the target speed v^* and the right bar is the actual speed v. The user focuses on the bars and tries to keep the actual speed as close as possible to the target. The screenshot was taken during a feedback control test. For identification, the target heart rate (HR*, upper left) is set to zero. The running-speed sensor has small dimensions and is attached directly to the running shoe, (b). The smartphone and wearable sensors facilitate closed-loop control of heart rate during outdoor running, (c).

A second contribution of the present work is the employment of analytical feedback design methods which use physiologically-accepted models of the heart rate response to changes in exercise work rate: we assume at the outset that the plant can be modelled by a mono-exponential (first-order) response with operating-point dependent gain and time-constant parameters, which is the usual and physiologically-validated assumption in the exercise sciences [11].

This starting point led to the development of a simple and transparent feedback design algorithm appropriate for embedded mobile applications: controller synthesis based on the low-order, physiologically-validated plant model requires only a single bandwidth-related tuning parameter. It transpires that, despite its simplicity, the algorithm gives high-precision and robust heart-rate tracking performance. A similar approach has previously been employed in the context of rehabilitation robotics [12,13].

The aim of this work was to develop and to investigate the technical feasibility of a novel smartphone-based mobile system for feedback control of heart rate during outdoor running by automatically calculating a target speed for the runner.

2. Methods

2.1. Overall concept

The method proposed here for feedback control of heart rate is based on the idea of comparing the current, measured heart rate with a target heart rate and on this basis calculating a target speed for the runner. The target speed is displayed by the application on a smartphone display to the runner who then has the task of adjusting actual running speed to meet this target: the actual running speed, obtained from a sensor, is also displayed to the runner (Fig. 1).

The open-loop structure of the plant has two elements (Fig. 2): an internal control loop representing the runner's speed control dynamics ($v^* \to v$), and a dynamic block representing the heart rate response to changes in actual speed ($v \to$ HR). The overall plant P is the total dynamic response from target speed v^* to heart rate HR ($v^* \to$ HR). This structure is analogous to the plant structure for an automatic heart rate control system for a treadmill; but on a treadmill, the target speed is sent to the motor control electronics which maintain the actual speed close to the target and the runner is thereby forced to follow the speed of the treadmill belt.

The open-loop plant is embedded within a closed-loop feedback system for control of heart rate (Fig. 3). The target running speed v^* is calculated from a target heart rate profile HR* and a continuous

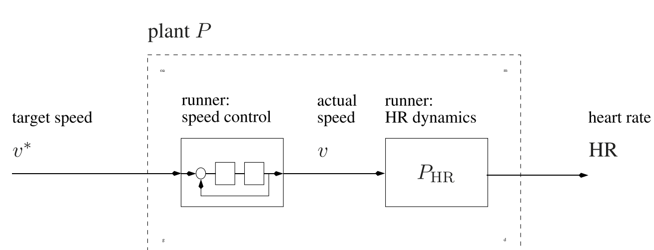

Fig. 2. Open-loop structure of the plant P, used for system identification and calculation of controller parameters. v^* is the target running speed, v is the actual speed and HR is heart rate. The "speed control" block represents the runner's internal speed control mechanism which is carried out by the brain in response to the displayed target and actual speeds. P_{HR} represents the notional dynamic response of heart rate to actual speed. The dashed block is the overall nominal plant model P, which represents the response from target speed v^* to heart rate HR, Eq. (1).