"BABEŞ-BOLYAI" UNIVERSITY
CLUJ-NAPOCA
FACULTY OF PHYSICAL EDUCATION AND SPORT
DOCTORAL SCHOOL OF PHYSICAL EDUCATION AND SPORT

DOCTORAL THESIS

- ABSTRACT -

Scientific advisor:
Prof. univ. dr. Hanțiu Iacob

Candidate:
Pătrașcu Adrian

2019

“BABEŞ-BOLYAI” UNIVERSITY
CLUJ-NAPOCA
FACULTY OF PHYSICAL EDUCATION AND SPORT
DOCTORAL SCHOOL OF PHYSICAL EDUCATION AND SPORT

Intelligent control system for heart rate during aerobic training on the treadmill

Scientific advisor:
Prof. univ. dr. Iacob Hanțiu

Candidate:
Adrian Pătrașcu

2019

Table of contents

Key-words: training, control system, heart rate, effort intensity, heart rate variability, fuzzy logic

Introduction

A way to determine the risk-factor generated by the multiple variables that appear during a physical exercise was done by using a fuzzy logic controller. Physical fitness level, basic physical information and the grade of illness were used to determine the impact of the risk generator factors on the subject (Rudas et. al., 2012). They also proposed a way to determine the risk-factor generated by the multiple variables that appear during a physical exercise was done by using a fuzzy logic controller. Physical fitness level, basic physical information and the grade of illness were used to determine the impact of the risk generator factors on the subject.

In (Jacobs, 1997), a controller with 36 if-then rules that was applied to a model that had three sets of variables was proposed by the author managed to integrate abstract knowledge from physiology with a decent level of success. Moreover, it has been proved (Rudas et al., 2012) that the human drives and motives can be integrated into a fuzzy logic controller to model the human decision-making. Even though there is a gap in the literature describing the methodology of creating such a controller, the authors proposed a 10 step method that allowed them to include abstract variables like motivation and drives.

Part I

Theoretic argumentation of the thesis

Chapter 1. Physical effort in aerobic training

1.1. Concepts

Through physical training the body is forced into a state of adaptation. The physical training is a guided process for maintaining this adaptation (Dragnea, 1996). Generally, it is considered that during training the body is under constant stress. This stress is called physical effort (Cârstea, 2000).

1.2. Effort parameters

Through the modification of the four core training parameters (volume, intensity, density and complexity), the overall physical effort level may be controlled (Bompa, 2002). The physical intensity of a training may be defined as a ratio between the overall work and the time spent in that activity (Feher, 2017).

At the same heart rate, two subjects may have different intensity levels during the same type of training (Bompa, 2002).

1.3. Training individualization

A successful training is tied to the ability to mold the training plan according to the subject's individual characteristics. Abilitatea de a modela conținutul unui antrenament pentru caracteristicile subiectului poate reprezenta cheia succesului pregătirii. Atenta urmărire a capacității de efort, și concomitent a intensității, poate oferi o imagine asupra eficienței conținutului folosit (Mircescu & Cojocaru, 1970).

1.4. Summary

Physical training may be considered an organised activity through which the physical fitness may be improved. The efficiency of a physical training must permanently be investigated and analysed. In this way, a constant advancement of knowledge is assured.

An increase or decrease in the intensity of a workout allows for a direct modification of the type of training one undergoes. In aerobic trainings, the heart rate is tied to the intensity of the training. A higher intensity will determine a higher value of the heart rate.

Chapter 2. Heart rate physiology

2.1. Cardiac performance

The cardiac output can be the main performance indicator in high intensity workouts, according to Stoian (2007). The fast adaptation of the body to the workout stress is mainly done through the heart rate. The quick increase of the heart rate during training determines an increase in cardiac output (Sbenghe, 2008).

2.2. Heart rate adaptation

During effort the body undergoes an adaptation that spreads over five different directions: heart size, stroke-volume, rested heart rate, cardiac output and blood pressure.

2.3. Cardiovascular response

Aerobic training intensity and the cardiac output are directly proportional. A higher intensity will trigger a higher demand for oxygen and thus an increase in cardiac output. This link between the two remains constant up until the value of 190 beats per minute of the heart rate (Fu & Levine, 2013).

2.4. Heart rate dynamic

The heart rate dynamic is the alternation between higher and lower values of the heart rate during a workout. This may be short term (during an exercise) or viewed overall for the entire training (Stoian & Petrache, 2007).

2.5. Heart rate factors

Numerous factors may influence the heart rate during a physical workout. Age, gender body temperature, illnesses or fatigue are some of these factors.

2.6. Summary

The observation of heart rate values is, in some situations, a way to identify the level of intensity of a workout. Identifying the moments when the heart rate was out of bounds, may allow for the discovery of a problematic moment in training.

Studying the heart rate dynamic during a training period may allow an increase in training efficiency, through constant interventions in the training schedule.

Chapter 3. Heart rate and aerobic running training

3.1. Heart rate monitoring during training

The heart rate during training may be used as a physiological feed-back. Monitoring the heart rate during training is a direct way of having access to the subject's feed-back in a simple and yet effective way (Stoian & Petrache, 2007).

3.2. The use of heart rate in running workouts

The heart rate may be used to analyse the efficiency of a training, usually after it is over. The impact a workout has over a subject may be indentified, to some degree, by observing the behaviour of heart rate dynamic (Stoian & Petrache, 2007). The aerobic endurance training is the main way to directly influence one's level of overall fitness, due to the fact that this type of training forces the main system responsible with sustaining long term activities to work to its limits. The cardiovascular system, as stated before, is the main supplier of oxygen to the working tissues. The real physiological link between the cardiovascular system and the respiratory system allows the integration of two most important systems in the body during an aerobic endurance training, and thus improving the overall fitness. The heart rate increases during this type of training and can rise from 70 bpm during resting to around 170 bpm. This range in heart rate is enough to exert a moderate stress on the body's systems that will eventually result in a series of physiological adaptation of the body to physical activity

3.3. Effort control during aerobic training

Monitoring the heart rate in real time during the workout allows for a quick modification of the training intensity if the heart rate exceeds the preset values. Depending on the situation, either an increase or a decrease of the intensity may be required (Suh, 2015).

3.4. Devices

Heart rate monitors are devices that allows for an easy observation of the behaviour of the heart rate. They may be used by amateurs or by professional athletes (Suh, 2015). There are various types of monitors, some very simple and others very complex. The decision of what type to use rests on the user and what his goals are (Tang & Po, 2015).

3.5. Summary

A treadmill running workout may be controlled by a precise recording and analysis of the heart rate. Setting the training schedule for a longer period of time may also be achieved through the use of heart rate. An increase or decrease in aerobic workout intensity may be implemented through the observation of the heart rate value and making a change.

The behaviour of the heart rate during a part of the training may offer a qualitative evaluation over the efficiency of the activity.

A heart rate monitor is a simple yet effective way of visualising the subject's progress. Some types of monitors offer special functions like statistical analysis or multiple recordings at the same time. Whichever monitor is used, it still serves its pupose. The use of computers for recording, storing and analysing data from a workout opens the possibility of more complex software to be developed. Complex systems that allows for a direct evaluation of the heart rate dynamic may offer an objective way of controlling the workout.

Chapter 4. Intelligent control systems

4.1. System – concept and utility

Human body, in its entirety, may be viewed as a nonlinear system. Considering all the various subsystems of the body we can state that the human body is a memory system, nonlinear, multivariable with discrete and continous components. It also has a stochastic functioning type with either open or closed loops.

4.2. Artificial intelligence

'Computing with words rather than numbers' is in fact one way of describing the fuzzy logic. This can be extrapolated to the fuzzy control ending up with the following description: 'control with sentences rather than equations'. (Meystel & Albus, 2002).

4.3. Artificial intelligence and human physical training

Mixing artificial intelligence and human physical training may seem odd due to the different goals of the two fields of study. Even so, the ability to use one set of knowledge from one field to another will allow for the expansion of the overall knowledge. The use of artificial intelligence in some parts of the workout may allow for a better and more objective way of controlling the outcome of the training.

4.4. Intelligent control systems: fuzzy logic

A controller with the ability to auto-adapt itself to the changes in the surrounding environment must have adjustable parameters and a mechanism for adjusting these parameters. (Cîrtoaje, 2013).

4.5. Control systems and human physical activity

Due to the nature of some subsystems in the human body, there is a theoretical bridge between the fields of control systems and physical training. This bridge allows for a free-flow of concepts between the two that, in the end, allows for the implementation of a control system in a running workout.

4.6. Summary

The concept of system may be found in various scientific fields. It may be used to represent a number of different phenomena with many forms of manifestation. Nevertheless, no matter what the definition of the system is or its use, there will always be a bridge between these scientific fields.

The human body may be viewed as a sum of different subsystems, each of these may then be analysed and interpreted through the concepts from control systems. Using special devices to interact with the human body in an objective, measurable way, allows for complex systems to be build for a specific subsystem of the human body.

Using artificial intelligence to model the human logic makes it possible to implement the reasoning behind the control of the heart rate duing a running workout. By succesfuly implementing a control system for the heart rate, both fields gain new knowledge.

The control strategy used for operator controlled systems has a more natural feel if the *if-then* clauses would be written in sentences. If this kind of system is developed so that it would sustain itself without the human intervention it becomes an adaptive system. Considering the fact that in everyday life to adapt means to make a change ones state to cope with new changing situations. Following this definition of adaptation, an adaptive fuzzy control system is a system that can intuitively modify its state to match the eventual changes that may appear.

There is a striking resemblance between the architecture of some motor functions and the logic schemes in control systems. This is another argument why the implementation of a control system may be done successfully in the field of physical training.

Part II

Pilot research regarding the building, tuning and validating the components of the intelligent system for heart rate dynamic control

Chapter 5. Desinging, building and verifying the control system

5.1. Introduction

Several studies regarding the analysis and modelling of HR had been carried out so far, some of which included the development of controllers for regulating HR. Brodan et al. (1970) and Hajek et al. (1980) modelled the HR response during exercise and recovery situations. The models contain a feed-forward and feed-back components and are trustworthy for exercises that require short time. The models are not sufficient for a long term perspective. A non-switching non-linear antiwindup integral control for the long duration heart rate response to treadmill exercise was developed by Scalzi et al. (2012).

Su et al. (2007) have identified a first order model for the behavior of heart rate during training. Cheng et al. (2008) was able to develop a nonlinear model for heart rate dynamic. In order to account for the nonlinearities in the real world process, a further approximation has been performed in this paper, in which each parameter of the first order approximation has been modelled as a function of treadmill velocity, based on the experimental results presented by Weng et al. (2010).

Measurement of HRV for use in monitoring training and recovery involves analysis of the beat-to-beat variation. By accurately measuring the time interval between heartbeats, the detected variation can be used to measure the psychological and physiological stress and fatigue on the body during training. Generally speaking the more relaxed and unloaded (free from fatigue) the body is the more variable the time between heartbeats.

Fuzzy logic controllers are the ideal way of achieving the real time control of a subject's heart rate due to the fact that they are able to incorporate vague, abstract values. These vague values have their origin in the fuzzy quantification of certain variables found in the methodology of aerobic training. The ability of fuzzy controllers to incorporate the non-crisp values found in sport training, allows us to create a base set of rules that model the so called "classic" training methodology (Passino & Yurkovich, 1998).

5.2. The aim of the pilot research

The aim of this research was to validate the fuzzy controller for our control system, to test the tool for setting the training intensity and to discover the ideal mathematical model for the heart rate's behaviour during running on a treadmill.

5.3. Pilot research objectives

1. Testing the fuzzy controller;
2. Identifying the mathematical model for heart rate during running;
3. Designing the software for setting the workout intensity;
4. Testing the software for wotkout intensity.

5.4. Research hypotheses

For this research we formulated 3 hypotheses:

1. The fuzzy controller developed by us can be implemented in a control system for heart rate;
2. Using genetic algorithms we can determine the mathematic heart rate model;
3. The tool for setting the workout intensity can be used in practice.

5.5. Materials and methods

We've used a Polar Wearlink heart rate monitor to record all the data for this study. The treadmill used was Kettler Boston XL. The software part was designed and built in Matlab 2018.

Figure No. 16 - Kettler Boston XL running treadmill

Figure No. 17 – Polar Wearlink Bluetooth Monitor

Fuzzy controller for heart rate dynamic

The structure of the proposed system is made up of three parts: a heart rate monitor, a fuzzy controller and a treadmill. Each of these components are linked through a laptop and are able to communicate between each other through the software we've designed.

$$\dot{y}(t) = \frac{1}{p_T(u(t))}\left(u(t)p_K(u(t)) - y(t)\right)$$
$$p_K(u) = c_3u^3(t) + c_2u^2(t) + c_1u(t) + c_0$$
$$p_T(u) = b_3u^3(t) + b_2u^2(t) + b_1u(t) + b_0$$

Figure Nr. 20 – Heart rate model-system developed by us with information obtained from Su et al. (2010)

Using prerecorded data we were able to reach the model in Figure No. 20. This model started from other models but was modified and changed to suit our needs better.

After the simulation, we moved on to a real time testing of the whole system. For this we used a 32 years old male subject.

The protocol for this testing was as follows:

1. Running at heart rate of 100 bpm – 6 minutes;
2. Running at heart rate of 120 bpm – 5 minutes;
3. Running at heart rate of 140 bpm – 3 minutes;
4. Running at heart rate of 120 bpm – 3 minutes;
5. Running at heart rate of 100 bpm – 3 minutes.

To evaluate the performance of our system during the testing we've used the following mathematical coefficients:

1. Integral of absolute error (IAE) – it offers information regarding the overall error of the system;
2. Modification tendency (MT) – it shows the degrees with which our system tries to modify the speed of the treadmill;
3. Mean of absolute error (MAE) – this shows us the instantaneous error of our system and it is the main one we will focus on.

Mathematical model of heart rate during running of a treadmill

The data for identifying the mathematical model of the heart rate was obtained from two male subjects, ages of 24 and 33 years old.

The protocol for gathering the first set of data was:

1. 15 minutes warm-up;
2. 7 minutes movement at 4 km/h; 7 minutes at 6 km/h; 5 minutes at 8 km/h;
3. 5 minutes movement at 10 km/h;
4. 5 minutes running at 12 km/h;
5. 5 minutes running at 14 km/h;

6. 15 minutes gradual cooldown;
7. 10 minutes stretching.

A doua etapă a avut următorul protocol pentru efectuarea înregistrării frecvenței cardiace:

1. 15 minute organismului pentru test;
2. 5 minute deplasare la 6 km/h; 5 minute alergare la 12 km/h;
3. 10 minute revenirea graduală după efort.

The tool for setting the intensity of a workout

In order to simulate and validate the module, a Matlab implementation "Training Intensity Analyzer" has been obtained (Figure 21). Using the resulting application, for each of the input variables, the operator needs to input two values: the "Reference R-R Interval", the "R-R Interval Before Session", the "Work Heart Rate Two Sessions Ago" and the "Work Heart Rate Last Session". Pressing the "Calculate" button returns the "Recommended Training Intensity", that suggest an increase or decrease of the intensity for the next training session, and by how much.

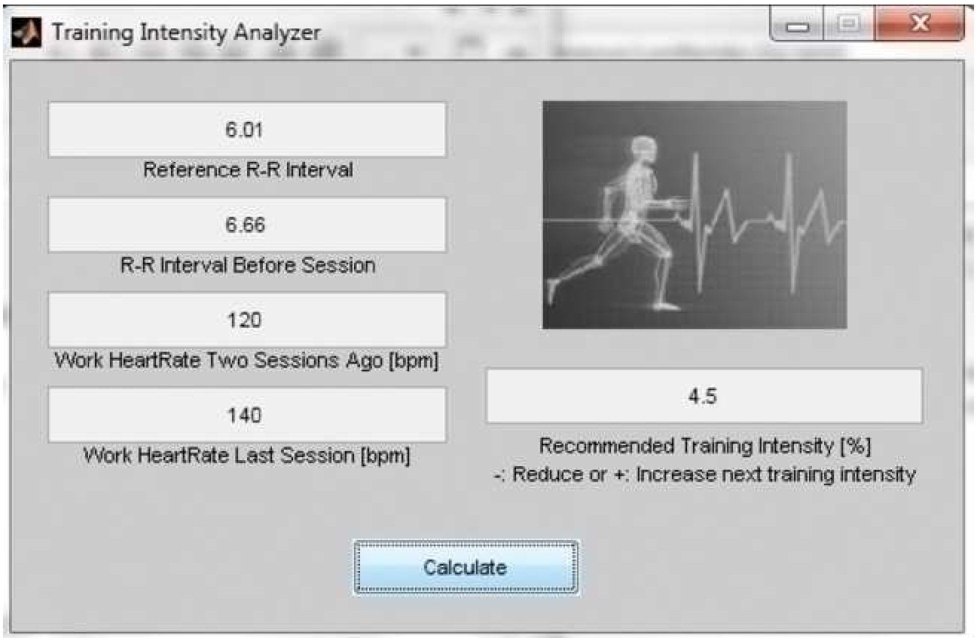


Figure No. 21 – Interface for Training intensity analyzer

For the testing and validation of the instrument we've recorded 4 subjects, all female, with the ages between 21 and 23 years old. We've recorded the subject's R-R intervals and also the heart rates during training sessions during 13 days, because we need 10 entries to determine the Reference R-R Interval and the extra 3 were used in testing and comparing the application.

5.6. Results

Validating the fuzzy controller

Both systems have yielded small deviations from the desired heart rate, and a rapid response to setpoint changes, as seen in Table No 3. Both control systems present stability for the entire duration of the simulated exercise and a steady state deviation below the 5% limit.

Tabel No. 3 - Output results of the two model-systems that were tested

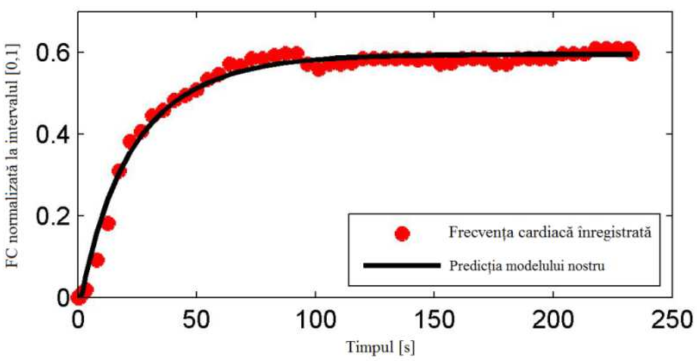
	Primul Model (nonlinear)	**Al doilea Model (variabile de ordinul întâi)**
Deviația ritmului stabil	0.4% ÷ 2.1%	0.5% ÷ 2.5%
Timpul de stabilizare la creșterea FC	40 ÷ 55 secunde	5 ÷ 7 secunde
Timpul de stabilizare la scăderea FC	28 ÷ 63 secunde	4 ÷ 9 secunde
Viteza maximală a covorului rulant	7.2 km/h	7.2 km/h
Viteza minimală a covorului rulant	2 km/h	2 km/h
Sistem stabil	da	da

Determining the mathematical heart rate model

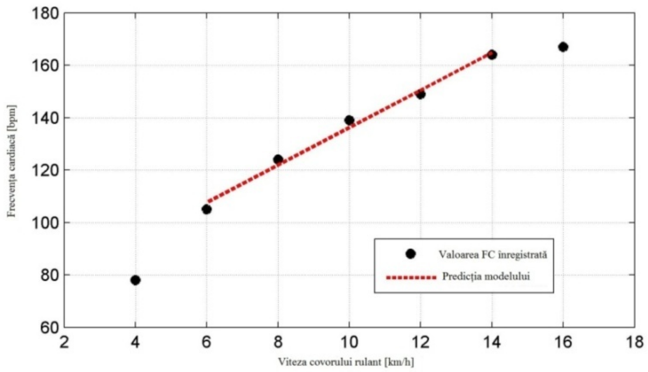
$$H(s) = K \cdot \frac{(T_1 s + 1)}{(T_2 s + 1)(T_3 s + 1)}$$

Figure No. 23 – Heart rate model developed by us

After the analysis of the mathematical model we were able to determine that it was ideal for our situation.



Graphic No. 11 – Prediction of the heart rate model and the data recorded by us



Graphic No. 12 – Prediction of our model using prerecorded data

Validating the tool for setting the workout intensity

Tabel No. 6 – Evolution of R-R interval and reference of R-R interval

	A	B	C	D
Referința înaintea zilei 11	6.01	5.19	5.87	5.14
Intervalul R-R ziua 11	6.44	5.21	6.12	5.14
Referința înaintea zilei 12	6.03	5.17	5.88	5.13
Intervalul R-R ziua 12	6.39	5.30	5.40	5.31
Referința înaintea zilei 13	6.05	5.17	5.75	5.14
Intervalul R-R ziua 13	6.50	5.19	5.80	5.27

As can be seen in Table No. 6, subjects A and B had a gradual increase in their work heart rate with low and few decreases, while the other two subjects had many relatively high variations. The need to objectively control the variation of the work heart rate during a long training schedule that span over many months is fundamental in maintaining the fatigue level in check.

This situation can also be observed in Table No. 7, that displays the value of the reference and R-R interval for all the subjects. Here it can be observed that by using our application the level of fatigue for the two subjects is kept in check and at a lower individual value, allowing for a more efficient training. There is a need for an objective tool that can reliably offer an interpretation of the heart rate variability. Due to the fact that using our application we were able to control the fatigue levels through constant adjustment by a certain percentage of the work load, we may have found an easy to use tool for both professional athletes or amateurs.

Tabel No. 7- Work heart rate for each of the subjects

	A	B	C	D
Ziua 11	120	120	130	122
Ziua 12	132	124	141	123
Ziua 13	150	136	129	139
Ziua 14	145	140	134	145

5.7. Discussions

The intensity of the running effort is projected into the heart rate value in classical training design. The heart rate at any point in the training is the current intensity of the effort. There is a difficulty in defining, in practice, the following elements: reference heart rate and treadmill speed. Reference heart rate is the value at which one exercise is desired to be done. This is actually the heart rate into our program. Setting the reference heart rate is the way the program understands at what level of intensity a training should be performed.

The concept of treadmill speed is somewhat difficult to define. It is neither work intensity nor current intensity. These two notions are already defined using heart rate. The treadmill speed, and consequently the running speed of the subject, is the element generating the intensity, but it is not the intensity itself. Its fluctuation generates a change in heart rate. Thus, we felt the need to introduce the concept of „magnitude of the effort". Fuzzy logic controllers are the ideal way of achieving the real time control of a subject's heart rate due to the fact that they are able to incorporate vague, abstract values. These vague values have their origin in the fuzzy quantification of certain variables found in the methodology of aerobic training. The ability of fuzzy controllers to incorporate the non-crisp values found in sport training, allows us to create a base set of rules that model the so called "classic" training methodology.

The magnitude of the effort is the level of subject's energy consumption when doing physical activity, in our case of rolling on the carpet. The high energy consumption corresponds to an increased magnitude, quantified in the numerical value of the treadmill speed. Therefore, magnitude modification allows for increased intensity to be generated by the amplitude of energy consumption. It should be noted that, in the context of this definition, different values of different magnitude may be present for identical subjects at identical intensity values. The interface of the heart rate dynamics management system is shown in Figure no. 26. It is able to graphically display the heart rate during training, as well as the numerical values for the main variables: heart rate, the reference HR, current speed of the treadmill and the previous one, and the increment of the velocity.

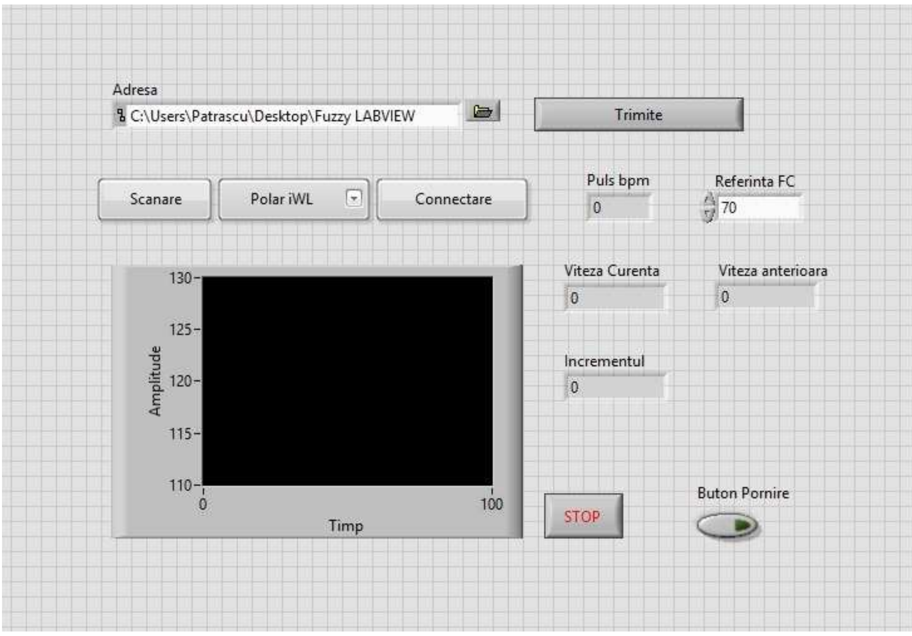
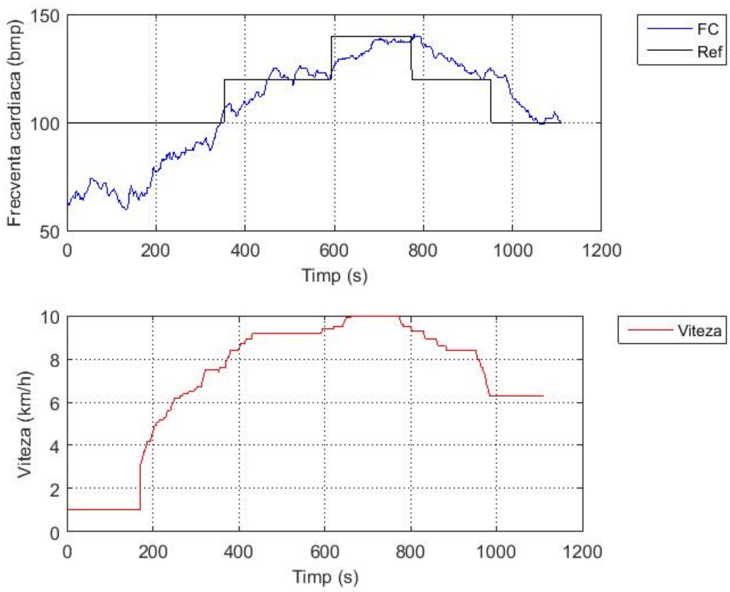


Figure Nr. 26 – Heart rate control system interface

The Graphic No. 13 shows the evolution of heart rate and velocity during the preliminary test of the system. The poor way the system controls the heart rate dynamics during the start-up phase of the training is also found in this graph. The speed of the carpet accompanies the increase or decrease of HR throughout the registration. The maximum speed reached by the subject was 10 km / h from the 140 bpm intensity part. A permanent fluctuation can be identified throughout the recording in the context of this preliminary test of the system. This instability is not a negative aspect. It has shown weaknesses of the system that need to be adjusted to mitigate this variation.



Graphic No. 13 – Heart rate (HR), Reference (Ref) și Speed recording during pilot test

5.8. Conclusions

1. The first study of this research focused on identifying the optimal solution for a non-linear cardiac waveform management system during running on treadmills. The results of the analysis have shown that our designed controller has maintained its performance within the ideal limits, thus giving us the confidence that we will be able to use it to control a workout under normal conditions;

2. Using the genetic algorithms method of analysis has provided us with a way of identifying and calculating a viable mathematical model of cardiac frequency behavior during treadmill running;

3. Our application for determining exercise intensity uses information from the literature on the use of heart rate variability. This tool allows a gradual increase or decrease of intensity over a long period of preparation. Integrating past training information allows for better adjustment of the intensity change rate for the next workout. The result of this study has paved the way for implementing this software in an application on smart mobile devices;

4. The way the system adapts to the running process offers a dynamic solution for a non-linear problem. By integrating physiological elements and aerobic training concepts, the system allows an internal adaptation to the way the subject reacts. The control of the heart rate takes into account the non-linear model of human physiological reaction during the training;

5. An intelligent system was constructed that allows the integration of human rationalization from a methodological point of view in heart rate control;

6. We proposed the introduction of a new concept for aerobic running training on the treadmill - the magnitude of the effort;

7. The construction and implementation of the system covers a scientific field that remains relatively unfamiliar: controlling the heart rate dynamics using the fuzzy controller in real time and during running.

Part III

Personal research regarding the implementation of a heart rate dynamic control system during running on a treamill

Chapter 6. I[st] Study. Heart rate dynamic control system during running on a treadmill: functionality testing

6.1. Introduction

A high theoretical value is attained through the idea of applying an intelligent driving system for the control of physical exercise. At the same time, due to the complexity of trying to use an artificial intelligence application (programming using fuzzy logic), in a field that is operating in an ocean of variable factors, we can predict that the possibility of publishing results will be optimal, so the importance and contributions to the field will be high.

The practical value of this study consists of: the chosen solution, the results and the innovation offered to the field. Innovation is the one that takes precedence over the practical value of the topic, as it attempts to eliminate the human decision-making factor in the management process. In this way an objective way of controlling the effort during training can be achieved. Moreover, this will increase the efficiency of the used exercise.

6.2. Aim

The purpose of our research regains its necessity from the proposed hypothesis. This is reflected in demonstrating that automated driving systems can be used to control heart rate dynamic during aerobic training on a treadmill. In order to be able to demonstrate this, two aspects of research must be addressed:

1. system robustness;
2. reliability from the point of view of effort physiology.

6.3. Objectives

In order to be able to accomplish the above-mentioned goals and, at the same time, test the hypothesis, we have proposed a series of objectives to be fulfilled:

1. recording heart rate during an aerobic exercise using the system;
2. calculating the system error indicator;
3. calculating system performance;
4. identifying differences between subject categories;
5. identifying system adaptability.

6.4. Materials and methods

The devices and protocols used in this study were those described and tested in the preliminary investigation.

Subjects

A total of 13 subjects participated in this study. Of these, 7 were female and 6 male. The age range ranged from 20 to 37 years.

Subjects were elected to meet three criteria:

1. age criterion - under and over 30 years of age;
2. physical training criterion - trained and non-enrolled;
3. gender criterion - men and women.

6.5. Results

During the training session three main variables were recorded: the heart rate, the reference to which he intended to run and the speed of the treadmill. These recordings were performed in real time with the system running, with a rate of about 0.3 seconds. After the recording of the variables, their values were used to calculate the following mathematical indices: MT, IAE and MAE.

Tabel No. 8 – Average values of the calculated coefficients

Trepte	Indici		
	MT (bpm/s)	MAE (bpm)	IAE
Global	5.51±1.04	7.98±1.5	16529.62±3145.24
T100	8.07±4.4	9.15±4.6	1451.77±793.37
T110	4.48±3.15	5.85±3.7	1074.23±756.29
T120	3.19±1.15	4.04±1.39	573.38±207.86
T130	2.27±0.4	2.92±0.5	1362.31±245.27
T140	2.42±0.65	3.19±0.83	1449.54±391.30
T150	2.75±1.59	4.47±2.37	1652.54±955.23
Revenire	15.13±4.85	29.10±8.65	9077.31±2914.96

The final results show that the system has a 7.98 bpm error for controlling heart rate steps throughout the aerobic exercise. At the beginning of the training (T100, T110 and T120) the system error is 9.15 bpm, 5.85 bpm and 4.04 bpm. The content of the training, that is for the 130, 140 and 150 bpm stages, the system error is 2.92 bpm, 4.19 bpm and 4.47 bpm. The last part of the training, the return, is a 29.10 bpm error.

Regarding system robustness and efficiency, the MT calculated over the duration of training provides a heart rate trend of 5.51 bpm / s for a 50-minute workout. All stages of the training have a MT index between 2.27 and 8.07. The last part of the training has a heart rate trend of 15.13 bpm / s.

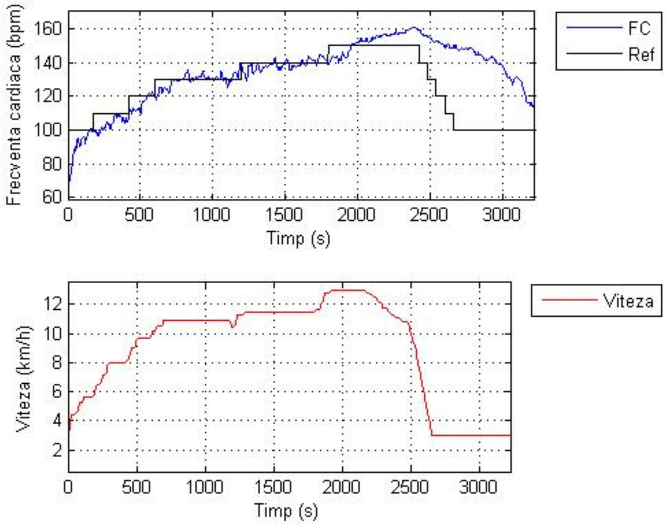
6.6. Discussions

Interpretation of indices

The first index to be discussed is MAE - Global. This is the system error for the entire workout. The 7.98 bpm value indicates that during a training with 7 different stages of intensity, the system can control heart rate throughout the training session with an accuracy of 7.98 bpm. This value is within 10 bpm of the effort dynamics control system during a training session. From the point of view of how the system was built, the minimum allowable treadmill should be 10 bpm. So the system proved to be precise in the control of the training steps, offering the possibility of a minimum difference between steps of 7.98 bpm.

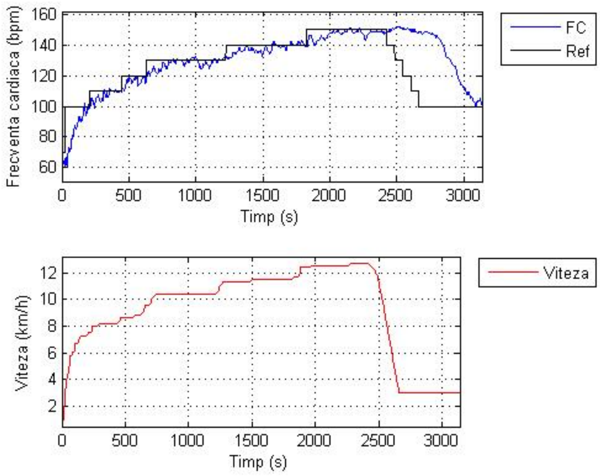
The system error drops below the 6 bpm limit, when the subject begins to run or move at a speed higher.

Graphic analysis



Graphic No. 28 – HR and speed values recorded during a training of a female subject over 30 years old – ideal reaction

Graphic No. 28 shows an ideal reaction of the system. The control of the treadmill dynamics is visible through the treadmill speed. The control of the heart rate dynamics is reflected in keeping of the heart rate values close to the reference line. The lack of disruptive elements allows a clear observation of how the system maintains the control of heart rate dynamics by changing the treadmill speed to bring the heart rate to the desired value.



Graphic No. 29 – HR and speed values recorded during a training of a male subject over 30 years old – ideal reaction

Graphic No. 29 displays how the system controlled a training session for a male subject over 30 years of age. In this case, the lack of disturbing factors allows visualization of an optimal reaction of the system.

Due to the specificity of the system, for example the ability to wait for a reaction of the body after any change in speed, a finer control of the heart rate dynamics is allowed. The flexibility of setting the speed of the carpet allows for the off-line setting of the workload to be dropped because, at a certain value, the magnitude of the effort can be changed to maintain the desired level.

6.8. Conclussions

The analysis of the data gathered following the study, revealed a series of conclusions that delimit the functionality of the system in a normal workout. The study confirmed our expectations and the study hypothesis. The research has highlighted a number of aspects regarding the adaptability of the system under unexpected training conditions. The following can be concluded from the study:

1. The average system heart rate control throughout the workout regardless of the number of intensity stages is 7.98 bpm. The system is able to control the heart rate dynamics for steps with a minimum difference of 7.89 bpm. System accuracy is below 10 bpm between different stages of training according to the limit originally projected;

2. The system can control the heart rate with respect to the training content part with an accuracy of 2 to 5 bpm for heart rate values between 120 and 150 bpm. The starting part of the training, which does not always consist of running, has an average error of 9 bpm;

3. The system can adapt to factors other than those strictly related to the physiological aspect: the treadmill or movement technique;

4. The system is adaptive in terms of some irregularities of the respiratory system during training;

5. The flexibility of setting the treadmill speed allows for an off-line setting of the working intensity. The magnitude of the effort can be changed to maintain the desired level of the heart rate;

6. The system has the ability to adapt to individual variations of the heart rate by altering both the magnitude of the direct effort and the subsequent increase corresponding to the needs of the situation;

7. Breath rate is another factor that the system can compensate for;

8. The system can control a differentiated training start for trained and non-trained subjects. The system fulfills its purpose for this step: introducing the subject into effort and controlling heart rate by bringing it to the desired level.

Chapter 7. IInd Study. Training intensity during running on a treadmill software: MOTION-AE

7.1. Introduction

MOTION-AE (Figure No. 27) was designed with the intention of being able to determine the intensity of the training in an off-line way. It combines several advantages of stand-alone devices with the benefits of smartphones, but it is not a hybrid solution. The application data can be recorded with any carrier system, so the data used to determine the level of the next training is correct. The decision-making application is independent of the portable system, meaning that users can record training data and then enter them into the application. The portable device must not be connected to the smartphone and users can leave their smartphone at home during training.

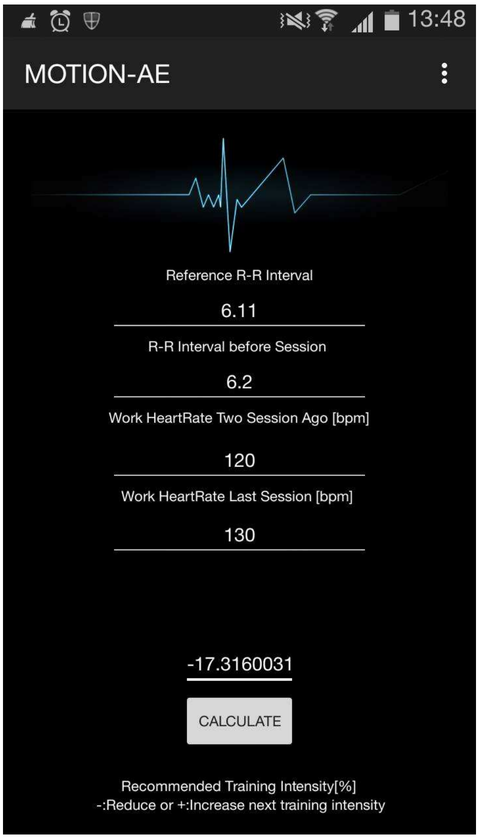


Figure Nr. 27 – MONTION-AE interface

The interface through which the user can use the Motion-AE application is illustrated in Figure no. 27. Through this, the user can enter the values for the R-R reference from the previous day and for the current day. Additionally, the heart rate values with which the last two exercises were performed will be entered. Using this data, the application calculates the percentage by which the workout intensity of the next training should be changed. Positive values of the proposal are percentage increases, and negative values indicate the need for decreasing intensity.

This interface is similar in structure to that presented in preliminary research, but with a different form determined by the device for which it was created.

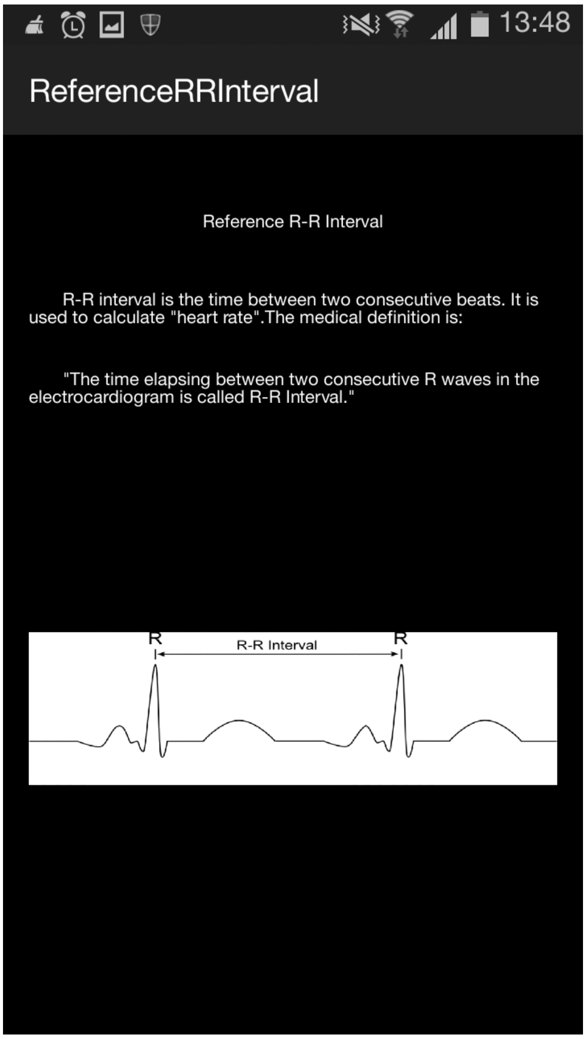


Figure Nr. 28 – MOTION-AE window with information regarding the R-R Interval

R-R interval information is provided to the user in a window in the application menu (Figure No. 28). In Figure No. 29 there is presented another window explaining the meaning of cardiac frequency and a series of information related to its use.

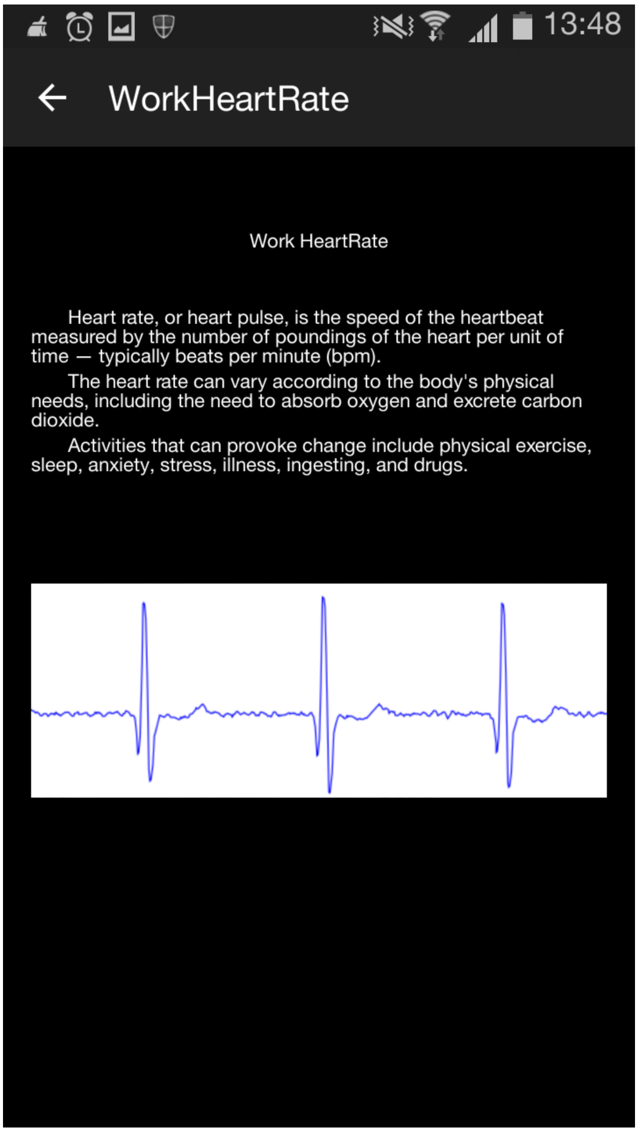


Figure Nr. 29 – MOTION-AE window that explains the work heart rate concept

7.2. Aim of the research

The purpose of this research is to demonstrate that Android-powered mobile device complies with the optimal operating limits demonstrated in preliminary research. Demonstrating the possibility of translating the software developed in the preliminary research into an application for a smart device has been a second goal of this study for us.

7.3. Research objective

Using the MOTION-AE application presented in this paper, we wanted to demonstrate that it can control the intensity to the same extent as the software from the preliminary research.

7.4. Materials and methods

This application is based on the structure of the software developed in the preliminary research. Due to the similarity of the two applications' framework, to demonstrate that MOTION-AE works as expected, we compared the result it provided with the result of the preliminary software.

For the analysis of Motion-AE usage situations, the recorded data of four female subjects aged 21-23 years were used. The first of these subjects was a trained, sporting performance person. The second subject was a trained person without being a performance athlete. The other two subjects are non-enrolled.

7.5. Results and discussions

Tabel No. 14 – Final calculation of the two softwares: the pilot one and MOTION-AE

Referința intervalului R-R	Referința intervalului R-R înainte de antrenament	FC de lucru cu un antrenament în urmă [bpm]	FC de lucru cu două antrenamente în urmă[bpm]	Intensitatea calculată de softul preliminar [%]	Intensitatea calculată de MOTION-AE [%]	Diferență [%]
6.01	6.66	120	140	-24.6	-24.58	0.02
6.01	6.66	120	170	-25.5	-25.31	0.19
6.01	6.66	120	100	-10.5	-10.49	0.01
6.01	6.66	120	80	-10.2	-10.35	0.15
6.01	6.01	120	132	0.3	0.06	0.24
6.01	6.3	120	132	-17.4	-17.45	0.05
6.01	5.7	120	132	8.1	8.32	0.21

According to Table No. 14, the difference between the intensity of the MOTION-AE application, compared to the preliminary software, is between 0.02% and 0.24%. These values are negligible for the final result.

Based on the fact that Motion-AE does not have the large computing gap compared to previously developed software, we can analyze five situations where Motion-AE can be used. These five situations are: the heart rate in the workout remains unchanged on successive days, the heart rate in the workout increases by 20 bpm on successive days, the heart rate in the workout increases by 30 bpm on successive days, the heart rate in the workout decreases by 20 bpm on successive days , the heart rate in the workout decreases by 30 bpm on successive days.

7.6. Conclussions

1. The MOTION-AE mobile application improves the performance of aerobic training, providing a gradual and controlled way of determining training intensity, compared to the classic interpretation of heart rate variability to determine the intensity of training;

2. The MOTION-AE application follows previous exercise sessions and subject performance, providing trainers and coaches with an objective tool that can be used in aerobic training programs;

3. The MOTION-AE application opens the way to a larger driving system implementation foraerobic endurance training, providing reference points for heart rate management systems in setting up specialized training sessions. By implementing a fuzzy decision-making tool, the application ensures that uncertainties in measurements and variation of input parameters due to physical characteristics of individuals are taken into account when calculating the optimum intensity for the next training session;

4. Due to its portability as a mobile application and its low cost of use, MOTION-AE can successfully indicate training intensities even for everyday users who need help in improving their aerobic fitness.

General conclussions

1. Our research confirmed the possibility of adapting and modeling knowledge from the theory of intelligent driving systems in the field of human motor science by identifying the common elements of the two domains;

2. Applying common knowledge to the two areas has resulted in the development of an intelligent driving system that allows the control of heart rate dynamics during running on a treadmill. The precision range obtained for the system was +/- 6 bpm, this value being much lower than the system initially projected limit of +/- 10 bpm;

3. We succeeded, through the developed system, to obtain an objective means of conducting a non-linear process: the human body. The adaptive character of the system allows for flexibility in overcoming unexpected events during a treadmill treadmill: crash, coughing, changing treadmill speed;

4. In addition to the intelligent driving system, we have succeeded in creating an application, MOTION-AE, for mobile devices (phones, tablets) that allows the intensity of training to be determined using heart rate variability in an innovative way. This application ensures that the fatigue threshold is avoided as much as possible during a physical training period, but allows for maximum potential by providing the optimum intensity for the next training session.

Selective bibliography

Alaqtash, M., Yu, H., Brower, R., Abdelgawad, A., & Sarkodie-Gyan, T. (2011). Application of wearable sensors for human gait analysis using fuzzy computational algorithm. *Engineering Applications of Artificial Intelligence*, 1018–1025.

Bompa, T. (2002). *Periodizarea: teoria si metodologia antrenamentului.* Bucuresti: Ex Ponto.

Brodan, V., Hajek, M., & Kuhn, E. (1970). An analog model of pulse rate during physical load and recovery. *Physiologia Bohemoslovaca*, 189-198.

Cârstea, G. (2000). *Teoria și Metodica Educației Fizice și Sportului.* București: AN-DA.

Cheng, T., Savkin, A., Celler, B., Su, S., & Wang, L. (2008). Nonlinear modelling and control of human heart rate response during exercise with various work load intensities. *Biomedical Engineering*, 2499-2508.

Cîrtoaje, S. S. (2013). *Teoria sistemelor automate.* Ploiești: UPG.

Dragnea, A. (1996). *Antrenamentul sportiv.* Bucuresti: Didactica si Pedagogica.

Feher, J. (2017). *Quantitative Human Physiology (Second Edition).* Academic Press. doi:https://doi.org/10.1016/B978-0-12-800883-6.00030-6

Fu, Q., & Levine, B. D. (2013). Chapter 13 - Exercise and the autonomic nervous system. *Handbook of Clinical Neurology, 117*, pg. 147-160.

Hajek, M., Potucek, J., & Brodan, V. (1980). Mathematical model of heart rate regulation during exercise. *Automatica*, 191-195.

Jacobs, R. (1997). Control model of human stance using fuzzy logic. *Biological Cybernetics*, 63-70.

Mazenc, F., Malisoff, M., & De Querioz, M. (2011). Tracking control and robustness analysis for a nonlinear model of human heart rate during exercise. *Automatica*, 968-974.

Meystel, A., & Albus, J. S. (2002). *Inteligent Systems - Architecture, Design, and Control.* New York: John Wiley & Sons. Inc.

Mircescu, L., & Cojocaru, V. (1970). *Individualizarea antrenamentului sportiv.* Bucureşti : Editura Consiliului Naţional pentru Educaţie Fizică şi Sport.

Passino, K., & Yurkovich, S. (1998). *Fuzzy Control.* Menlo Park: Addison Wesley Longman.

Rudas, I., Takacs, M., & Laufer, T. E. (2012). Risk and Uncertainties of Physiological Processes Handled by the Fuzzy Implementation. *WSEAS International Conference on System Science and Simulation in Engineering*, 37-43.

Sbenghe, T. (2008). *Kinesiologie - Știința mișcării.* București: Editura Medicală.

Scalzi, S., Tomei, P., & Verrelli, C. (2012). Nonlinear control techniques for the heart rate regulation in treadmill exercises. *Biomedical Engineering*, 599-603.

Stoian, I., & Petrache, A. (2007). *Monitorizarea antrenamentului: puls sau lactat?* București: LightHouse.

Su, S., Wang, L., Celler, B., Savkin, A., & Guo, Y. (2007). Identification and control for heart rate regulation during treadmill exercise. *Biomedical Engineering*, 1238-1246.

Suh, M. (2015). *Electronic Textiles.* Woodhead Publishing.

Tang, S., & Po, L. (2015). *Textiles for Sportswear.* Woodhead Publishing.

Tapia, E. M., Intille, S. S., Haskell, W., & Larson, K. (2007). Real-Time Recognition of Physical Activities and Their Intensities Using Wireless Accelerometers and a Heart Rate Monitor. *11th IEEE International Symposium on Wearable Computers*, 37-40.

Weng, K., Turk, B., Dolores, L., Nguyen, T., Celler, B., Su, S., & Nguyen, H. (2010). Fast tracking of a given heart rate profile in treadmill exercise. *Engineering in Medicine and Biology Society*, 2569-2572.