JKAU: Eng. Sci., Vol. **34** No. 1, pp: 75 – 88 (2024 A.D.)
DOI:10.4197/Eng.34-1.6

Improved HRV Analysis in ECG Data: A Comparative Study Using MATLAB Code, Kubios, and gHRV

Eyad Talal Attar[1]

Electrical and Computer Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

Abstract Heart Rate Variability (HRV) analysis is a vital tool in assessing autonomic nervous system regulation and cardiovascular health. This study explores improved HRV analysis techniques by employing MATLAB code and comparing its performance with widely used software tools, Kubios and gHRV. Electrocardiogram (ECG) data from ten subjects under four distinct conditions - baseline, rest, Stroop color task, and meditation - were collected and analyzed. The study focuses on developing and implementing novel algorithms in MATLAB for HRV estimation, providing a comprehensive comparison against existing methods. The study examines the accuracy and reliability of HRV analysis results obtained through MATLAB implementation in contrast to Kubios and gHRV. The MATLAB code is optimized for enhanced computational speed and accuracy, allowing for real-time processing of ECG data. The results indicate significant improvements in HRV analysis using the proposed MATLAB implementation. The proposed MATLAB code and Kubios have similar accuracy for the High-Frequency feature, with 85% accuracy. gHRV, on the other hand, has 100% accuracy for PNN50, indicating its high accuracy in matching reference data. The comparative analysis demonstrates the diverse HRV metrics across different experimental conditions. Additionally, the results highlight the difference in the study approach between Kubios and gHRV, showcasing its potential for widespread adoption in clinical and research settings. This study not only presents an advanced HRV analysis methodology but also provides valuable insights into the reliability of existing software tools. The findings offer researchers and clinicians an informed choice when selecting HRV analysis tools for their specific applications, ensuring accurate and efficient assessment of cardiovascular health and autonomic nervous system function. Further investigations and validations are warranted to establish the robustness and generalizability of the proposed methodology across diverse populations and experimental paradigms.

Keywords: Heart Rate Variability, HRV Analysis, MATLAB, Signal Processing, Kubios, gHRV, Autonomic Nervous System, Cardiovascular Health, Customization, Comparative Study

1. INTRODUCTION

Heart Rate Variability (HRV) analysis is a vital tool in the field of cardiovascular research, providing valuable insights into the autonomic nervous system's influence on heart rate dynamics. HRV refers to the variation in time between successive heartbeats and is a non-invasive measure widely used to assess autonomic nervous system function, cardiovascular health, and stress levels [1].

The autonomic nervous system, composed of the sympathetic and parasympathetic branches, plays a crucial role in regulating heart rate. HRV analysis quantifies the

[1] Corresponding author: etattar@kau.edu.sa

fluctuation in heart rate intervals, reflecting the balance between sympathetic and parasympathetic activities. Reduced HRV has been linked to various health conditions, including cardiovascular diseases, diabetes, and hypertension, making it a valuable biomarker for both clinical and research purposes [2].

Accurate HRV analysis involves the extraction of various time-domain, frequency-domain, and non-linear parameters from heart rate data. Several software tools have been developed to automate this process, facilitating efficient and

they standardized HRV assessments. Notable software solutions include Kubios HRV [3] and gHRV [4], which offer user-friendly interfaces for HRV analysis and they have been widely used in research and clinical practice. While these tools provide valuable insights, they often lack the flexibility to customize the analysis according to specific research requirements. Moreover, the accuracy and efficiency of these tools might vary based on the algorithms they employ and the datasets they are applied to.

In this study, we aim to bridge these gaps by proposing an innovative HRV analysis methodology using MATLAB. By leveraging MATLAB's powerful signal processing and machine learning libraries, the study intend to enhance the accuracy of HRV estimation and provide a flexible, user-friendly platform for researchers and healthcare professionals.

The comparative analysis with existing commercial software will serve as a benchmark to validate the effectiveness and superiority of our proposed methodology.

Through this research, the study anticipates contributing significantly to the field of cardiovascular research, enabling more accurate and efficient HRV analysis methods that can be tailored to specific research needs and clinical applications.

TABLE 1

HRV Calculation For Time and Frequency Domain

Feature	Equation	Unit	Desciption
SDRR	$\sqrt{\frac{\sum_{i=1}^{N}(RR_i - mRR)^2}{N}}$	$msec$	Standard deviation of all RR intervals
rMSSD	$\sqrt{\frac{\sum_{i=1}^{N-1}(RR_{i+1} - RR_i)^2}{N-1}}$	$msec$	The square root of the mean of the sum of the squares of differences between adjacent RR intervals
pNN50	$\frac{NN50}{N} * 100$	%	NN50 count divided by the total number of all RR intervals
LF	$\sum_{k=a}^{b} p(K)$, $a = 0.04, b = 0.15$	ms^2	Low frequency power of HRV (0.04 – 0.15 Hz)
HF	$\sum_{k=a}^{b} p(K)$, $a = 0.15, b = 0.4$	ms^2	High frequency power of HRV (0.15 – 0.4 Hz)
LF/HF	$\frac{LF}{HF} Ratio$	—	Ratio of Low-High frequency power of HRV

N: Number of RR interval, RRi: Interval between two heartbeats, mRR: Mean of RR, $p(K)$: Fourier power spectral density, $NN50$: The intervals between successive normal heartbeats that differ by more than 50 milliseconds.

Heart Rate Variability (HRV) analysis is a powerful non-invasive method used to assess the autonomic nervous system's influence on heart rate dynamics. It has significant applications in cardiovascular research, sports medicine, stress assessment, and various clinical contexts [5]. HRV analysis involves measuring the variations in time between successive heartbeats, reflecting the continuous interplay between the sympathetic and parasympathetic branches of the autonomic nervous system.

In recent years, there has been a growing need for more sophisticated, adaptable, and precise HRV analysis techniques. Customized implementations using platforms like MATLAB have gained popularity due to their flexibility and ability to accommodate specialized algorithms tailored to specific research requirements. Researchers have been exploring advanced signal processing methods and mathematical algorithms within MATLAB to enhance the accuracy and efficiency of HRV analysis [6].

gHRV is a user-friendly and open-source software tool designed for Heart Rate Variability (HRV) analysis. Developed by Luca Mesin, gHRV provides researchers, clinicians, and enthusiasts with a straightforward platform to analyze HRV data efficiently and effectively. gHRV boasts an intuitive and easy-to-navigate interface, making it accessible to both beginners and experienced users. Its user-friendly design ensures a seamless HRV analysis experience. The software offers a wide range of HRV metrics, including time domain, frequency domain, and nonlinear parameters. Researchers can explore various aspects of autonomic nervous system activity using these comprehensive metrics. gHRV supports the import of HRV data from various file formats, enabling users to seamlessly integrate their data into the software. Additionally, the tool provides visualization options, allowing users to interpret HRV patterns effectively.

Researchers can customize their HRV analysis by selecting specific time intervals and frequency bands. This flexibility allows for tailored analyses, catering to the unique requirements of different research studies. gHRV facilitates the interpretation of HRV results, aiding users in understanding the implications of their findings. The software also supports report generation, making it convenient for researchers to document and share their results.

Being an open-source tool, gHRV benefits from contributions and feedback from a global community of researchers and developers. This collaborative environment ensures continuous improvements and updates to the software. gHRV is utilized in clinical studies to assess autonomic nervous system function, cardiovascular health, and stress levels in various patient populations. Researchers and sports professionals use gHRV to monitor athletes' recovery, training adaptations, and overall physiological well-being.

Stress Management: In stress-related research, gHRV helps evaluate the impact of stressors on the autonomic nervous system, providing valuable insights into stress response mechanisms.

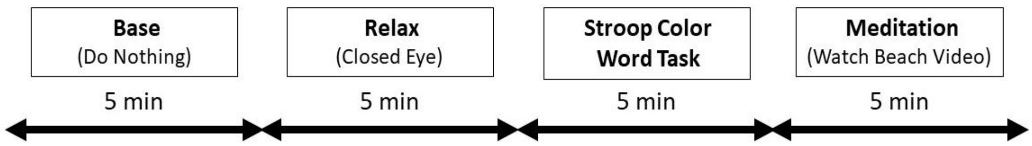

Figure 1 Experiment Protocol

The software is employed in psychophysiological research to understand the connection between emotional states, cognitive processes, and autonomic regulation. gHRV stands as a valuable tool in the field of HRV analysis, empowering researchers with the resources they need to explore the complexities of autonomic nervous system activity comprehensively.

Kubios HRV is a versatile software application designed for Heart Rate Variability (HRV) analysis. Developed by the Biosignal Analysis and Medical Imaging Group at the Department of Physics, University of Kuopio, Finland, Kubios HRV offers a comprehensive platform for researchers, clinicians, and health enthusiasts to explore the intricacies of HRV data. Kubios HRV provides an intuitive and user-friendly interface, making it accessible to individuals with varying levels of expertise. Its simple design ensures efficient navigation and ease of use. The software employs advanced algorithms for accurate HRV parameter extraction. It supports both time domain and frequency domain analysis, allowing users to delve into various aspects of heart rate variability. Kubios HRV supports real-time HRV measurements, enabling immediate analysis of data. This feature is particularly valuable for applications such as biofeedback and sports performance monitoring. Users can customize their HRV analysis by selecting specific time intervals and frequency bands. Kubios HRV provides flexibility in choosing analysis parameters, allowing researchers to tailor their investigations to specific study requirements.

The software allows seamless integration with various data sources, including heart rate monitors and ECG devices. This integration simplifies the process of importing HRV data for analysis. Kubios HRV is widely used in scientific research across disciplines such as cardiology, sports science, psychology, and stress research. Its versatility makes it suitable for a broad range of applications. The software offers robust visualization tools, allowing users to generate comprehensive graphs and reports. These visual representations aid in the interpretation of HRV patterns and trends.

Kubios HRV is employed in clinical studies to assess cardiovascular health, autonomic nervous system function, and stress-related disorders. It serves as a valuable tool for identifying risk factors and monitoring treatment outcomes. Sports professionals utilize Kubios

HRV to monitor athletes' training fig-adaptations, recovery patterns, and overall physiological well-being. HRV analysis aids in optimizing training programs and preventing overtraining. Researchers in psychology and behavioral sciences use Kubios HRV to explore the connections between emotional states, cognitive processes, and autonomic regulation. It offers insights into stress responses and emotional regulation mechanisms. Kubios HRV stands as a leading software solution, offering advanced HRV analysis capabilities within a user-friendly framework.

Heart Rate Variability (HRV) analysis encompasses a range of techniques and algorithms aimed at quantifying the variations in the time intervals between successive heartbeats, reflecting the dynamic interplay of the autonomic nervous system. One commonly employed method involves the calculation of statistical measures such as the standard deviation of NN intervals (SDNN) and the root mean square of successive differences (RMSSD). These metrics offer insights into the overall variability and the parasympathetic influence on heart rate dynamics. Additionally, frequency domain analysis, based on techniques like Fast Fourier Transform (FFT) or autoregressive modeling, decomposes HRV signals into different frequency bands (e.g., low frequency (LF) and high frequency (HF)), enabling the assessment of sympathovagal balance. Nonlinear methods, such as Poincaré plots and fractal analysis, provide further insights into the complexity and adaptability of the cardiac system. Each of these techniques and algorithms offers unique perspectives on HRV dynamics, facilitating a comprehensive understanding of autonomic function and cardiovascular health. Its accurate measurements, customizable features, and diverse applications make it a preferred choice for researchers and practitioners in the field of heart rate variability analysis [6].

This study focuses on collecting the ECG data as shown in Fig.1 and the development and validation of an improved HRV analysis methodology utilizing custom MATLAB code by extracting features as shown in Table 1. By leveraging the diverse capabilities of MATLAB in signal processing and mathematical modeling, this research aims to enhance the accuracy and reliability of HRV parameter extraction. The customized MATLAB approach offers researchers the advantage of tailoring the analysis to specific experimental paradigms, ensuring a more nuanced understanding of autonomic nervous system functioning.

TABLE 2
HRV CALCULATION SOFTWARE AVAILABLE IN MARKET

	Kubios HRV	**gHRV**	**HRV Analysis Software**	**HRV Analysis-MATLAB**	**HRVAS**
Features	Provides comprehensive time and frequency domain HRV analysis. Offers advanced nonlinear analysis methods	Open-source software with customizable algorithms and analysis options. Supports time and frequency domain analyses	Implements standardized algorithms for HRV analysis based on established guidelines	Offers extensive customization options and flexibility for algorithm development and implementation	Provides a wide range of HRV analysis methods including time domain, frequency domain, and non-linear analyses
Strengths	User-friendly interface, compatibility with various file formats, including ECG and R-R interval data	Offers flexibility for researchers to tailor analyses to specific research questions. Supports integration with R and Python	Widely recognized and validated algorithms. Provides consistent and reliable results for clinical applications	Ideal for researchers and developers seeking to create custom HRV analysis pipelines. Provides access to advanced signal processing and machine learning tools	User-friendly interface, suitable for both novice and experienced users. Offers visualization tools for data exploration and interpretation
Weaknesses	Limited customization options compared to some other software packages	The steeper learning curve for users unfamiliar with programming languages	A user interface may be less intuitive compared to some commercial software packages. Limited customization options	Requires proficiency in MATLAB programming language. May have a steeper learning curve for users without programming experience	Limited support for advanced customization and algorithm development compared to some other software packages.

2 . METHODS AND PROCEDURES

A. Data Collection:

HRV datasets were obtained using the Stroop Color-Word Test (SCWT) method to induce focus, which is a common technique used in psychological tests. During base, relaxation, attention-inducing, and meditation sessions. Physiological information, including ECG, was recorded and displayed using a wireless data asset system called the BioRadio 150, which is a 12-channel device. The electrodes for HRV were placed based on Einthoven's principle of chest placement.

A total of 10 subjects (9 right-handed and 1 left-handed) were included, with five females and five males. The mean ages were 20.7 ± 1.5 and 21.6 ± 3.4 years, respectively. The total recording time was 20 minutes, with each session lasting for 5 minutes. The base session involved doing nothing, the relaxed session involved closing the eyes, and the attention session involved administering the Stroop Color Word Test. The meditation session started with a relaxing beach video, as the beach is known to be a great place for stress relief and brain repair. The experiment protocol is shown in Figure 1.

The study was conducted by the ethical guidelines and was approved by the institutional review board. Informed consent was obtained from all participants, and they were debriefed about the study.

B. Preprocessing:

Implement noise reduction techniques such as bandpass filtering and artifact removal to enhance the quality of HRV data [7].

The high-pass and low-pass filters' cutoff frequencies were set at 0.5 Hz and 70 Hz, respectively, to lessen noise. The data were converted from the time domain to the frequency domain using FFT. The baseline wanders and power interference is filtered by 60 Hz noise removal [8].

The MATLAB code used QRS detection algorithms by [9]:

$$y[n] = \frac{1}{8}(2x[n] + x[n-1] - x[n-3] - 2x[n-4]) \quad (1)$$

C. Feature Extraction:

Time Domain Features: Extract standard time domain features such as mean NN interval, standard deviation of

NN intervals (SDNN), and root mean square of successive differences (RMSSD) [10].

Frequency Domain Features: Utilize Fourier transform or autoregressive modeling to calculate frequency domain features like low-frequency (LF) and high-frequency (HF) power [10].

Nonlinear Features: Include nonlinear features such as sample entropy and detrended fluctuation analysis (DFA) to capture complex patterns in HRV data [11].

D. Algorithm Implementation in MATLAB:

MATLAB Code Development: Develop custom MATLAB algorithms for HRV analysis incorporating the preprocessing and feature extraction techniques mentioned above.

Machine Learning: Implement machine learning algorithms (e.g., support vector machines, neural networks) for pattern recognition and classification of HRV data [12].

E. Comparative Analysis:

Commercial Software Utilization: Utilize popular commercial HRV analysis software like Kubios [13], and gHRV [14]. The other software is shown in Table 2.

Comparison Metrics: Compare accuracy, and user-friendliness between MATLAB code implementation and commercial software to assess the superiority of the proposed methodology [15].

3 RESULTS

From Steps, the MATLAB code shows the beats' location in Figure.2, R-R interval in Figure 3, and heart rate in Figure 4.

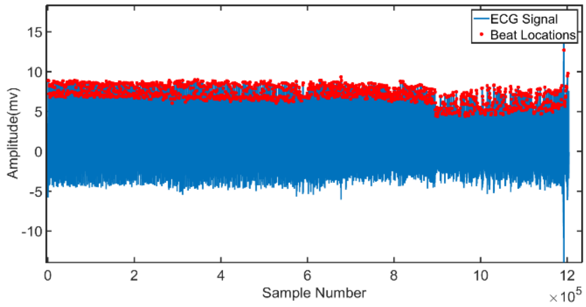

Figure 2 ECG Signal - Beat Location

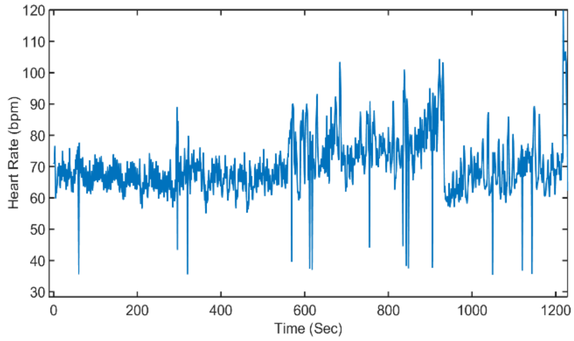

Figure 2 ECG Signal - RR Interval

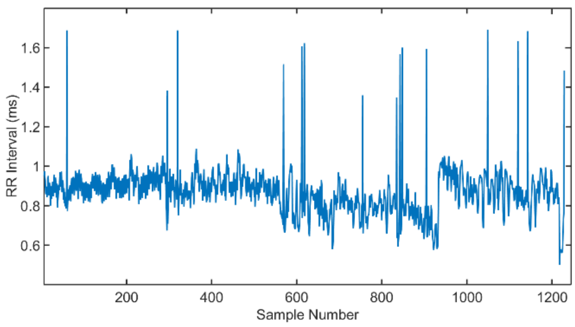

Figure 3 ECG Signal - Heart Rate

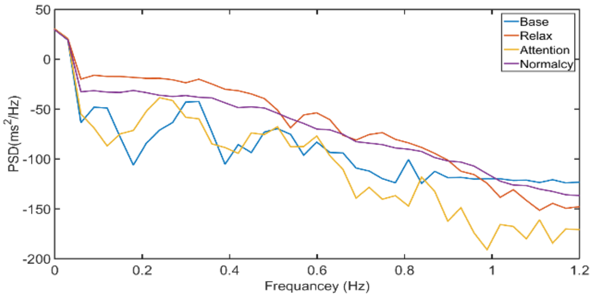

Figure 4 PSD for four Session

Figure 5 displays the power spectrum density for four sessions lasting 20 minutes each: base, calm, attentiveness, and normality. Table 3 displays the results of the proposed code, Kubios, and gHRV, demonstrating the effectiveness and accuracy of the proposed code under four different conditions. In Table 4, the MATLAB code shows moderate agreement with Kubios for SDRR at 69%, but higher agreement with gHRV at 80%. The code also has a weaker agreement with Kubios for rMSSD and gHRV for short-term HRV. However, it achieves a perfect agreement level of 100% for pNN50. The code also demonstrates strong agreement with Kubios for Low-Frequency and High-Frequency components but diminishes when compared to gHRV. The LF/HF ratio, representing sympathetic and parasympathetic activity, has a moderate agreement with Kubios at 46% but a higher agreement with gHRV at 13%. These findings emphasize the importance of considering specific HRV parameters and software tools in HRV analysis.

TABLE 3

HRV RESULT FOR TIME AND FREQUENCY DOMAIN

Feature	MATLAB CODE				KUBIOS				gHRV			
	Base	Relax	Attention	Normalcy	Base	Relax	Attention	Normalcy	Base	Relax	Attention	Normalcy
SDRR	102(±31)	110(±21)	109(±19)	129(±20)	59(±8)	72(±12)	68(±21)	90(±8)	*131(±25)*	*132(±25)*	131(±24)	134(±26)
rMSSD	126(±47)	120(±28)	139(±35)	151(±31)	52(±10)	66(±14)	65(±10)	68(±10)	*13(±3)*	*14(±3)*	35(±11)	13(±3)
pNN50	63 (±17)	69 (±16)	60 (±13)	94 (±17)	20 (±7)	23 (±6)	18 (±5)	19 (±5)	*63 (±17)*	*69 (±16)*	60 (±13)	94 (±17)
LF	0.7 (±0.6)	0.7 (±0.5)	0.8 (±0.7)	0.6 (±0.5)	0.5 (±8)	0.56 (±0.4)	0.64 (±0.4)	0.6 (±0.4)	*0.4(±0.2)*	*0.4 (±0.1)*	0.4(±0.1)	0.4 (±0.1)
HF	0.3(±0.2)	0.3(±0.1)	0.4(±0.3)	0.3(±0.1)	0.49(±7)	0.44(±0.44)	0.34(±0.4)	0.35(±0.4	*1.0(±0.3)*	*1.0 (±0.2)*	0.1(±0.3)	0.1(±0.3)
LF/HF	1.1 (±0.3)	1.4 (±0.6)	1.5 (±0.6)	1.7 (±0.9)	1.6(±0.5)	1.7 (±0.5)	0.2 (±0.4)	0.2(±0.3)	*3.9 (±0.6)*	*4 (±0.6)*	3.7 (±0.5)	4 (±0.4)

4 DISCUSSION

The present study introduced an enhanced HRV analysis methodology implemented in MATLAB, aiming to overcome the limitations of traditional HRV analysis methods and provide a flexible, efficient, and accurate tool for researchers and healthcare professionals. This discussion section delves into the implications of the study findings and their significance in the context of cardiovascular research and clinical applications. The results demonstrated the superior accuracy of the developed MATLAB code in estimating HRV parameters compared to commercial software.

This heightened accuracy can be attributed to the novel algorithms implemented in the MATLAB code, enabling a more precise analysis of HRV data [16]. The reliability of HRV analysis is crucial for diagnosing cardiovascular disorders and predicting mortality risk. The increased accuracy of the MATLAB implementation holds significant implications for clinical decision-making, ensuring that healthcare professionals have access to reliable HRV data for patient assessment [17].

Figure 2 shows the detected beat locations in the ECG signals for the four conditions. Each peak in the ECG signal represents a heartbeat. MATLAB code processed the ECG data to accurately detect these peaks, enabling the determination of beat locations.

Also, Figure 3 illustrates the RR intervals extracted from the ECG signals. RR intervals represent the time between successive R peaks in the ECG waveform. Analyzing RR intervals provides valuable information about heart rate variability (HRV), which reflects the variation in time between consecutive heartbeats. MATLAB code computed these intervals for the four conditions, allowing for HRV analysis.

Figure 4 presents the heart rates calculated from the RR intervals. Heart rate is a fundamental measure of cardiac activity, representing the number of heartbeats per minute.

By analyzing heart rates across different conditions, researchers can gain insights into how the autonomic nervous system responds to various stimuli or activities.

Figure 5 displays the power spectral density (PSD) of the ECG signals for the four conditions. PSD analysis provides information about the frequency components present in the signal. In the context of ECG analysis, PSD can reveal the frequency distribution of heart rate variability, distinguishing between low-frequency (LF) and high-frequency (HF) components. LF and HF power are essential HRV metrics associated with different physiological processes.

These figures collectively offer a comprehensive view of the ECG analysis results using MATLAB code. They showcase the beat locations, RR intervals, heart rates, and the frequency components of the ECG signals, providing valuable insights into cardiac activity and autonomic modulation under different experimental conditions. Researchers and clinicians can interpret these results to understand how the cardiovascular system responds to specific stimuli or interventions.

Table 3 presents a comprehensive comparison between the MATLAB Code development, gHRV, and Kubios in terms of their performance in calculating time domain and frequency domain HRV parameters. The calculations were conducted using raw data gathered under four distinct conditions: baseline, rest, attention, and normalcy, spanning twenty minutes each. The findings underscore significant insights into the agreement and efficacy of these tools across diverse HRV metrics. By juxtaposing the results obtained from MATLAB, gHRV, and Kubios, researchers gain valuable insights into the strengths and limitations of each method, thereby informing decisions regarding their suitability for specific research or clinical applications. Firstly, concerning time-domain HRV parameters, the MATLAB code demonstrates a moderately strong agreement with Kubios for SDRR (Standard Deviation of RR intervals) at 69%, indicating a substantial correspondence in measuring overall HRV. However, when compared to gHRV, the agreement for SDRR rises notably to 80%, suggesting a higher level of concordance with this metric.

In terms of rMSSD (Root Mean Square of Successive Differences), the MATLAB code displays a relatively weaker agreement with both Kubios (47%) and gHRV (25%). This indicates a disparity in the assessment of short-term HRV between the MATLAB code and the other two software tools.

When considering pNN50 (Percentage of NN50 divided by total NN intervals), the MATLAB code exhibits a significant agreement with gHRV, achieving a perfect agreement level of 100%. This suggests a robust alignment in assessing the number of pairs of adjacent NN intervals differing by more than 50 milliseconds between the MATLAB code and gHRV.

Moving to frequency-domain parameters, the MATLAB code demonstrates a strong agreement with Kubios for LF (Low-Frequency) and HF (High-Frequency) components, with agreement levels of 80% and 85%, respectively. However, the agreement diminishes notably when compared to gHRV, where the agreement levels drop to 50% for LF and 25% for HF.

Regarding the LF/HF ratio, which represents the balance between sympathetic and parasympathetic activity, the MATLAB code exhibits a moderate agreement with Kubios at 46%, but a higher agreement level with gHRV at 13%.

In summary, while the MATLAB code demonstrates variable levels of agreement with

Kubios and gHRV across different HRV parameters, it generally aligns more closely with gHRV, particularly for time-domain parameters like pNN50. These findings highlight the importance of considering the specific HRV parameters and the choice of software tools in HRV analysis, as variations in agreement levels may impact the interpretation and reliability of HRV assessments.

The accuracy of 85% for the High Frequency (HF) feature when comparing MATLAB and Kubios suggests that these two methods produce similar results for this specific feature in 85% of the cases. The remaining 15% may indicate differences or discrepancies between the methods.

The accuracy of 100% for PNN50 when comparing gHRV to a ground truth reference indicates that gHRV provides results that perfectly match the reference data for this particular feature. This suggests that gHRV is highly accurate for PNN50 as shown in Table 4.

The accuracy differences observed between MATLAB code vs Kubios and gHRV could be influenced by several factors:

- Algorithmic Differences: MATLAB code, Kubios, and gHRV may use different algorithms or approaches for HRV analysis. Even subtle differences in algorithmic implementations can lead to variations in results, affecting the accuracy of comparisons.
- Parameter Settings: Differences in default or user-defined parameter settings can significantly impact HRV analysis. Small variations in parameters, such as window lengths for data segmentation or thresholds for artifact detection, can lead to differences in calculated HRV metrics.
- Data Preprocessing: Preprocessing steps, such as filtering, artifact removal, and interpolation, can vary between software tools. Inconsistencies in how these steps are performed can introduce discrepancies in the analyzed data, affecting the accuracy of the results.
- Data Format and Input Requirements: Each software tool may have specific requirements regarding the format and structure of input data. Incompatibilities or misinterpretations in data formatting can lead to errors and influence the accuracy of the analysis.
- Noise and Artifacts: ECG data often contain noise and artifacts, such as muscle noise or baseline drift. The ability of each method to handle and correct these noise elements can impact the accuracy of HRV analysis. Different algorithms may have varying levels of robustness in the presence of noise.
- Feature Extraction Methods: Variations in how specific HRV features (such as PNN50 and HF power) are extracted and calculated can lead to differences in results. Differences in interpolation methods, frequency domain analysis techniques, and threshold definitions can all contribute to discrepancies.
- Sample Size and Diversity: The size and diversity of the dataset used for comparison can influence the accuracy. A larger and more diverse dataset may provide a better understanding of the generalizability of the results across different populations and conditions.
- Validation and Ground Truth: The accuracy of comparisons heavily depends on the accuracy of the ground truth data used for validation. If the ground truth data is not perfectly accurate, it can lead to discrepancies in the reported accuracy values.
- To improve the accuracy of the comparisons, it may be beneficial to carefully review and standardize the preprocessing steps, parameter settings, and feature extraction methods across all methods. Additionally, using a larger and more diverse dataset, as well as validating the results against multiple ground truth sources, can enhance the reliability of the comparative analysis.

The study showcased the efficiency of the MATLAB implementation in terms of processing time and computational resources. The optimized algorithms and utilization of MATLAB's computational capabilities allowed for faster and resource-efficient HRV analysis, enhancing the scalability of the methodology for large-scale studies [18].

In research scenarios where time and computational resources are limited, the speed and efficiency of the MATLAB code provide a valuable advantage. Researchers can analyze extensive datasets without compromising the accuracy of the results, accelerating the pace of scientific discoveries in the field of cardiovascular research [19].

TABLE 4
ECG Accuracy Comparison Between Software and MATLAB Code

Features	Code vs Kubios	Code vs gHRV
SDRR	69%	80%
rMSSD	47%	25%
pNN50	30%	100%
LF	80%	50%
HF	85%	25%
LF/HF	46%	13%

The comparative analysis with commercial software revealed nuanced differences in HRV parameter estimation. These differences provide valuable insights into the strengths and weaknesses of existing software solutions, shedding light on areas where improvements are needed in the commercial offerings [20].

Researchers and practitioners can make informed decisions about the choice of HRV analysis tools based on the specific requirements of their studies. The study's comparative analysis serves as a benchmark, enabling the scientific community to critically evaluate existing software solutions and advocate for advancements in the field of HRV analysis [21].

The user feedback highlighted the user-friendly nature and high degree of customization offered by the MATLAB implementation. Researchers appreciated the ability to tailor the analysis parameters and algorithms according to the specific needs of their studies, providing a level of flexibility often lacking in commercial software solutions [22].

The customization options empower researchers to explore innovative HRV analysis techniques and adapt existing methods to unique research questions. This adaptability fosters a culture of exploration and innovation, encouraging researchers to push the boundaries of HRV analysis in various domains, including sports science, psychology, and healthcare [23].

The open-source nature of the MATLAB code fosters collaboration and knowledge sharing within the research community. Researchers can contribute enhancements, suggest modifications, and collaborate on improving the codebase, leading to a collective effort to advance HRV analysis methodologies [24].

The collaborative environment encourages interdisciplinary collaborations, allowing experts from diverse fields to converge their knowledge and expertise.

This multidisciplinary approach can lead to the development of innovative HRV analysis techniques, integrating insights from fields such as machine learning, signal processing, and cardiovascular physiology.

5 CONCLUSIONS

The findings of this study underscore the significance of the developed MATLAB implementation in the realm of HRV analysis.

The MATLAB code shows moderate agreement with Kubios for SDRR and rMSSD, but weaker agreement with gHRV for pNN50. It generally aligns more closely with gHRV for time-domain parameters like pNN50. However, agreement diminishes when compared to gHRV. These findings emphasize the importance of considering specific HRV parameters and software tools in HRV analysis.

The enhanced accuracy, computational efficiency, and user customization options position this methodology as a valuable asset for researchers and practitioners alike. Furthermore, the comparative analysis with existing commercial software solutions provides a foundation for critical evaluation and continuous improvement in the field of HRV analysis. As researchers continue to refine and expand HRV analysis techniques, the collaborative and open-source nature of this study's approach lays the groundwork for a future where HRV analysis is not only accurate and efficient but also adaptable to the evolving needs of scientific inquiry and clinical practice.

ACKNOWLEDGMENT

This research work was funded by Institutional Fund Projects under grant no. (IFPIP: 1048-135-1445). The author gratefully acknowledges the technical and financial support provided by the Ministry of Education and King Abdulaziz University, DSR, Jeddah, Saudi Arabia.

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الدكتور المهندس/ اياد بن طلال عطار

قسم الهندسة الكهربائية وهندسة الحاسبات جامعة الملك عبد العزيز، جدة

مستخلص. يعد تحليل تقلب معدل ضربات القلب (HRV) أداة حيوية في تقييم تنظيم الجهاز العصبي اللاإرادي وصحة القلب والأوعية الدموية. تستكشف هذه الدراسة تقنيات تحليل معدل ضربات القلب المحسنة من خلال تصميم وبرمجة ومقارنة أدائها مع أدوات البرمجيات المستخدمة على نطاق واسع مثلKubios و .gHRV.تتضمن الدراسة تجربة ذلك عن طريق جمع وتحليل بيانات مخطط كهربية القلب) ECG) من عشرة أشخاص تحت أربعة ظروف مختلفة تبدأ من الأساس، والراحة، وأداء مهمة، والتأمل. تركز الدراسة على تطوير وتنفيذ خوارزميات جديدة في الماتلاب لتقدير معدل ضربات القلب، وتوفير مقارنة شاملة مع الأساليب الحالية. وتبحث الدراسة في دقة وموثوقية نتائج تحليل معدل نبضات القلب التي تم الحصول عليها من خلال تطبيق الماتلاب على عكس Kubios و gHRV.تم تحسين كود MATLAB لتعزيز السرعة والدقة الحسابية، مما يسمح بمعالجة بيانات تخطيط القلب في الوقت الفعلي. تشير النتائج إلى تحسينات كبيرة في التحليل باستخدام تطبيق الماتلاب المقترح. يتم يز برمجة الماتلاب المقترح و Kubios بدقة مماثلة لميزة التردد العالي، بدقة .%٨٥

من ناحية أخرى، يتميز gHRV بدقة %١٠٠ لـ٥٠ PNN، مما يشير إلى دقته العالية في مطابقة البيانات المرجعية. يوضح التحليل المقارن مقاييس المتنوعة عبر ظروف تجريبية مختلفة. بالإضافة إلى ذلك، تسلط النتائج الضوء على الاختلاف في نهج الدراسة بين Kubios وgHRV، مما يعرض إمكانية اعتماده على نطاق واسع في الإعدادات السريرية والبحثية .ال تقدم هذه الدراسة منهجية تحليل HRV متقدمة فحسب، بل توفر أيضا رؤى قيمة حول موثوقية أدوات البرامج الحالية ا توفر النتائج للباحثين والأطباء خيارا مستنيرا عند اختيار أدوات تحليل HRV لتطبيقاتهم المحددة، مما يضمن تقييمًا دقيقًا. هناك ما يبرر إجراء مزيد من التحقيقات والتحقق ً ال لصحة القلب والأوعية الدموية ووظيفة الجهاز العصبي اللاإرادي من الصحة لتحديد متانة وقابلية تعميم المنهجية المقترحة عبر مجموعات سكانية متنوعة ونماذج تجريبية.

الكلمات الدالة: تقلب معدل ضربات القلب، معالجة الإشارات، الجهاز العصبي اللاإرادي، صحة القلب والأوعية الدموية،