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HEALTHeBIKES – Smart E-Bike Prototype for Controlled Exercise in Telerehabilitation Programs

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Abstract. E-Bikes in telerehabilitation programs could be a new intervention for more sustainable rehabilitation results. The aim is to design and build a prototype of an E-Bike usable for rehabilitation – a HEALTHeBIKE. It should avoid over-exercising, work independently of the environment and it should enable cycling in a group despite different reference exercise intensities. To achieve these goals, requirements for this system architecture have been identified. A system architecture including an Arduino microcontroller, an Android smartphone and a telemonitoring platform was presented. A power output regulated proportional-integral controller to adjust the motor assistance has been implemented. A feasibility study with two subjects cycling in a group was performed. Seven test rides on varying terrain (flat, hilly, mountainous and uphill) with the same and different exercise intensities were completed. The mean power output was close to or below the target power output of the cyclist for all test rides with a maximal error of 6.7 % above and 27.6 % below the target. Although the exercise intensities of the two subjects were clearly different, cycling in a group was possible without over-exercising.

Keywords. E-Bike, electric bike, power output control, telerehabilitation

1. Introduction

Prescribing physical exercise as medicine is a key element in the rehabilitation of chronic diseases [1]. For efficient and safe physical exercises, it is important to appropriately choose the exercise intensity. In rehabilitation programs, stationary cycling ergometers are widely used for physical exercise. Individual power output based training profiles are applied to achieve the individual recommended exercise intensity [2,3]. However, most rehabilitation programs have in common that after initial success they are not further pursued [4]. Therefore, new interventions are necessary to secure sustainable effects.

An approach for sustainable rehabilitation could be based on eHealth and mHealth closed loop solutions, in which the health status of the patient is continuously monitored and the therapy is adapted as needed by healthcare professionals. Various groups have

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demonstrated the effect of tele-training on long-term adherence [5,6]. In a previous work, we have developed a closed loop system consisting of a cycle ergometer, an Android Smartphone and a backend telehealth platform [7].

Electric bicycles (E-Bikes) are growing in popularity and are used for daily transportation and leisure activities. Compared to stationary cycling ergometers, E-Bikes can be used outside, in unrestricted groups and as part of daily life activities. Usual commercial E-Bikes have multiple assistance levels, which can be changed manually. On a stationary ergometer, it is easily possible to maintain and alter the exercise intensity by regulating the workload. Indicators for the exercise intensity can be the power output of the cyclist and the heart rate. However, on an E-Bike, more degrees of freedom (e.g. road gradient, gear transmission ratio, wind) must be considered. Continuous adaptions of speed and motor assistance are required to reach and maintain the desired exercise intensity. Such adaptions currently need to be done by the cyclist. Automatic regulation of the motor assistance could support the cyclist in maintaining the required exercise intensity and prevent over-exercising.

Meyer et al. [8] presented such a system which used a sliding mode controller and a feedforward controller to keep the heart rate constant and achieved good tracking performance. Corno et al. [9] developed a heart rate regulated bicycle which kept the heart rate within 10 bpm by adjusting the transmission ratio. However, with this approach cycling in a group with individual intensities is not possible. Furthermore, the heart rate shows a non-linear relation to the workload and it is dependent on several additional parameters, such as inter-subject variability or exogenous factors (temperature, humidity) [10,11]. Therefore, for such approaches, an individual heart rate model is required. The power output of the cyclist is a widely used parameter for the evaluation of the exercise intensity, especially for competitive cycling. The power output is instant whereas the heart rate responds with some delay. Therefore, a power regulated control system could lead to a more intuitive regulation and faster reactions, which results in a better riding experience.

Aim of this paper is to design and build a prototype of an E-Bike usable for rehabilitation – a HEALTHeBIKE which fulfils the following requirements: (a) avoid overload by keeping the power output of the cyclist at or under a desired intensity level, (b) work independently of the environment and (c) allow cycling in a group with different individual exercise intensities.

2. Materials and Methods

2.1. Prototype components

The commercial E-Bikes crossroad inframe and wellness inframe (EBIKE EXPERTS EUROPE Limited, Austria) were used and modified for this study. The E-Bikes were equipped with a 500 Watt rear hub motor connected to a motor controller, a speed sensor and a torque sensor. The motor controller featured a throttle interface, which required a voltage signal as input. This throttle interface was used to adjust the motor assistance.

The power output of the cyclist and the heart rate were chosen as indicators for the exercise intensity. With Polar H7 heart rate chest straps (Polar Electro, Finland) heart rate measurements were performed. Built-in bottom bracket torque sensors were used to measure torque applied by the cycler and angular velocity of the pedal crank. The product of torque * angular velocity was used to calculate the power output applied to the pedals by the cyclist.

An Arduino microcontroller was used to capture and process sensor signals from the speed and bottom bracket torque sensor. By that, the speed of the bike and the cadence and power output of the cyclist could be obtained during riding. Furthermore, the Arduino microcontroller was used to set the motor assistance through the throttle input of the E-Bikes motor controller. The Arduino microcontroller provided a pulse-width modulated voltage signal (PWM) which was low pass filtered to get the desired voltage level. Through this approach, a continuous motor assistance was achieved.

An Android smartphone hosted the control system and acted as display. Furthermore, it was used for collecting data and communicating with the telemonitoring platform. The E-Bike was integrated into a closed loop rehabilitation scenario, where the training sessions could be monitored and adapted as needed.

To calculate the power output of the cyclist with the signal provided by the built-in torque sensor additional steps were necessary. The torque signal was sampled in 18 degrees steps of the pedal position, resulting in 20 measurements per cycle. For a physically meaningful interpretation, the torque signal was calibrated with a Garmin Vector power meter (Schaffhausen, Switzerland). Simultaneous measurements of the build-in torque sensor and a Garmin Vector power meter while increasing the power output from 30 W to 300W were performed and a correlation coefficient of 0,93 was found. Through least-mean-square-fitting, a transformation from the voltage signal of the torque sensor to a representing torque signal was then obtained. In case, the cyclist did not perform a full rotation within 2 seconds, the output power was set to 0 W.

To comply with the Austrian jurisdiction, the motor assistance had to be stopped if the 25 km/h limit was exceeded or the cyclist stopped pedalling.

2.2. Feasibility study

Feasibility of controlled exercise in a group on the prototype was evaluated with two healthy subjects cycling together on the two modified E-Bikes. Subject 2 was defined as the "leader" and subject 1 as the "follower". Seven test rides were performed which included flat, hilly, mountainous and uphill terrain. The subjects performed two test rides with the same target power and six test rides where the target power was different by minimal 40 Watts and maximal 60 Watts. The target power was varied for the subjects and test rides from 60 Watts to 220 Watts. The subjects were permitted to cycle at a cadence of 60-70 rpm. In order to simulate an unexperienced cycling behaviour, shifting the transmission ratio had to be changed as little as possible. Subject 2 ("leader") was requested to stay in maximal distance of 10 m behind subject 1 ("follower").

3. Results

3.1. Prototype

The results of the prototype are split in two parts. First the system architecture is described, followed by the used control system.

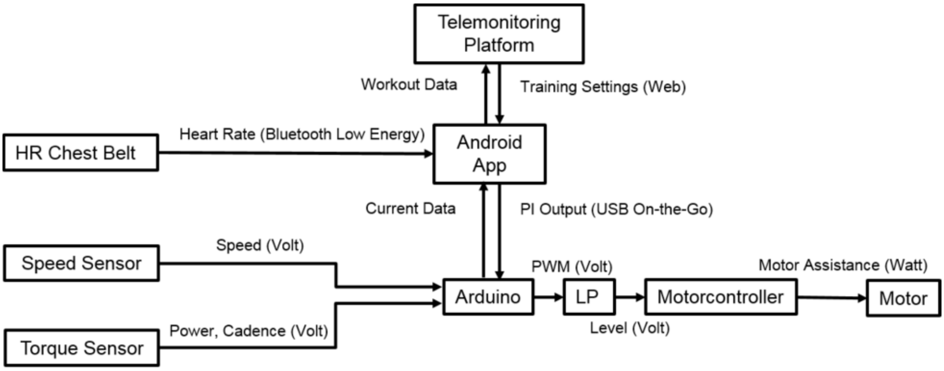

Figure 1. System architecture of the HEALTHeBIKES prototype

3.1.1. System architecture

The system architecture of the designed and built prototype can be seen in Figure 1. The Android smartphone was connected to the Arduino microcontroller via USB-On-the-Go (USB-OTG), to the heart rate chest strap via Bluetooth Low Energy (BLE) and to the AIT telehealth platform via web. The workout data and training settings were transmitted between the telemonitoring platform and the Android smartphone. Current speed, cadence and power data were captured by the Arduino microcontroller and sent to the Android smartphone. The control system hosted on the Android smartphone calculated the required motor assistance based on the current data and the training settings and sent to the Arduino microcontroller.

3.1.2. Control system

The cyclist was assumed to maintain the target velocity (via cadence and gear transmission ratio) through power output adjustments. The target velocity was defined as the personally preferred velocity or – when cycling in a group – the velocity of the group leader.

The controller was designed as a proportional-integral controller (PI controller), see Eq. 1. The output *u(t)* was a voltage level that was applied on the throttle input of the E-Bikes motor controller to set the corresponding motor assistance.

$$u(t_k) = u_0 + K_p \times e(t_k) + K_i \times \sum_{j=1}^{k} e_j(t_k) \times (t_j - t_{j-1}) \tag{1}$$

The error term *e(t)* was the difference between the desired reference power output of the cyclist and the current power output of the cyclist. The term u_0 was a default offset. Motor assistance started when then power output was higher than this offset. With the coefficients K_p and K_i the proportional and integral terms were weighted. A new power value was calculated after a full rotation of the pedal. Therefore, the sampling time $(t_j - t_{j-1})$ was the inversed cadence. Furthermore, an anti-windup method was implemented.

The coefficients $K_p$and K_i were determined through experiments with the goal of a fast settling time but without overshoot for good riding experience. K_p was set to 0.001 V/W and K_i to 0.0025 V/Ws.

Table 1. Evaluation of the performed test rides in a group of two as achieved during 7 test rides. Reference power output (Power ref), mean power output (Power mean) and the difference (Diff.) between these two values are shown.

			Subject 1			**Subject 2**		
No.	**Gradient**	**Duration**	**Power ref**	**Power mean**	**Diff.**	**Power ref**	**Power mean**	**Diff.**
#	-	min	Watt	Watt	%	Watt	Watt	%
1	flat	5.5	100	106.7	6.7	100	100.6	0.6
2	hilly	9.6	60	59.9	0.2	120	92.9	22.6
3	hilly	10.4	120	96.1	19.9	60	55.9	6.8
4	hilly	11.3	100	86.3	13.7	100	83.1	16.9
5	mountainous	23.6	80	68.1	14.9	120	107.9	10.1
6	hilly	15.4	100	96.6	3.4	140	125.1	10.6
7	uphill	6.7	160	161.6	1.0	220	221.3	0.6

Additionally, a heart rate limit was implemented. When the subject reached this limit, he/she was warned through the display and requested to reduce the workload or to stop exercising.

3.2. Feasibility study

In Table 1, the comparison of the desired reference power output (Power ref) to the mean power output (Power mean) for the two subjects as well as the difference between these two values for each test ride can be seen. In total, the difference between Power ref and Power mean ranged between 0.2 % and 22.6 %.

Subject 2 confirmed that it was possible to follow the group leader subject 1. The maximum distance to the group leader of 10 m during all the test rides was not exceeded.

The system behaviour is illustrated in Figure 2. Data from test ride 7 of subject 2 are shown. In the beginning, the power output of subject 1 was lower than the target of 220 Watts, since the road gradient was too low to reach this target at the group leader's target velocity. As the road gradient increased, the power output of the cyclist increased to a maximum of 331 Watt (50 % over the target power output). As soon as the power output

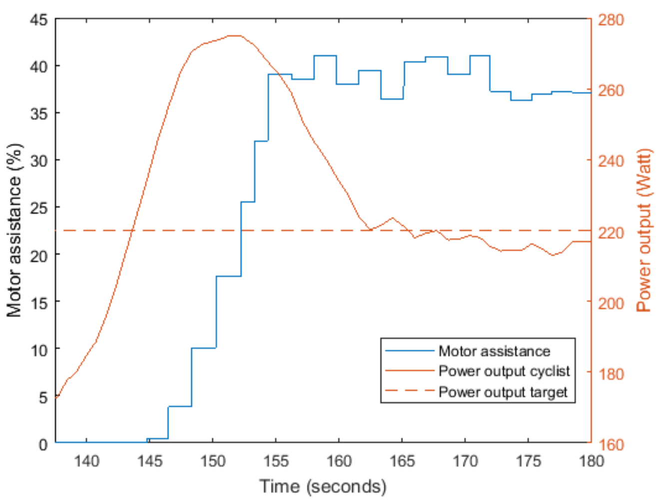

Figure 2. Regulation of the motor assistance due to changed power output of the cyclist of test ride No. 7 for subject 2. A moving average window of 10 s is applied to the power output of the cyclist.

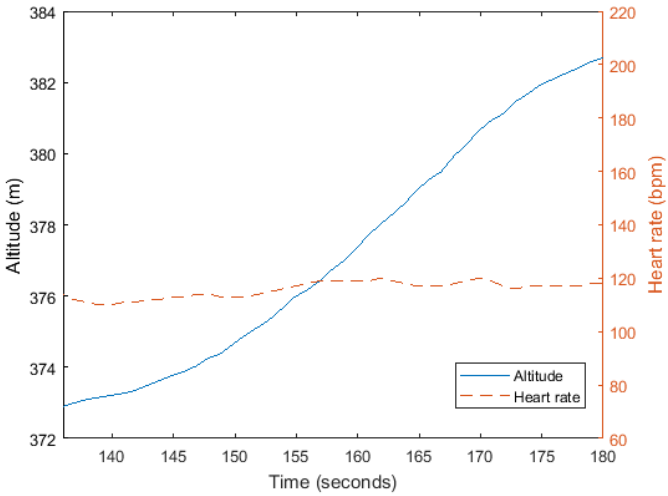

Figure 3. Altitude profile and heart rate of test ride No. 7 for subject 2

of the cyclist was above the target power, the motor assistance increased which can be seen at second 145. The motor assistance settled after around 15 seconds when the desired power output was reached. The heart rate of the subject stayed constant over this time indicating that the regulation was fast enough to avoid overloading of the subject.

4. Discussion

In this paper, a smart E-Bike for controlled exercising in telerehabilitation programs has been presented. An Arduino microcontroller and an Android smartphone were added to an E-Bike to gather and process the sensor data, to hosts a control system and to communicate with a telemonitoring platform. A PI controller regulated the motor assistance based on the difference between the reference power output of the cyclist and the actual power output.

Results show that the mean power output of the cyclists for the different test rides were mostly close or below the target power outputs and single peaks heavily above but short enough to be save. Therefore, based on mean power output, over-exercising was successfully prevented.

For flat and uphill tracks, the target power could be reached very closely. On hilly and mountainous tracks, however, the mean power output of the cyclists was lower than the necessary power output, especially for the subject with the higher reference power output. This can be explained by the downhill road sections, where the cyclists' power was lower than the target power. For the subject with the higher reference power it was earlier not necessary to provide the reference power while maintaining the cadence and gear selection. Additionally, restrictions because of traffic, road curves and intersections reduced the mean power. If a system to maintain the target power output even during downhill sections was required, an active braking element is required, e.g. a motor with recuperation could be used. However, we expect that – due to the resulting unusual cycling behaviour – this might have negative effects on the compliance.

Since the physiological responses are not only dependent on the mean power output of the cyclist, further analyses are required, e.g. if the system reacts fast enough to limit the amplitude and duration of power output peaks of the cyclist to secure a safe and efficient physical exercise.

In our example with strong increases in power output of the cyclist, we found a constant heart rate during this time, indicating that the system reacted fast enough in this situation for the subject to secure a safe cardio-respiratory strain below given limits. By changing the PI coefficients, the system dynamics can individually be adapted to each subject.

Since subject 2 could keep the distance to subject 1 within a range of 10 m in all test rides, we conclude that cycling in a group of two is possible for different intensity values, within the chosen intensity range and terrain. Cycling in a group may increase patient motivation and therefore increase the compliance.

As a next step, further studies with healthy male and female subjects as well as eligible patients from Phase III / IV cardiac rehabilitation of a local rehabilitation centre will be performed to validate and further improve the HEALTHeBIKES prototype in a cardiac rehabilitation scenario.

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