Visual Analysis of Digital Electrocardiographic Signals Using 2D and 3D Poincarè Plot

Evgeniya Gospodinova
Department of Medical Robotics
Institute of Robotics
Bulgarian Academy of Sciences
Sofia, Bulgaria
jenigospodinova@abv.bg

Penio Lebamovski
Department of Medical Robotics
Institute of Robotics
Bulgarian Academy of Sciences
Sofia, Bulgaria
p.lebamovski@abv.bg

Miroslav Dechev
Department of Medical Robotics
Institute of Robotics
Bulgarian Academy of Sciences
Sofia, Bulgaria
miroslav.dechev@gmail.com

Krasimir Cheshnedzhiev
Department of Medical Robotics
Institute of Robotics
Bulgarian Academy of Sciences
Sofia, Bulgaria
cheshmedzhiev@gmail.com

Ekaterina Popovska
Department of Medical Robotics
Institute of Robotics
Bulgarian Academy of Sciences
Sofia, Bulgaria
Ekaterina.popovska@gmail.com

Yoan-Aleksandar Tsanev
Technical University-Varna
Varna, Bulgaria
joan.al2001@gmail.com

Abstract*— The article presents the results of visual analysis of heart rate variability (HRV) of digital electrocardiographic (ECG) signals. The study covers subjects with cardiovascular diseases and athletes, analyzed before and after training. The analysis was performed using a software application developed in the MATLAB environment, and the 2D and 3D Poincaré method was applied to evaluate the data. Visualization of cardiac data (RR intervals) using this method allows for a quick assessment of changes and detection of anomalies that may be indicators of disease states. In addition, the method is useful for analysing the response of athletes to physical exertion during training. From the obtained graphical results of the studied athletes, it follows that during training, the RR data, which take into account the intervals between consecutive heartbeats, become more uniform and the graphs appear compressed, i.e. the variability of the intervals between heartbeats decreases. Similar results are also observed when studying subjects with the following cardiovascular diseases: arrhythmia, heart failure and syncope. The results obtained show that the Poincaré method is effective for visual assessment of heart rate variability in both healthy athletes and patients with cardiovascular diseases. Through the graphical representation of RR intervals, physiological adaptations to physical exertion can be quickly identified, as well as for the detection of potential pathological changes. This makes the method useful both in clinical medicine - for early diagnosis and monitoring of cardiovascular diseases, and in sports medicine - for assessing the physical fitness of athletes, regulating the training process, optimizing recovery after exertion and predicting potential health problems or injuries.

***Keywords*— Electrocardiogram (ECG) signal, Heart Rate Variability (HRV), RR time intervals, Poincarè plot.**

I. INTRODUCTION

One of the priority areas of scientific research in modern clinical and sports medicine is related to the search for highly informative, non-invasive methods for studying heart rate variability and determining the cardiac health of athletes. One of the widely used methods for studying the bioelectrical activity of the heart is the electrocardiogram (ECG), and an important diagnostic parameter that can be determined from it is heart rate variability (HRV), taking into account the difference between consecutive heartbeats (RR intervals) [4]. HRV can be a useful tool for studying the influence of various cardiovascular diseases, as well as mental [1,2] and physical exertion during training [9,10,11], on the heart rate of patients and athletes. ECG signals provide important information about cardiac activity, which can be used not only in non-invasive medical examinations, but also for monitoring the cardiac health of patients and athletes, using specially developed software applications [4]. Methods for analysis and assessment of HRV fall into two main classes: linear and nonlinear. Linear methods perform HRV analysis in the time and frequency domains [12]. These methods are used in the clinical practice of doctors because they are standardized and their reference values are known. Nonlinear methods are potentially promising tools, but currently they are used to a limited extent, since they are not standardized and are in the process of active research. According to a document [3] of the European Society of Cardiology and the North American Society of Electrophysiology, the study of the applicability of linear and nonlinear mathematical methods for HRV analysis is defined as one of the most important priority areas for research, prediction and improvement of human cardiac health. This document confirms the relevance of this type of research. The Poincaré method allows for a graphical representation of the dynamics of heart rate variability, allowing for a quick visual assessment of the cardiac condition. By analysing the distribution of points in the Poincaré diagram, various conditions can be identified – from normal physiological reactions to pathological changes associated with cardiovascular diseases. With the development of technology, the use of automated software applications for HRV analysis is expanding, implementing algorithms for ECG signal processing in environments such as MATLAB, R or Python. In recent years, there has been increased interest in the integration of artificial intelligence (AI) and machine learning (ML) methods for automatic classification of heart rhythms and prediction of cardiac risks.

Despite their advantages, nonlinear methods, including analysis using Poincaré diagrams, still face challenges related to the lack of established clinical standards and reference values. Future research in this area is aimed at validating these methods using large clinical databases and developing new hybrid approaches combining linear and nonlinear techniques for more precise assessment of cardiac health. The study of nonlinear methods for HRV analysis has significant academic interest, especially in the field of clinical and sports medicine. The potential for developing new software products opens up opportunities for more effective use and application of HRV analysis in real-world settings. In addition to patients with cardiovascular diseases and professional athletes, these methods may also be useful for the wider population, including people with chronic diseases and the elderly, who also need balanced physical activity.

The present article aims to present the results of a study of HRV in patients with various cardiac diseases and athletes. The Poincaré method was used for the analysis, which allows for a visual assessment of heart rate variability. Using a developed software application in the MATLAB environment, the RR intervals are visualized, which allows for monitoring their changes and calculating the quantitative parameters SD1 and SD2 - indicators of short-term and long-term heart rate variability. It is expected that the obtained results will contribute to a better understanding of the relationship between HRV and cardiac health, as well as support the future development of standardized analysis methodologies to be integrated into clinical and sports practice.

II. Poincarè plot method

A. *Poincarè plot algorithm*

The Poincaré method is a relatively new technique that can be used for visual analysis of the nonlinear dynamics of ECG signals to detect periodic or chaotic structures in them [6,8,13,14]. It can be used to visualize the time RR intervals between successive heartbeats, as well as to provide information about the dynamics of the heart rhythm. The algorithm for plotting with the method is as follows:

Step 1: Preparing the data for analysis.

An electrocardiographic device records the ECG signals and determines the RR intervals, which are the time intervals between successive R peaks of the electrocardiogram. Once the RR intervals are recorded in a file, the data can be processed to remove the artefacts and unwanted noise, by applying filters or data processing algorithms to improve the quality of the RR interval series. Modern electrocardiographic devices provide information about the RR intervals of the recorded ECG signals.

Step 2: Constructing the Poincaré graph.

Each RR interval is represented as a function of the previous interval and is plotted as a point in a rectangular coordinate system, with the abscissa of each point being the current RR(n) interval and the ordinate being the next RR(n+1) interval in the time series. When forming the graph shown in Figure 1, a segment of points is obtained, the centre of which is located on the identity line. The identity line is represented by the function x=y (RR(n)=RR(n+1)). If the point is located above the identity line, this indicates that the current interval is longer than the previous one and vice versa. Additional elements, such as ellipses, can be added when constructing the graphs.

The ellipse is a basic analytical method for assessing heart rate variability, which visually represents the short-term and long-term heart rate variability and can be used to assess the cardiac health of the studied individual. The centre of the ellipse is located on the identity line, and its parameters are SD1 (Standard Deviation 1) and SD2 (Standard Deviation 2). SD1 represents the standard deviation of the points that are perpendicular to the identity line. This parameter is related to short-term HRV and its higher value means a healthier heart rate. SD2 represents the standard deviation of the points that are along the identity line. This parameter is related to long-term HRV and is usually associated with greater physical exertion, fatigue or disease. A higher value of the SD1/SD2 ratio is associated with higher HRV and better cardiac health.

Step 3: Visual analysis.

The visual analysis is performed based on the following parameters [5,4,7,8]:

- The shape of the figure formed by the Poincaré points, which depends on the characteristics of the dynamical system and is related to its stable or chaotic behaviour. Some of the shapes that can be observed are:

  o a comet that is characterized by a narrow lower part and widening towards the top. This form means a stable or periodic dynamic mode in the system;

  o a torpedo, which is observed in systems with quasi-periodic or chaotic behaviours;

  o a fan, which is characterized by a widening or narrowing shape of the Poincaré graph. This is observed in systems with chaotic attractors or close to the limit of chaos;

  o a complex shape that consists of several segments and is characteristic of fractal structures.

- Symmetry of the points relative to the identity line indicates the equilibrium state of the system.

Step 4: Quantitative analysis.

The quantitative analysis is determined by the values of the parameters: SD1, SD2 and the ratio SD1/SD2 and are used to further assess the dynamic behaviour of the system.

Step 5: Generate a protocol.

As a result of the analysis, a protocol is generated that includes numerical and graphical information. The protocol can be saved in text format or as a PDF file.

B. *Pseudocode for generating Poincarè plot*

The pseudocode for generating the Poincaré plot is shown in Fig. 2. It can be used in various medical and sports applications, providing valuable information about the dynamics of the heart rate. Specifically, the plot can be applied in the following cases:

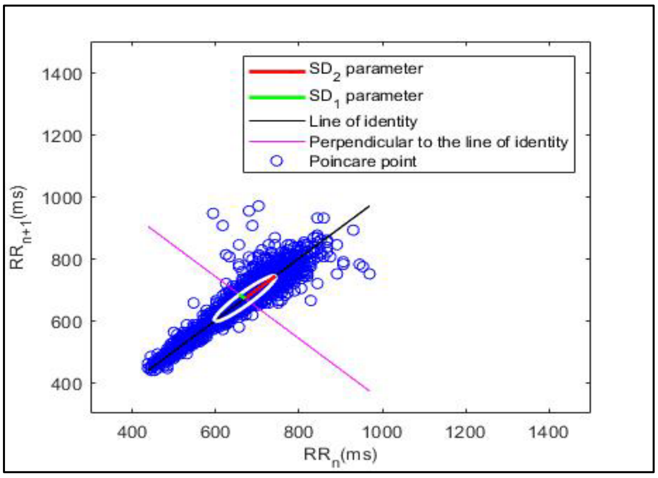

Fig. 1 Components of the Poincaré plot method.

- Early diagnosis of cardiovascular diseases – Analysis of heart rate variability using Poincaré plots allows the detection of abnormalities associated with diseases such as arrhythmia, hypertension and autonomic dysfunction. By visualizing the points in two-dimensional space, characteristic patterns can be identified that signal the risk of heart problems.
- Tracking recovery in athletes after exercise – The Poincaré graph is a useful tool for assessing the state of the autonomic nervous system after exercise. By analysing short-term and long-term heart rate variability, the degree of recovery of the body can be determined and the training regimen can be optimized.
- Assessment of stress and the psychophysiological state of the individual;
- Analysis of the effectiveness of drug therapy in patients with heart disease;
- Studying the impact of various factors (such as sleep, diet, and physical activity) on heart rate.

This visualization method provides an easy and intuitive way to analyse complex physiological processes, making it a valuable tool in medicine, sports, and scientific research.

Algorithm for generating Poincarè plot

1. Input: RR_intervals (array of RR intervals).
2. If length of RR_intervals <2, then return "Insufficient data".
3. Initialize empty array X and Y.
4. For i=1 to length(RR_intervals)-1:
   - X(i)=RR_intervals(i);
   - Y(i)=RR_intervals(i+1).
5. Compute SD1 and SD2:
   - SD1= standard deviation of (Y-X)/sqrt(2);
   - SD2= standard deviation of (Y+X)/sqrt(2).
6. Plot Poincarè diagram:
   - Scatter plot of (X, Y);
   - Plot identity line (y=x);
   - Plot perpendicular to the line of identity;
   - Plot ellipse with SD1 and SD2.
7. Output: Poincarè plot, values of SD1 and SD2.

Fig. 2 Pseudocode for generating Poincarè plot.

The pseudocode description is as follows:

1. Input: The input is a list (array) of RR intervals – the time between two consecutive heartbeats, measured in milliseconds (ms) or seconds (sec).
2. It checks whether the list contains at least two elements. If not, the algorithm stops with an appropriate message.
3. Creating two empty arrays X and Y that will contain the corresponding coordinates of the points in the Poincaré graph.
4. Initialization of the coordinates (X, Y): It is implemented by taking two consecutive RR-intervals:

- X(i) = RR(i);
- Y(i) = RR(i+1).

5. Calculation of the parameters SD1 and SD2.

- SD1 (short-term variability) is calculated as the standard deviation of the differences between consecutive RR intervals divided by √2.
- SD2 (long-term variability) is calculated as the standard deviation of the mean of consecutive RR intervals divided by √2.

6. The graph is generated :

- A scatter plot is used to plot all points (X, Y).
- The diagonal line (y = x) is added, which shows the ideal case without variability.
- An ellipse is drawn based on SD1 and SD2 to visualize the distribution of points.

7. The output is a plot that shows the scatter of the points and visualizes the heart rate variability. The values of SD1 and SD2 are output, which can be used for quantitative analysis..

This method of HRV visualization provides an easy and intuitive way to analyse complex physiological processes, making it a valuable tool in medicine, sports, and scientific research.

III. Data

This article presents the graphical results of the studied cardiological signals recorded with a Holter device. The data are divided into two groups:

1. Group 1: Healthy individuals, patients with cardiovascular diseases: arrhythmia, heart failure and

syncope. The duration of the recordings is 24 hours with approximately 100,000 RR intervals.

2. Group 2: Athletes training in wrestling. The duration of the recordings is 30 minutes with about 2000 RR intervals recorded before and after training.

IV. RESULTS AND DISCUSSION

A. HRV analysis of patients with cardiovascular diseases with 2D Poincare plot

Figure 3 shows the graphical results obtained with the Poincaré method for a healthy individual, patients with heart failure, arrhythmia and syncope. Based on the obtained graphical results, the following conclusions can be drawn:

1. The Poincaré points for the subjects are symmetrical about the identity line, indicating that they do not have rhythm disturbances. The points that are above the identity line are colored blue, and those below the identity line are colored red.
2. Healthy individual (Fig. 3A): The points are evenly distributed around the identity line. A relatively tight cloud of points is observed, which has the shape of a comet with a pointed lower part that widens towards the top. The graph is an indication of normal heart rate variability.
3. Heart failure patient (Fig. 3B): The points are more scattered, grouped into several segments, indicating reduced heart rate variability. This pattern may be an indicator of reduced autonomic regulation of the heart.
4. Arrhythmia patient (Fig. 3C): The graph is fan-shaped, with the points more randomly spaced. This is typical of an irregular heart rhythm.
5. Syncope patient (Fig 3D): The distribution of dots resembles a torpedo and reflects sudden changes in heart rate. There are areas with a greater concentration of dots, suggesting instability in heart rate regulation.

Summary: 2D Poincaré diagrams are a useful tool for assessing cardiac activity and can aid in the diagnosis of various cardiac conditions.

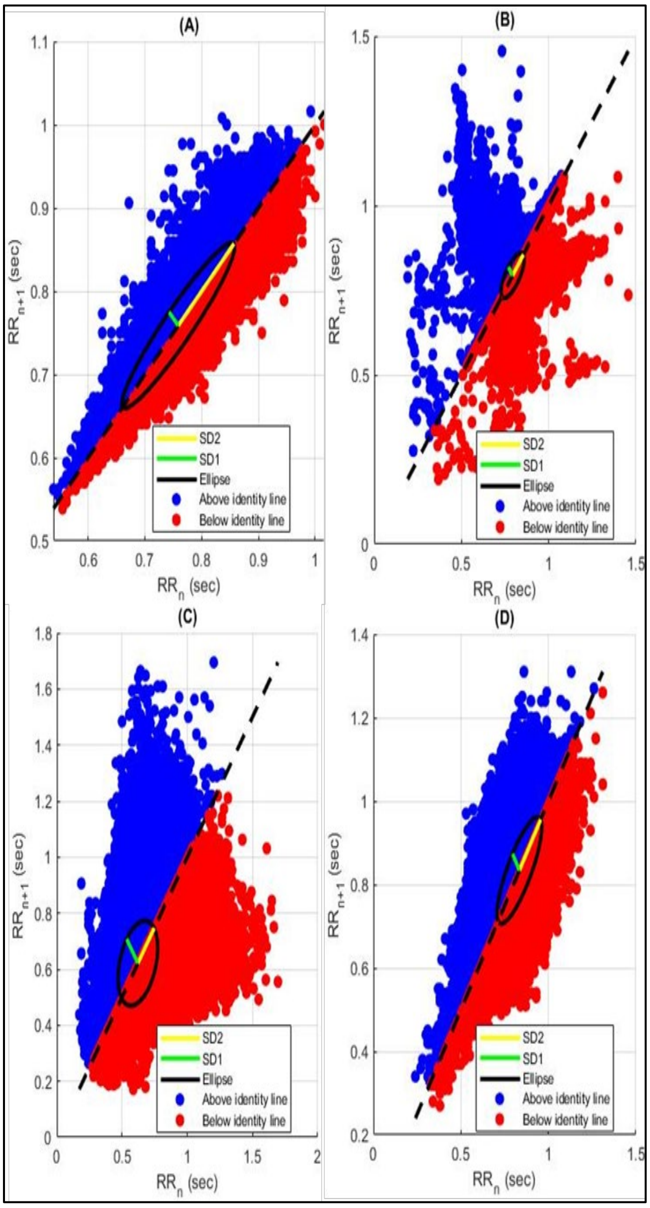

Fig. 3 2D Poincarè plot for subjects: (A) normal, (B) heart failure, (C) arrhythmia and (D) syncope.

The 3D Poincaré plot (Fig. 4) can provide additional information that is not as obvious in the standard 2D version. Here are a few key advantages:

B. HRV analysis of patients with cardiovascular diseases with 3D Poincarè plot

1. Additional dimension of information: In the classic 2D Poincaré plot, each point represents a pair of consecutive intervals RR(n) versus RR(n+1). In the 3D Poincaré plot, another dimension is added, often RR(n+2), which allows for a better understanding of long-term dependencies and dynamics of the heart rate.
2. Better recognition of complex patterns:

In the 2D graphs, some points may overlap, making analysis difficult. In 3D space, different layers or cluster structures may be observed, indicating specific rhythmic abnormalities.

3. Long-term relationships and trends: Heart rate variability can be analysed over a longer time range, revealing trends not visible in 2D. This is especially useful in patients with arrhythmia, atrial fibrillation, or autonomic dysfunction.
4. Better visualization of chaotic and deterministic structures: In healthy individuals, 3D graphics often retain an ordered structure. In patients with heart disease, increased chaos may be observed, which is more easily noticeable in 3D.
5. 3D Poincaré plots not only expand visualization, but also add a new level of analysis. They can help with more accurate diagnostics, earlier disease detection, and a better understanding of heart rhythm dynamics.

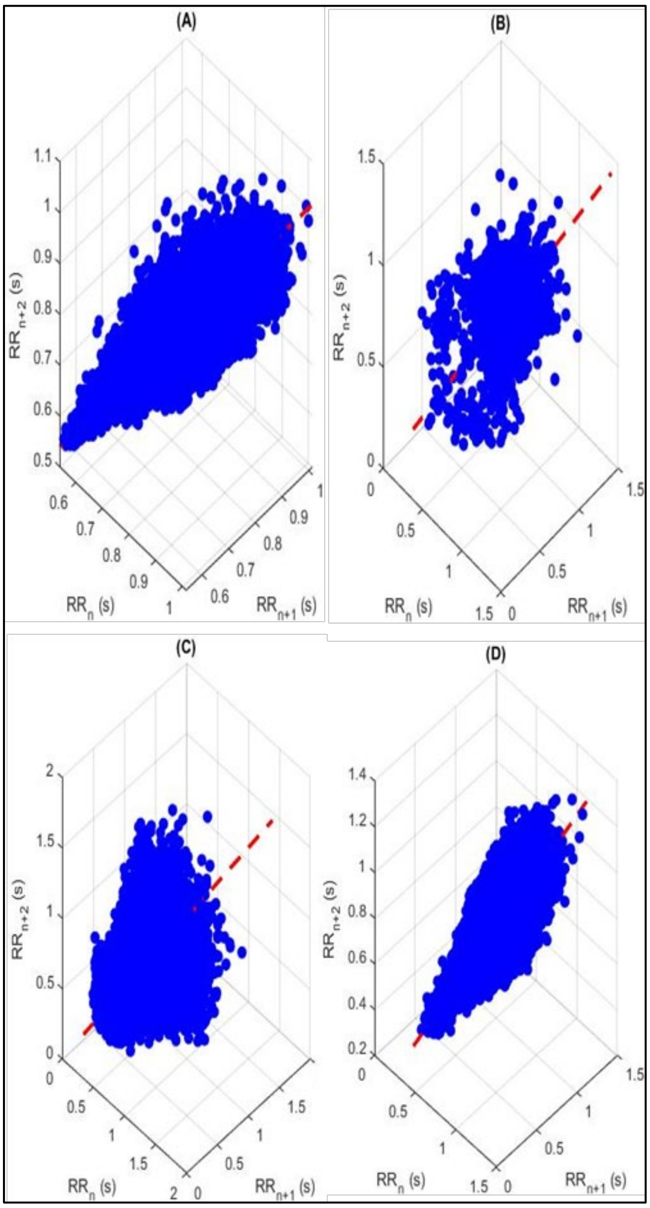

Fig. 4 3D Poincarè plot for subjects: (A) normal, (B) heart failure, (C) arrhythmia and (D) syncope.

B. HRV analysis of athletes before and after training

Figure 5 and Figure 6 show the graphical results obtained with the Poincaré method of athletes before and after training. Based on the graphical results, the following conclusions can be drawn:

1. The graphs of the six athletes studied before training (Fig.5) have the shape of a comet, with a pointed lower part that widens towards the top. The shape of the graphs shows that the athletes are cardio logically healthy and have a high HRV, according to previous publications [4, 8]. The Poincaré points for all six athletes are symmetrical about the identity line, indicating that the athletes do not have rhythm disturbances.
2. The graphs of athletes after training (Fig. 6) are compressed because the intervals between heartbeats become more even as a result of physical exertion during training and the HRV decreases.

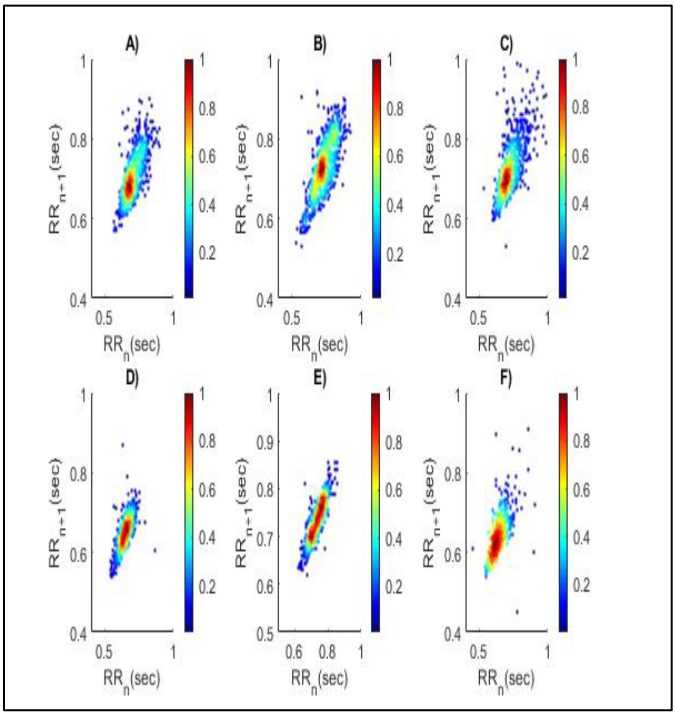

Fig. 5 Poincarè plots of athletes before training

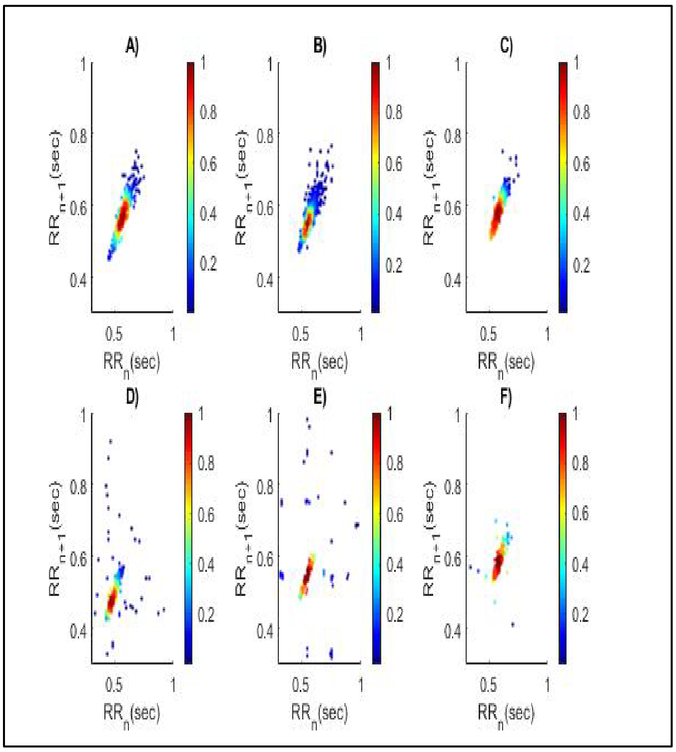

Fig. 6 Poincarè plots of athletes after training

V. CONCLUSIONS

In recent years, heart rate variability has been the subject of extensive scientific research and has found applications in clinical and sports medicine. New technologies and mathematical methods for analysing HRV contribute to a better understanding of its role in both diagnostics and sports.

HRV plays an essential role in sports medicine, providing valuable information about the health status and training of athletes. It helps to optimize training programs and sports results. In addition, it can be used as an indicator of the adaptation of the cardiovascular system to training loads and to assess the level of physical exertion.

The application of mathematical methods for visual analysis, such as the Poincaré method, provides additional information about the physical condition of athletes. This method facilitates the personalization of training programs and load management in order to improve sports performance, prevent overloads and reduce the risk of injuries.

The advantage of the Poincaré method is that it allows for easy visualization of the dynamics of the heart rhythm. It allows all RR intervals to be seen on the graph, which allows for the rapid identification of deviations related to cardiovascular diseases or overload during training.

ACKNOWLEDGMENT

THIS RESEARCH WAS FUNDED BY THE NATIONAL SCIENCE FUND OF BULGARIA (SCIENTIFIC PROJECT “RESEARCH, MATHEMATICAL ANALYSIS AND ASSESSMENT OF THE IMPACT OF STRESS ON CARDIAC DATA”), GRANT NUMBER KP-06-M72/1, 5 DECEMBER 2023.

REFERENCES

[1] U. Rimmele, B. Zellweger, B. Marti, R. Seiler, C. Mohiyeddini, U. Ehlert, and M. Heinrichs. “Trained men show lower cortisol, heart rate and psychological responses to psychosocial stress compared with untrained men,” Psychoneuroendocrinology. 32(6):627-635, 2007. https://doi.org/10.1016/j.psyneuen.2007.04.005

[2] A.-K. Lennartsson, I. Jonsdottir, and A. Sjörs. “Low heart rate variability in patients with clinical burnout,” Int J Psychophysiol, 110:171-178, 2016. https://doi.org/10.1016/j.ijpsycho.2016.08.005

[3] M. Malik. “Task Force of the European Society of Cardiology and the NorthAmerican Society of Pacing and Electrophysiology, Heart rate variability – standards of measurement, physiological interpretation, and clinical use,” Circulation. 93, 1043–1065. Doi: 10.1161/01.CIR.93.5.1043, 1996. Available: https://www.escardio.org/static_file/Escardio/Guidelines/Scientific-Statements/guidelines-Heart-Rate-Variability-FT-1996.pdf

[4] E. Gernot. Heart Rate Variability. Springer: London, UK, 2014.

[5] R. Gomes, L. Vanderlei, D. Garner, M. Santana, L. Abreu, and V. Valenti. 2018. “Poincaré plot analysis of ultra-short-term heart rate variability during recovery from exercise in physically active men,” J Sports Med Phys Fitness, 58(7-8):998-1005. 2018. https://doi.org/10.23736/S0022-4707.17.06922-5

[6] M. Fishman, F. Jacono, S. Park, R. Jamasebi, A. Thungtong, K. Loparo, and T. Dick. “A method for analyzing temporal patterns of variability of a time series from Poincare plots,” J Appl Physiol, 113(2):297-306, 2012. https://10.1152/japplphysiol.01377.2010

[7] P. Kamen, H. Krum, and A Tonkin. “Poincaré plot of heart rate variability allows quantitative display of parasympathetic nervous activity in humans,” Clin Sci (Lond), 91(2):201-208, 1996. https://10.1042/cs0910201

[8] A. Khandoker, C. Karmakar, M. Brennan, M. Palaniswami, A. Voss. 2013. Poincaré Plot Methods for Heart Rate Variability Analysis, Springer New York, NY, 2013. https://doi.org/10.1007/978-1-4614-7375-6

[9] B. Hoffmann, A. Flatt, L. Silva, M. Młyńczak, R. Baranowski, E. Dziedzic, B. Werner, and J. Gąsior. “A Pilot Study of the Reliability and Agreement of Heart Rate, Respiratory Rate and Short-Term Heart Rate Variability in Elite Modern Pentathlon Athletes,” Diagnostics, 10, 833, 2020. https://doi.org/10.3390/diagnostics10100833

[10] C. Urzealˇ, A. Bota, S. Serbanoiu, M. Mezei, F. Dutheil, and D. Courteix. “Heart Rate Variability as a Possible Predictor of Sport Performance in Junior Rhythmic Gymnastics,” Isokinetics and Exercise Science 28, 171 – 179, 2020. https://doi.org/10.3233/IES-192222

[11] J. Blásquez, G. Font, and L. Ortís. “Heart-rate variability and precompetitive anxiety in swimmers,” Psicothema, Vol. 21, nº 4, pp. 531-536, 2009.

[12] R. Acharya, J. Suri, J. Spaan, and S. Krishnan. Advances in Cardiac Signal Processing. Springer-Verlag Berlin Heidelberg., 2007. https://doi.org/10.1007/978-3-540-36675-1

[13] M. Martinis, A. Knežević., G. Krstačić, and E. Vargović. “Changes in the Hurst exponent of heart beat intervals during physical activities,” Phys. Rev. E, 70, 012903., 2004. https://doi.org/10.1103/PhysRevE.70.012903

[14] Y. -A. Tsanev, G. Georgieva-Tsaneva and K. Cheshmedzhiev, "Heart rate variability-based software analysis of cardiac data," *2024* 28th International Conference on System Theory, Control and Computing (ICSTCC), Sinaia, Romania, 2024, pp. 51-56, doi: 10.1109/ICSTCC62912.2024.10744664.