Katrin Hoffmann, Josef Wiemeyer, Sandro Hardy, Stefan Göbel: **Personalized adaptive control of training load in exergames from a sport-scientific perspective**. In: Proceedings of Gamedays 2014, Springer, LNCS, April 2014.

Personalized Adaptive Control of Training Load in Exergames from a Sport-Scientific Perspective

Towards an Algorithm for Individualized Training

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Abstract. The following paper addresses the development and first tests of an algorithm for individual control of physical load in Serious Games for Sports and Health. The purpose is to monitor and control the heart rate (HR) as an individual indicator of optimal training load. In the context of the Serious Game "LetterBird", developed by KOM, a playful and yet effective physical training can be realized. In this game the flight of a pidgeon is controlled by a cycle ergometer. The goal is to collect letters approaching the bird at different altitudes.

From the perspective of computer science in sport, the aim was to generate an algorithm that approaches and maintains a defined target HR effectively and efficiently in individuals with different properties (e.g., age, sex, performance and health level) within the game.

For an initial application and testing of this algorithm, a two-part test series was performed with 4 participants. The results are promising: The intended HR could be evoked in all participants. Yet further tests need to be done to improve the adaptations.

1 Introduction

The current socio-demographic situation in many countries is characterized by a high prevalence of physical inactivity as one major risk factor for mortality [1], [11]. Therefore, many professional organizations and governmental agencies call for more physical activity (PA), particularly aerobic training. Nevertheless, the recommendations of these organizations to increase the number of burned calories per week are very challenging and hard to fulfill. Hence, motivational issues are a serious barrier to increasing PA.

Serious Games offer a possible option to solve this problem because these games claim to exploit the engaging and motivating effects of computer games to reach serious goals. Concerning the increase of PA level, "Games for Health" or "Exergames" requiring whole-body movements to control the game have been focused by numerous research projects. These studies show that Exergames have the potential to enhance physical fitness, at least at low levels [6], [12]. To improve health and fitness

S. Göbel and J. Wiemeyer (Eds.): GameDays 2014, LNCS 8395, pp. 129–140, 2014.

in a sustained manner, these games need to be designed in a way to ensure that players will be effectively engaged rather than quitting the game because of excessive demand or boredom.

The key problem in physical training is that identical workload (stress, i.e., defined external influences such as power, speed, etc.) can lead to different individual reactions in different organisms (strain). Therefore, the individual control of workload (stress) and strain is the key to an optimal adaptation of the organism during the physical training process.

To neither underchallenge nor overstrain the particular participant, an individual training control is important for an optimal adaptation and therefore essential for the success of the specific training.

The goal is to establish and immediately control individual workload by means of an adaptive algorithm using the example of a game-based endurance training. Hardy et al [3] developed a model addressing the relevant aspects for the development of such an Exergame (see Fig. 1). The model distinguishes between static and adaptive aspects of user and game system.

Based on this model, the game "LetterBird" was implemented. The approach of this study aims at improving the training module, embedded in the adaptive part of the system as highlighted in Fig. 1.

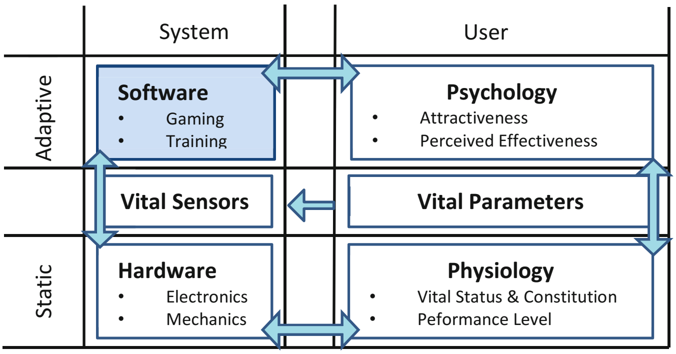

Fig. 1. Refined Model of the relevant aspects for the development of Exergames [3] (see text for details)

2 Development of the Algorithm

Various requirements from sport science need to be considered to develop an effective and efficient algorithm for the individualized and adaptive control of workload in endurance training.

When exercising, several physiological processes in the human organism are activated, ranging from the brain to the muscles. Therefore, numerous indicators can be used to measure physical workload. Among these, the heart rate (HR) is an often-used valid indicator of individual physiological workload that is easy to measure as compared to other possible indicators that can be applied to controlling a training process like oxygen uptake, hormones or lactate [2]. Different studies (e.g. [10]) show that in the range of submaximal workloads the increase of HR is linearly related to workload (i.e., exercise intensity). So, under certain conditions, the cardiopulmonary strain of the participant can be specifically controlled and an overload can be prevented by the use of submaximal HR.

Concerning appropriate training equipment, the usage of a cycle ergometer has advantages for cardio training. The weight of the participant is supported during the training process and a defined movement constrained by the limited (bio)mechanical degrees of freedom is performed. Therefore, the risk of injuries is reduced and a good comparability of the data is guaranteed [2]. To apply a cycle ergometer as training device in Serious Games, two purposes are required: control of training load and control of the game. In the game "LetterBird", power (P) in W can be adjusted specifically and accurately, e.g., by varying resistance, and was therefore chosen as load parameter. Pedal rate (PR) was chosen for game control.

To ensure accurate control of workload by P, PR should be kept within a range that does not substantially influence workload. In this regard, Löllgen et al. [5] were able to demonstrate that at submaximal workloads (70% VO_2 max) the PR on a cycle ergometer ranging from 40 revolutions per minute (rpm) to 80 rpm has only a small and non-significant effect on the HR. However, HR rises considerably at higher PRs (100 rpm). At maximal workload (100% VO_2 max) PR has no effect at all. Because the HR is the parameter to be influenced, the game settings need to be adjusted accordingly to ensure that PR is well below 100 rpm.

A major problem with the control of training load via HR is that HR normally shows a delayed response to the onset of training bouts as well as to the change of training load [7], [9].

Based on this evidence and original HR data provided by the Klinikum Darmstadt, an algorithm was developed controlling P of the cycle ergometer relative to the monitored HR of the participant.

The algorithm consists of two parts:

In the first part, the target load evoking the required target HR is calculated using the measured data of the individual HR response at two defined load levels. Therefore, the target HR scope is set submaximal, ranging from 70 to 80 % of the maximal heart rate (HRmax; implemented in the game as target HR scope = 75%HRmax ±10 bpm). In the game, the target HR is calculated as 75%HFmax. The HRmax is calculated using the equation

$$HRmax=220 - age \text{ [8].}$$

The second part of the algorithm sets P of the ergometer according to the calculated target load and, after a defined phase of adaptation, controls P depending on the actual HR of the participant. Provided that the target HR is reached or at least approached and due to the delayed response of the HR, control is set to adapt in steps of ±10 W every 30 s, if the HR leaves, i.e., exceeds or falls below, the target range. On the one hand, this procedure prevents an oscillation of the HR caused by the slow adaptation; on the other hand it avoids overloading the participant.

3 Method

In this two-phase pilot study participants performed a 4 min calibration phase to measure and calculate data required for the exercise phase. The goal of this study was to test the performance of the adaptation algorithm.

3.1 Participants

A convenience sample of four adults (2 men, 2 women, age: range = 26 – 56 yr., *M* = 41 yr., *SD* = 13.58, body weight: *M* = 73 kg, *SD* = 14.04) participated in this study. All participants reported to be healthy and to work out regularly at a non-competitive level. Demographical and anthropometric data is illustrated in Table 1.

Table 1. Demographic and anthropometric description of the participants

	Participant 1	***Participant 2***	***Participant 3***	***Participant 4***
Sex	male	female	male	female
Age [yr.]	53	29	56	26
Weight [kg]	80	70	90	52
Height [cm]	182	175	180	161
BMI	24.2	22.9	27.8	21.6
Smoker	no	no	yes	yes
Target HR[1] [bpm]	125	143	123	146

[1] Formula: *target HR = 0.75 * (220 – age)*

3.2 Apparatus

All tests were performed on a cycle ergometer with a flywheel (Daum Ergometer 8008 TRS). Height and distance of the saddle were adjusted to the participant and kept constant throughout the study. The HR was monitored by a chest belt (POLAR, T31) and processed by the ergometer during the whole testing.

After starting the game "LetterBird" the HR data of the participant was logged and saved together with a corresponding timestamp, as well as P in W (measured by the ergometer) and PR (measured at the flywheel of the ergometer).

The ergometer settings only allow a differentiation in steps of 5 W, so the ergometer automatically rounds up or down. The ergometer is directly connected to a computer, where the software controlling the game "LetterBird" runs.

The goal of the game "LetterBird" is to collect randomly occurring letters with an animated pigeon. The approaching letters are differentiated into two types:

- Type 1: slow, score: 100 points
- Type 2: fast, score: 500 points

The altitude of the pigeon is controlled by the PR. With increasing PR the pigeon rises and if the PR is decreased, the pigeon sinks down. The PR range controlling the game is set to a range from 70 to 90 rpm. A higher or lower PR does not influence the game play: Below 70 rpm the pigeon stays at the bottom, beyond 90 rpm the pigeon flies at the top of the screen.

3.3 Procedure

The study was divided in two phases: calibration and exercise phase. Four participants passed a first tests series, whereas one participant was tested twice, i.e., repeated the calibration and exercise phase procedure after correction of the algorithm.

Calibration Phase

After a short explanation about the game principle, the participants performed a 4 min calibration phase playing the game "LetterBird" at two successive load levels for 2 min each. The two load levels were adjusted depending on the BMI classification of the participant (normal weight vs. overweight):

- Normal weight (BMI ≦25):

– Load Level 1: 1 W/kg bodyweight (BW)
– Load Level 2: 2 W/kg BW

- Overweight (BMI>25):
  - Load Level 1: 0.5 W/kg BW
  - Load Level 2: 1 W/kg BW

While the measured data was analyzed and the required data calculated, the participant stopped exercising allowing the individual HR to return to pre-exercise levels.

Exercise Phase

In the exercise phase the participants again played the "Pigeon game" on the cycle ergometer at four different load levels. The first two load levels matched the load levels in the calibration phase; participants 1 and 2 played for 2 min per load level and participants 3 and 4 played for a shortened time (1 min) per load level

All four participants performed at the third load level for one minute. At this load level, the calculated target load was set at the ergometer. The fourth and last load level represented the automatic load control, in which the ergometer controls and varies the load automatically according to the HR of the participant. The test was stopped after either 10 min or at a stable steady state at the target HR. The procedure is illustrated in Table 2.

3.4 Data Processing

First, sex, age, weight, height, sports and smoking behavior were recorded. BMI was calculated using the formula

$$BMI = weight\ [kg]\ /\ height^2\ [m])$$

to classify the participants into normal weight and overweight.

Table 2. Illustrated procedure of the exercise phase after onset of the exercise

	Timing procedure for participants 1 and 2 [min:sec]	Timing procedure for participants 3 and 4 [min:sec]
Load Level 1	0:00 – 1:59	0:00 – 0:59
Load Level 2	2:00 – 3:59	1:00 – 1:59
Calculated target load	4:00 – 4:59	2:00 – 2:59
Automatic load control	5:00 – 10:00	3:00 – 10:00

The target HR was calculated using formula target *HR = 75% (220-age)* (see Table 1).

Mean values (*M*) and standard deviation (*SD*) for HR over the last 60 s for every load level were calculated after the calibration phase. This data was used as HR for the corresponding load level. The target load evoking the target HR was calculated using the formula:

$$target\ load = BW * (load\_level\ 2 + \frac{target\ HR - (meanHR\ load\_level\ 2)}{(meanHR\ load\_level\ 2) - (meanHR\ load\_level\ 1)})$$

M and *SD* for PR were calculated for the whole testing period for all data >0.

4 Results

The algorithm performed satisfactorily in the first two participants, whereas the target HR of the other two participants was reached after a transient increase beyond the tolerance. As an example, the data of one participant of each group (participants 2 and 4) is illustrated.

4.1 First Test Series ($N = 4$)

In the first two participants the target HR was reached as expected at the third load level of the exercise phase (target load) and remained in a region of stable steady state. For participant 1, the target load level even matched load level 2, so the target HR was already reached in the calibration phase.

As expected, the HR showed an initial steep increase after the onset of exercise, followed by a leveling off in the course of the load level during the calibration phase. For participant 2 (see Fig. 2), average values of the HR in the last 60 s of each load level were 118 bpm for load level 1 (70 W) and 135 bpm for load level 2 (140 W). The target load was 2.31 W/kg BW (≙165 W) expecting to evoke the target HR of 143 bpm.

The mean PR for all valid data (values >0) was 80.69 rpm (*SD*=6.37).

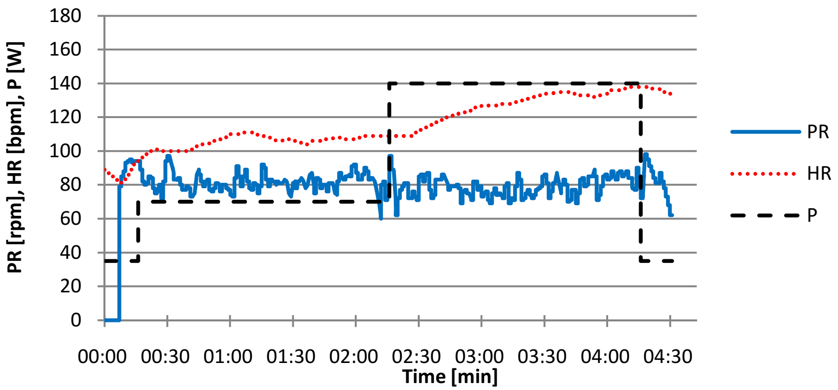

Fig. 2. Calibration phase of participant 2

The first minutes of the exercise phase replicated the calibration phase with a less fluctuating increase of the HR (see Fig. 3). Target HR was reached approximately 30 s after starting the target load level. Mean HR of the last minutes was 138 bpm (*SD*=1.098), i.e., slightly beneath the target HR (mean deviation from target HR: -4.87 bpm), but still in the intended training range (72%HFmax). An approach of the target HR "from beneath" was still realized and an overload was prevented.

In the exercise phase mean PR was 80.83 rpm (*SD*=5.99) for valid data (values >0).

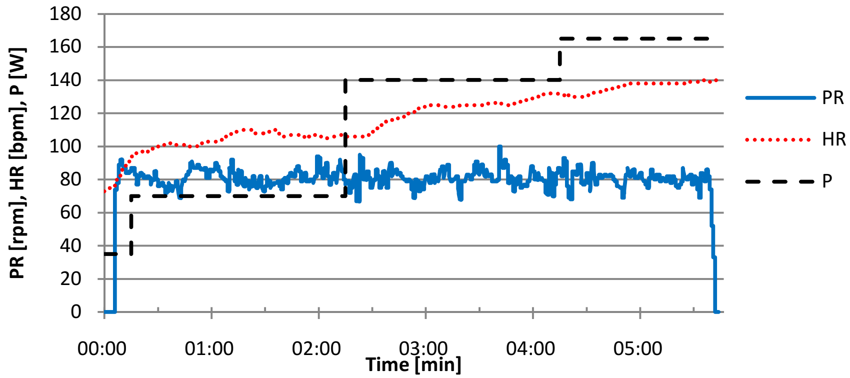

Fig. 3. Exercise phase of participant 2

In contrast, the analysis of the HR dynamics of participants 3 und 4 showed a different picture.

For participant 4, a continuous rise of the HR with no clear steady state of HR dynamics was found in the calibration phase (see Fig. 4).

Nevertheless, average values of the last 60 s for each load level were calculated (load level 1: *M* = 118 bpm; load level 2: *M* = 152 bpm). This resulted in a target load of 1.81/kg BW (≙94.12 W). A higher PR range than required to control the game (*M* = 79.35 rpm, *SD* =9.22) was identified already in the calibration phase,.

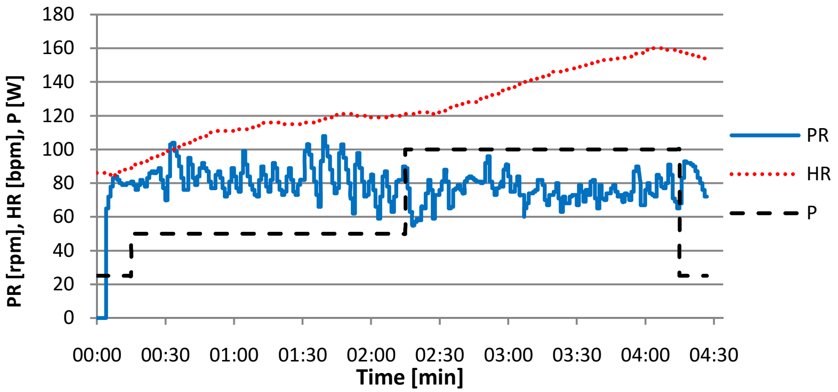

Fig. 4. Calibration phase of participant 4

A comparison of HR values in the exercise phase revealed considerable differences between participants 2 and 4. First, the HR recording in participant 4 was interrupted for 5 s (from 2:14 to 2:19) due to technical problems. Nevertheless, PR and P were still logged and due to the constant rise of the HR at this point the missing data could be interpolated.

Additionally, caused by the shortened duration of load level 1 and 2 causing a shortened adaptation time for the HR, the HR response was overshooting (Maximum HR = 161 bpm, corresponding to 82.99% HRmax). A downward adjustment of two steps (in total 20 W) was necessary to reach the target HR of 146 bpm (see Fig. 5)

In participant 4, the exception occurred that the calculated target load was beneath load level 2. Consequently, an approach of the target HR from beneath was rendered impossible.

However, average HR after the target load level (2 min after onset until the end of exercise) (M = 155 bpm, SD = 3.67 bpm) was within the intended training range (79.74% HRmax).

Mean PR in the exercise phase (for data >0) was 79. 51 rpm (SD = 8.86).

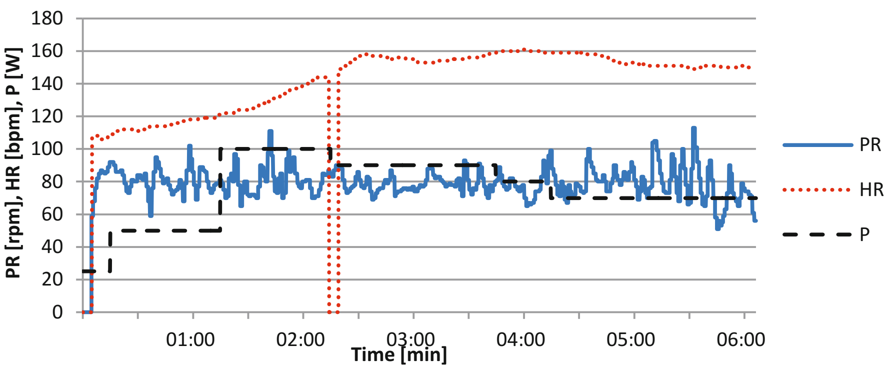

Fig. 5. Exercise Phase of participant 4. Note a short period of interrupted recording of HR in the exercise phase.

4.2 Adjustments

Before further testing, the following adjustments were made to improve the approach towards the target HR:

- If the calculated target load is lower than load at load level 2 of the calibration phase, this calculated target load is substituted as load at load level 2 in the exercise phase.
- A shortening of the load level duration turned out not to be suitable for the HR adaptation and is therefore set to two minutes. A slow and continuous adaptation to the workload is preferred.
- To minimize the risk of an excessive HR caused by a high PR level, the calculated load in the target load level is subtracted by 10%. Possible efficiency issues, i.e., longer time to reach the target HR, are accepted in favor of the HR approach from beneath.
- The calculation of the average HR in load level 1 and 2 is reduced to the last 30 s of each load level, so the HR has enough time to adapt to the current workload.

4.3 Second Test Series (Case Study)

Participant 4 was tested again to validate the adjustments of the algorithm and to test the efficiency.

The calibration phase matched the calibration phase in the first test (see Fig. 6). Maximum HR was lower (148 versus 161 bpm) than the maximal HR in the first test. Average value of the HR in the load level 1 (118 versus 118 bpm) is comparable, but in load level 2 mean HR was lower than in the first test (146 versus 152 bpm). Subtracting 10% of the calculated value resulted in a target load of 1.79 W/kg BW (90 W).

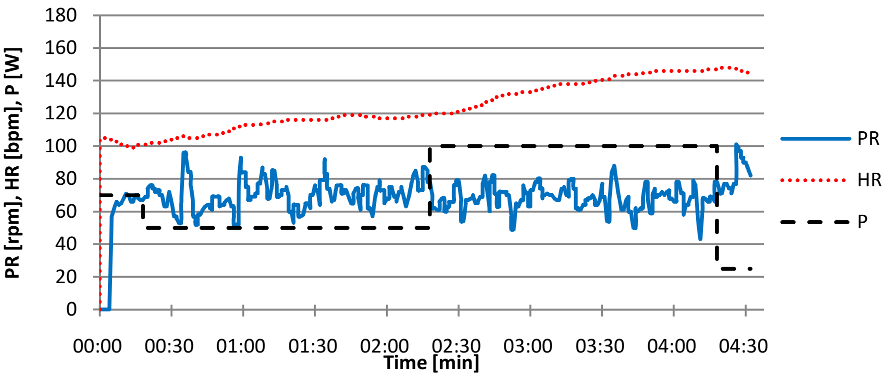

Fig. 6. Calibration phase of participant 4 (second trial)

Due to the adjustments the HR followed the expected HR dynamics during the exercise phase (see Fig. 7). A continuous rise of the HR towards the target HR was observed reaching a steady state after approximately four minutes from onset of exercise. Average HR during this steady state was 151 bpm (*SD* =1.61 bpm; range: *Minimum* =146 bpm, *Maximum* =155 bpm). The data also showed a two-step downward adjustment of P. Compared to the first test series this adaptation leads to a steady state of HR. As expected no overshooting or oscillations of the HR can be observed.

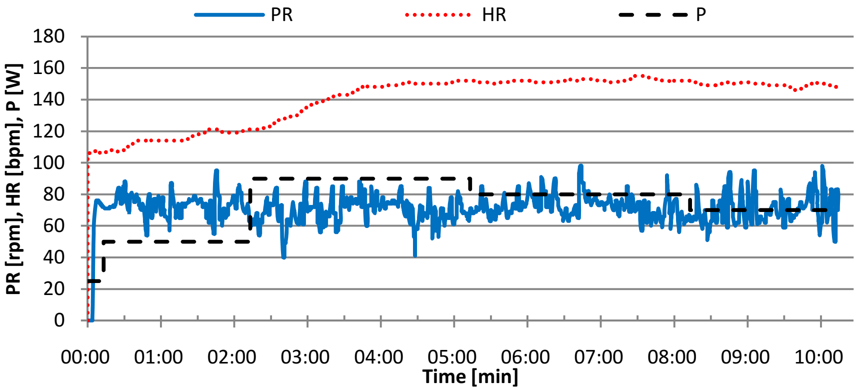

Fig. 7. Re-testing of participant 4 with the adjusted algorithm (exercise phase)

5 Discussion

The aim of this study was to develop and test an algorithm for individual adaptive control of training load from a sport scientific point of view in the context of the Serious Game "LetterBird". In the first test series, in all four participants average HR was inside the expected target HR range from the beginning of the automatic load control to the end of exercise. Nevertheless, the HR increased beyond the tolerances in two participants causing a successive downward adaptation of the algorithm for more than one step. This demonstrates that the automatic load control algorithm reacted to the increasing HR and adapted the workload as expected; in this regard, the algorithm was working correctly. However, the aim of this research was to guide the actual HR towards the target HR from beneath; this result was not established in two participants. Apparently, the calculation of the target load was not suitable for these two participants.

Compared to participant 1 and 2, participants 3 and 4 show several differences that may have caused the different HR response pattern:

- Smoking behavior:
  Participants 3 and 4 are smokers, whereas participants 1 and 2 did not smoke.
- Target load:
  Although all participants reported to be physically active, the target load of participant 1 and 2 was considerably higher than in participant 3 and 4, indicating a

lower fitness level (participant 1: 180 W, participant 2: 165 W; participant 3: 95 W; participant 4: 90 W). Therefore, the influence of fitness level needs to be considered to adapt the algorithm. Particularly, personal reports on engagement in sports disciplines, average work out time per week and PA level at leisure may serve as indirect indicators of performance or fitness level.

- Shortened length of load level 1 and 2:
  Participants 1 and 2 performed load level 1 and 2 in the exercise phase for 2 minutes, respectively. In contrast, participant 3 and 4 performed for only 1 minute at each load level.

In the adjusted version, technical sources of error leading to an incorrect calculation of the target load were corrected. Using this adapted formula calculating the target load appears to be a reasonable approach preventing an overshooting HR. The target HR was evoked efficiently and effectively in the presented trial.

6 Conclusion

The results of the reported tests are promising. The data indicate that the developed algorithm, especially the adjusted version, is a reasonable approach to ensure an individual adaptive control of training load in the game “LetterBird”. Of course, the small sample is not representative, so further tests including different age, BMI, cycling experience and performance level (e.g., athletes versus non-athletes) are needed to prove the effectiveness and efficiency of the algorithm.

A problem not yet solved is the influence of PR used to control the pigeon on the HR. Therefore, a further study is required to test the influence of these large short-term oscillations on HR dynamics.

Furthermore, the question has to be addressed, if the preferred PR of the participants has an influence on the HR. Previous studies on preferred PR confirm that the preferred PR exceeds the most efficient one [4].

In the future, the algorithm is intended to be integrated into a long-term training plan, taking into account the current physical condition to enable an optimal and individualized adaptation to training.

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