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A Combined ECG and PPG Signal Powered Artificial Intelligence-Based Prediction Model for Stroke

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Abstract

Stroke is one of the most common causes of morbidity and mortality around the world, and emphasis on prevention and early detection strategies cannot be overstated. This review aims to integrate techniques of artificial intelligence with electrocardiogram and photoplethysmogram signals to enhance stroke prediction and monitoring of cardiovascular health. All in all, the application of artificial intelligence that incorporates machine learning, deep learning, or hybrid models gives robust tools toward the analysis of very complicated bio-signals and enhances real-time, personalized early detection towards conditions like atrial fibrillation and vascular irregularity. Such developments can easily go hand in hand with these wearable technology and telemedicine applications. Despite the challenges of variability in data, noise, and ethical issues, ECG and PPG-based synergistic use with AI has immense potential to transform stroke prevention and patient outcome. This study highlights recent advancements, challenges, and future directions in this transformative field.

Keywords: Stroke prediction, artificial intelligence, ECG, PPG, machine learning, deep learning, hybrid models, wearable technology, telemedicine, cardiovascular monitoring

INTRODUCTION

Stroke ranks as the second biggest cause of mortality globally, accounting for about 5.5 million fatalities, and is one of the most prevalent and debilitating conditions [1]. Stroke is a life-threatening medical condition and one of the most important global health problems, as it refers to the sudden interruption of blood flow to the brain, resulting in the rapid death of brain cells. One of the leading causes of death and disability around the world, stroke impacts millions every year, leaving many with severe physical, cognitive, and emotional challenges [2]. A good majority of strokes are preventable due to links with modifiable risk factors such as high blood pressure, smoking, and poor lifestyles, which makes them pose significant burdens on healthcare systems and economies. The need for rapid treatment combined with long-term rehabilitation indicates a great need for stroke prevention in improving the understanding of public awareness and in relation to time access to care services [3].

Bio-signals like Electrocardiograms and Photoplethysmograms are the most important signals in predicting or preventing strokes. They contain critical information regarding cardiovascular as well as physiological conditions leading to the event. A key tool for monitoring heart electrical activity, ECG can be used to determine arrhythmia such as atrial fibrillation that is a major risk factor for ischemic stroke [4]. Sometimes, such pathological ECG patterns may be characterized by abnormal rhythms or prolonged QT intervals, thereby increasing the risk of clot formation. That is why ECG is highly essential in assessing and

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Figure 1. Top bio-signals and technologies in stroke prediction.

immediately treating a patient because it can foretell the chance of stroke with its actual-time detection of anomalies from the use of wearable ECG. A complement to ECG is the PPG, which uses sensors measuring volumes of blood in tissues via light, and thereby obtains details on heart rate, flow of blood, and even saturation of oxygen. This technique is non-invasive and sensitive to the detection of abnormal heartbeats and vascular abnormalities, which are precursors to stroke risk. Continuous cardiovascular monitoring in wearable technology like smartwatches can be achieved with PPG in support of ECG [5]. Thus, with both ECG and PPG, the accuracy of predicting stroke improves. It combines heart electrical activity data with vascular and blood flow patterns to enable early high-risk identification and facilitate timely preventive measures, such as medication or lifestyle changes. This is further enhanced by using wearable devices and telemedicine for an improved healthcare model that provides patients with real-time monitoring and alerts, facilitating early intervention and reducing the burden of stroke. These are crucial bio-signatures in the modern world since they play a transformative role in predicting and preventing one of the leading causes of disability and death globally [6].

Figure 1 illustrates how ECG and PPG signals are crucial in predicting stroke risks, along with the wearable technology and telemedicine interface. It demonstrates how bio signal analysis and advanced technologies integrate to encourage early identification as well as real-time monitoring of health, which will immediately allow for medical interventions before the occurrence of a stroke. AI plays a sensational role in combining ECG and PPG signals. Such an approach is powerful in understanding complex dynamics in cardiovascular systems. The former can give detailed insights into electrical activity, whereas the latter measures blood flow and volume changes in peripheral tissues. When both these signals are analyzed together, it offers complementary information regarding heart rhythm, blood circulation, and overall cardiovascular health [7]. AI, especially through the power of machine learning and deep learning algorithms, allows it to extract subtle patterns and correlations from these large, complex datasets that might otherwise be missed by traditional analysis methods. Such capability is critical for the early detection of conditions such as atrial fibrillation, and other cardiac abnormalities that markedly increase the risk of stroke. Thus, by combining information from both signals, AI also improves the accuracy of diagnoses through real-time monitoring and helps in predicting cardiovascular accuracy with more accuracy [8].

In wearable and in telemedicine solutions, wherein continuous monitoring is essential for continuous health tracking, ECG and PPG signals when combined become very useful for the user, with AI-driven signal processing for detecting anomalies and creating appropriate alerts [9]. This combination between bio-signals and AI can better help predict the probability of a stroke as it helps the healthcare services for better care through customized patterns. Besides this, AI-based systems are scalable and cost-effective cardiovascular monitoring systems, which can help bring advanced diagnostic capabilities to larger populations. This research is further expanding with great potential to revolutionize stroke prevention, enhance patient outcomes, and change the landscape of cardiovascular healthcare through its application of AI in integrating the analysis of ECG and PPG [10].

With the integration of ECG and PPG bio-signals, wearable devices, and AI-driven technologies, this stage has now been able to prevent and predict strokes. These tools will enable one to gain critical insight

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into cardiovascular health and to have the early detection of risk factors like arrhythmias and vascular abnormalities. Thus, adequate time would be provided for intervention [11]. Accurate diagnosis increases precision and enables real-time monitoring of health because AI can interpret large and complex data sets. This will improve stroke management and prevention, which allows access to more advanced solutions hence bringing the change in the cardiovascular world and reducing the global burden of stroke.

BIO-SIGNALS IN STROKE PREDICTION

Electrocardiograms represent essential tools in modern medicine; most importantly, they would provide a comprehensive view into electrical activity of the heart and relate very well to predicting and the prevention of strokes. ECGs can detect numerous abnormalities that often precede the most serious cardiovascular events from analysis of heart rhythm and pattern [12]. Of course, one of the most important of these is atrial fibrillation, an irregular heartbeat, which greatly increases the chance of having an ischemic stroke due to clots formed in this manner, which then travels to the brain and cuts off blood flow. Beyond this, ECGs may also identify other risk factors for stroke, including prolonged QT intervals and ventricular arrhythmias, indicative of some kind of underlying heart disease that may not be conducting blood well. ECG is a tool that has progressed along with wearable devices and the fact that they can continuously monitor real-time cardiac health. This allows the detection of minor alterations in heart rhythms over longer periods, which would otherwise not be noted in a routine clinical assessment [13]. It is of paramount importance for the high-risk patient, as the earlier it is detected, the better the prevention against further progression to stroke. With their advanced diagnostic capabilities married with ease of use and accessibility, ECGs have become indispensable tools in proactive cardiovascular care in predicting and mitigating risks for stroke while improving health outcomes [14].

Cardiovascular monitoring requires PPG information: they are a noninvasive means to acquire vital information regarding vascular health but represent an adjunct capability in ECGs. The principles of light-based sensors focus on changes in peripheral tissue blood volume as well as rate. It measures heart rate and blood flow. More notably, it monitors oxygen levels, which are significant features required when trying to establish if unusual heartbeats and patterns of vascular behavior might develop, increasing the likelihood for stroke [15]. These subtle alterations are responsive to PPG, and therefore, it is a highly useful tool for the early identification of stroke risk factors, particularly in people with some level of underlying vascular pathology. PPG has advanced further through its incorporation into wearable devices such as smartwatches, thereby making available an accessible, continuous, and real-time method for monitoring cardiovascular health. By supporting proactive management of vascular conditions, PPG enables preventive approaches to health care. The result is the early identification of risk factors and intervention before a person is likely to suffer a stroke or another cardiovascular event [16]. Accessibility, accuracy, and continuous monitoring through PPG make it the cornerstone in modern cardiovascular health assessment and management.

Combining analysis of ECG and PPG signals would form a synergetic, yet very effective approach toward the stroke-prediction mechanism as integrated strengths of both bio-signals provide a more panoramic view of cardiovascular health. While ECG concentrates on detecting electrical activity in the heart, it picks out some irregular heartbeats that mimic the rhythm of atrial fibrillation and other anomalies which are critical precursors for stroke [17]. The other technology, which monitors peripheral blood flow and vascular health by tracking changes in blood volume and oxygen saturation using light-based sensors, proves to be complementary when paired with this other technology. That is because when these technologies are combined, they together offer information on both the function of the heart and the condition of the blood vessels [18]. The integration of both ECG and PPG can significantly increase the accuracy in stroke risk prediction because they both can detect a larger scope of abnormalities, such as arrhythmias and vascular irregularities, which may not appear when one modality alone is used. Integration of ECG and PPG data helps healthcare providers approach the strategy in a holistic manner and enables early detection of problems with interventions targeted at the cardiac and vascular contributors of stroke risk [19]. This synergy would be especially valuable in the context of

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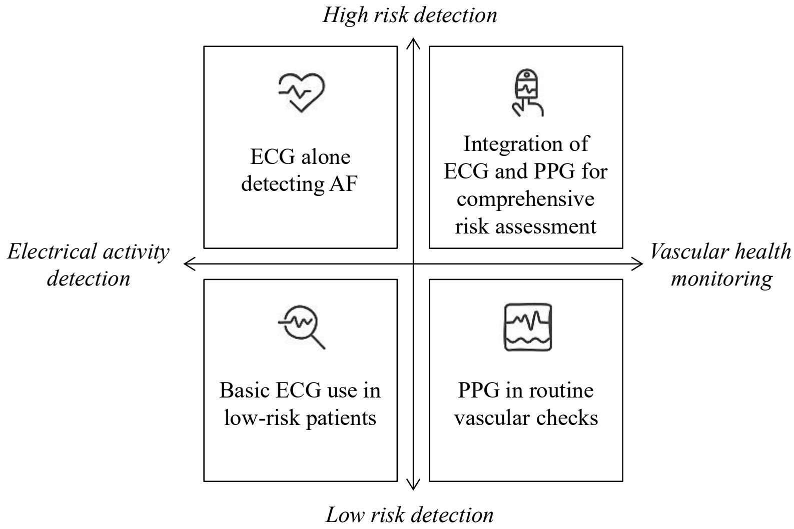

Figure 2. Comparative analysis of ECG and PPG in stroke risk prediction.

Table 1. Research developments in AI for ECG and PPG-Based cardiovascular analysis.

Reference	Study focus	Key findings	Outcomes
[1]	Stroke as a global health issue	Stroke is the second leading cause of mortality, largely preventable through modifiable risk factors.	Emphasized the importance of public awareness and preventive strategies to reduce stroke incidence and related healthcare burdens.
[4]	Role of ECG in stroke prediction	ECG detects arrhythmias like atrial fibrillation, a major stroke risk factor, through real-time monitoring.	Improved early detection and intervention, reducing the likelihood of ischemic stroke and its associated complications.
[5]	Role of PPG in cardiovascular monitoring	PPG provides insights into blood flow, heart rate, and vascular health using non-invasive light-based sensors.	Enhanced continuous monitoring and early detection of stroke-related vascular abnormalities, particularly through wearable devices.
[7]	AI in analyzing ECG and PPG signals	AI integrates ECG and PPG data to uncover subtle cardiovascular patterns and correlations.	Improved accuracy in diagnosing arrhythmias and predicting stroke risk, enabling real-time health monitoring and personalized interventions.
[9]	Combination of bio-signals and wearable technology	Wearables with AI-driven ECG and PPG analysis detect anomalies and generate alerts for healthcare providers.	Scalability and cost-effectiveness in cardiovascular monitoring, expanding access to advanced diagnostics for larger populations.
[10]	Potential of AI-driven ECG and PPG integration	AI models extract patterns from combined bio-signals, improving prediction accuracy.	Revolutionized cardiovascular healthcare with real-time, actionable insights through wearable and telemedicine solutions.
[20]	Machine learning for ECG and PPG signal analysis	ML algorithms like SVMs and Random Forests classify abnormalities and manage noisy datasets.	Reliable prediction of stroke risk with interpretable outputs, aiding clinical decision-making.
[22]	Deep learning for advanced bio-signal analysis	CNNs detect spatial features; RNNs model temporal dynamics for complex signal patterns.	High accuracy in identifying abnormalities and enabling real-time stroke prediction with deep learning architectures.
[24]	Hybrid models combining ML and DL approaches	Hybrid models integrate ML feature selection with DL for precise classification and robust analysis.	Enhanced scalability, robustness, and adaptability in real-world clinical applications, supporting early and accurate stroke prediction.
[26]	Challenges in implementing AI for bio-signal analysis	Challenges include data variability, noise, privacy concerns, and computational demands.	Recommendations for developing interpretable AI models, federated learning, and standardized protocols for broader clinical adoption.

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wearable technology; continuous monitoring of both signals can provide real-time assessment and support preventive healthcare with precise and actionable insights for patients and clinicians.

Figure 2 shows wearable devices and AI-driven technologies have integrated ECG and PPG bio-signals with immense potential to transform the approach to stroke prevention and management. These technologies offer insights into cardiovascular health by integrating electrical activity data from ECG with vascular and blood flow data from PPG. AI algorithms play an important role in this process, in that bio-signals can be analyzed in real time and subtle patterns, correlations, or anomalies identified that may foretell increase stroke risk. This stronger analytical capability helps enhance the possibility of diagnosis but also assists in tailoring personalized healthcare solutions, where preventive measures and treatments may be specifically tailor-made to meet the individual requirements. Practicality is taken to another level with the introduction of wearable devices that provide constant monitoring and timely alerts, empowering both the patients and their care providers to act on time. It is in this integration that ECG and PPG with AI-driven analysis promise to change cardiovascular monitoring systems for scalable accessible and precise tools in the reduction of a burdensome disease like stroke with great improvements in patient outcomes. Moreover, Table 1 underscores the research developments in AI for ECG and PPG-based cardiovascular analysis.

AI TECHNIQUES FOR ANALYZING ECG AND PPG

AI presents advanced tools for signal processing in ECG and PPG to enhance the detection of cardiac anomalies and stroke risk better with improved accuracy and efficiency. All the approaches from machine learning to deep learning and the hybrid models enable AI to attain accurate and complete bio-signal analysis, offering unique contributions to medical diagnostics and predictive healthcare.

Machine Learning

Among these algorithms, the most widely used ones are Support Vector Machines, Random Forests, and K-Nearest Neighbors algorithms. ECG and PPG are crucial signals in cardiovascular health; ML algorithms are of particular importance for analyzing these, particularly because they are very potent in finding intricate patterns or classifying abnormalities in signal analysis. They can even tell the condition of atrial fibrillation, an important risk for stroke. Their ability to detect slight changes in the signal's properties enables medical doctors to make diagnoses earlier and more precisely, which will result in better patient outcomes [20]. All these algorithms have distinct strengths and specific applications for use within the domain of bio-signals, rendering them valuable resources for medical technology applications today. For instance, Support Vector Machines have been extensively used for classifying normal and abnormal heart rhythms by constructing hyperplanes which separate distinct classes of signals. This capability makes SVMs very effective in distinguishing healthy cardiac activity from early manifestations of arrhythmias. Meanwhile, random forests are best for noisy high dimensional input data typically seen in clinical settings possibly due to some artifacts or environment affecting a particular signal.

Overall, because several decision trees are combined into their predictive algorithm, random forests are very accurate and robust enough, even so, making them particularly favored by these complex and variable datasets. KNN, with its simplicity and effectiveness in pattern recognition, is also used for bio-signals classification based on similarity to known patterns, thereby expanding the scope of ML applications in cardiovascular diagnostics. Most ML approaches rely on the extraction of key features from the bio-signals, such as heart rate variability, signal amplitude, and waveform morphology [21]. These features are used to train models capable of predictive tasks, such as risk assessment for stroke and the early detection of cardiovascular disorders. The reliance of the ML algorithms on these manually extracted parameters gives a robust and interpretable basis for analysis of bio-signals, hence ensuring that the insights obtained will be actionable in clinical decision-making. Integration of machine learning into bio-signal analysis is enhancing the precision of diagnosis while opening the doors to more personalized and preventive health strategies, thereby pointing out the transformative potential of this aspect in modern medicine.

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Deep Learning

Deep learning has dramatically improved the signal analysis in ECG and PPG. Automated features were previously extracted, as was done in machine learning methods with a lot of manual effort. This automaticity now enables the analysis of more complex and finer-grained features, and thereby more accurate and efficient diagnosis. Neural networks, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), have emerged as particularly effective tools for capturing complex patterns and temporal dynamics within bio-signals, revolutionizing the way these signals are processed and interpreted. In general, the capability to discover spatial features is outstanding within ECG and PPG waveforms of CNN in recognizing subtle anomalies, thereby helping in discovering cardiac malfunctions [22]. By processing information hierarchically, CNN can acquire a significant number of features or feature aspects related to shape, wave, and amplitudes that show remarkable accuracy in measurements. On the other hand, because RNNs are designed particularly for sequential data, making them highly suitable for handling temporal relationships inherent in the bio-signals, their design allows them to track temporal changes in signal patterns, giving deeper insights into conditions as dynamic as arrhythmias. More architectures include the LSTM network; this is a further enhancement of deep learning, giving the possibility of examining dependencies in time-series data which come with long durations. That is found useful in applications such as predicting real-time strokes and doing constant cardiovascular monitoring where it must be able to detect anomalies over long horizons [23]. By infusing deep learning into bio-signal analysis, the healthcare systems can provide levels of accuracy and efficiency unparalleled in the past with timely interventions and personalized care. It shows that these networks are indeed transformative in their capacity to learn directly from raw data and do not rely on features which are manually crafted by man, thus setting a new benchmark for innovation in predictive healthcare.

Hybrid Models

Hybrid models are the innovation that lies behind the thought of ECG and PPG signal analysis, bringing advantages from both ML and DL models towards greater accuracy, robustness, and scalability. In hybrid models, these inherent limitations easily overcome the applications by using ML alone or the applications by using DL alone, because here the methodology of AI is integrated nicely in a coherent manner. This integration enables a more holistic solution regarding reliability support and developing feasible frameworks for cardiovascular monitoring along with stroke predictions. The combination of technologies leads to even stronger systems that can manage their way through the demanding situations surrounding bio-signal analysis considering complexity [24]. The standard hybrid framework typically initiates the process by running machine learning algorithms such as the Random Forest algorithm, aiming at feature selection. The former step is highly significant due to the ability of any selected algorithm to indicate appropriate features from data sets relating to heart rate variability amplitude or waveform or any important metrics that represent the potential of cardiovascular health. ML algorithms work best in this initial phase, as they are simple and efficient with the ability to effectively process structured data. This helps the model to reduce the computation overhead regarding only the most important features and parameters most relevant for proper diagnosis.

Once the relevant features are identified, they are passed on to a deep learning model, like a Convolutional Neural Network (CNN). This now brings the more advanced capabilities in pattern recognition of the CNNs into the next analysis stage. These networks are best suited for detecting subtle, intricate, high-dimensional patterns in the data, mainly at their own sweet spot of complex classification/prediction of abnormalities in bio-signals [25]. This layered approach ensures that the preliminary computational efficiency and simplicity of ML is coupled with the advanced, data-driven learning capabilities of DL for obtaining a much more holistic and accurate analysis of bio-signals. Hybrid models have demonstrated great performance in handling various datasets and complex scenarios. For example, data in real-world medical settings is often noisy, high-dimensional, or imbalanced. Hybrid models are uniquely placed in addressing these challenges and have robust solutions that can scale for different applications and conditions. Hybrid models are particularly useful when applied in real-time stroke prediction scenarios, where fast and accurate analysis is the difference

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between effectiveness and inefficiency, or as part of personalized healthcare solutions in which tailored insights make effective treatment the difference between living and dying [26]. Hybrid models go beyond the sum of their parts, combining the strengths of ML and DL, to provide a cohesive and efficient solution for the analysis of ECG and PPG signals. Adaptability and scalability make them perfect candidates for next-generation diagnostic tools, which can open avenues for innovations in medical signal analysis. Hybrid models will set new standards in accuracy and reliability in healthcare. They transform the way cardiovascular conditions can be monitored, predicted, and managed due to the precise, efficient, and actionable insights they deliver. This is a considerable step forward, demonstrating the prospects of hybrid models revolutionizing medical diagnostics.

CHALLENGES AND FUTURE DIRECTIONS

AI for processing ECG and PPG signals is therefore accompanied by some challenges since it involves natural complexity and variability in the real-world data. Bio-signals are noise-prone and prone to artifacts and environmental factors that significantly affect the performance and reliability of the AI model. Wearable sensors, for example, will likely experience artifacts from motion artifacts or even inconsistent placements of the sensor leading to false predictions. Another critical challenge would be the generalization of AI models across diverse patient populations because of the variation in the physiological characteristics, underlying health conditions, and sometimes even lifestyle factors from culture or region may introduce biases that may limit the applicability of the models. Other significant issues are related to ethical and regulatory considerations in healthcare AI. Other challenges that need to be addressed before large-scale deployment include data privacy, achieving algorithmic transparency, and clinical validation requirements. Data generated by continuous monitoring through wearable devices is similarly vast and creates additional computational efficiency, storage, and security-related challenges. Therefore, these technologies must overcome many fundamental complications if AI is to be integrated successfully within cardiovascular health monitoring systems.

As the prospects for AI-driven bio-signal analysis are set to leap forward, the requirements for overcoming current constraints will determine the transformative advances that increase clinical adoption. Other significant areas include enhancing the interpretability and explainability of AI models to create trust among healthcare professionals and patients. Systems that produce not only accurate predictions but insights into decision-making processes, so that clinicians can understand and validate the outcome. A very important step will also be how one develops standardized protocols for how one should incorporate AI in clinical workflows such that it is easy for these technologies to be used in every form of health care facility. Research is also trending toward hybrid models that combine the best of machine learning and deep learning techniques to enhance accuracy, robustness, and scalability. Federated learning approaches also offer promising solutions to data privacy issues, allowing for decentralized training of AI models without compromising sensitive patient information. Wearable technologies, as well as telemedicine advancements, can potentially continuously monitor and analyze in real-time, providing a more customized and accessible system of health care. The above innovations, therefore, are expected to grow and mature with AI integration into stroke prediction and cardiovascular care in redefining preventive health care by improving patient outcomes and reducing the global burden of cardiovascular diseases.

CONCLUSION

Electrocardiogram and photoplethysmogram signals combined with artificial intelligence make tremendous changes in the stroke prediction and monitoring of cardiovascular diseases. AI techniques implement machine learning and deep learning for finding minute patterns amidst the complex bio-signals so that atrial fibrillation or other vascular irregularities might be enabled to detect conditions, timely intervention of which could reduce stroke risk. Accessibility in wearable devices and telemedicine can present a possibility for continuous monitoring and real-time monitoring together with linking patients who may be far from advanced care. Challenges concerning variability in the data, ethical concerns and the computational cost cannot override the promises AI-driven bio-signals could

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hold for altering the world. The above are challenges that are not only surmountable but through novel research in scalable solutions and interpretable AI models pave a way toward their widespread adoption in the clinics. Artificial intelligence will break the burden of stroke for millions, and advance preventive cardiovascular care with proactive and personalized healthcare.

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