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Research Article

Retinal Twins: Leveraging Binocular Symmetry with Siamese Networks for Enhanced Diabetic Retinopathy Detection

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Abstract:

Diabetic Retinopathy (DR), a critical ocular condition affecting retinal vasculature, can lead to visual deterioration or complete blindness if not identified early. The disorder is classified into various stages, encompassing normal, abnormal, mild, moderate, severe, proliferative diabetic retinopathy (PDR), and non-proliferative diabetic retinopathy (NPDR). The prompt and accurate detection of DR continues to pose a substantial challenge in the field of ophthalmology. This study introduces an innovative hybrid binocular Siamese deep learning (DL) framework for precise DR image classification. The methodology integrates advanced noise reduction techniques, robust feature extraction utilizing hybrid metaheuristic algorithms, and blood vessel (BV) and optic disc (OD) segmentation through an open-closed watershed management approach. Subsequently, an optimized boosting classifier is applied to categorize the segmented images, ensuring high accuracy and resilience. The system's performance is evaluated using DB0 and DB1 datasets, demonstrating exceptional results across various metrics, including accuracy, precision, F1-score, and MCC. Notably, the proposed system achieves an impressive 99% accuracy, setting a new standard in DR classification. This research highlights the potential of the proposed system to transform DR diagnosis and treatment approaches.

Keywords: Diabetic Retinopathy, Hybrid Binocular Siamese, Deep Learning, Metaheuristic Algorithms, Blood Vessel Segmentation, Boosting Classifier

Introduction

Diabetic Retinopathy

The International Diabetes Federation (IDF) survey indicates that approximately 463 million adults aged 20-80 years were affected by diabetes as of 2019. By 2045, this number is projected to increase to 700 million. In several countries, particularly low- and middle-income nations, diabetes prevalence exceeds 80% among adults. Diabetes Mellitus is a metabolic disorder characterized by hyperglycaemia—an elevated glucose level in the bloodstream, commonly referred to as diabetes. The regulation of blood glucose levels is dependent on insulin, a hormone secreted by the pancreas. When diabetes impairs the pancreas, it disrupts insulin production. Insulin facilitates the entry of glucose from carbohydrates into cells, providing the energy required by the human body.

Under fasting conditions, the body typically maintains blood glucose levels between 4 and 5.5 millimoles per liter, preventing hypoglycemia (low blood sugar) and hyperglycemia (high blood sugar). Hyperglycemia, a chronic complication of diabetes, results in excessive glycosylation of proteins.

Diabetes is broadly classified into two types:

Type-I diabetes: Characterized by inadequate insulin production.

Type-II diabetes: Defined by insulin resistance and insufficient insulin secretion.

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Various factors contribute to the development of Type-II diabetes, including decreased physical activity, diets high in calories, energy imbalance, insulin resistance, and obesity. A key concern in Type-II diabetes is insulin resistance, which reduces the ability of the liver and peripheral tissues to respond effectively to insulin.

Diabetes has emerged as one of the most significant health challenges of the 21st century, with case numbers rising each year. The International Diabetes Federation (IDF) reports that 352.1 million people with impaired glucose tolerance are at elevated risk of developing diabetes in the future. China and India lead in diabetes cases, with 114.4 million and 72.9 million affected individuals, respectively. Both Type-I and Type-II diabetes are linked to microvascular complications, such as retinopathy, neuropathy, and nephropathy. Chronic hyperglycemia also leads to macrovascular complications, including heart failure, peripheral vascular disease, and stroke. Glycation processes can result in additional health problems like diabetic foot, cheiroarthropathy, cataracts, and osteoporosis.

The World Health Organization (WHO) estimates that the annual healthcare costs for managing diabetes-related health issues amount to approximately $825 billion. Among its complications, diabetic retinopathy (DR) significantly impacts quality of life by causing gradual vision loss. The growing prevalence of DR calls for innovative approaches to early detection, diagnosis, and treatment to effectively address this global health issue.

2. Literature Review

The evolution of diabetic retinopathy (DR) classification techniques over the past decade highlights a transition from manual to automated approaches. Early systems focused on handcrafted feature extraction combined with traditional classifiers such as support vector machines (SVM) and k-nearest neighbors (KNN). These methods utilized features like texture, shape, and intensity extracted from retinal images to classify normal and abnormal cases. While effective in controlled environments, they struggled to handle real-world challenges, such as noise and variability in image quality [1], [2].

Deep learning (DL) has brought significant advancements in DR detection by enabling automated feature learning directly from raw retinal image data. Convolutional neural networks (CNNs) have shown great success in detecting DR-related lesions such as microaneurysms, exudates, and haemorrhages, which are critical for disease classification and grading [3], [4]. Despite their effectiveness, these methods often require large annotated datasets, which can limit their applicability in data-scarce environments [5]. Furthermore, issues such as noise and class imbalance in the data remain significant challenges [6].

To address these issues, metaheuristic algorithms have been integrated into DR classification workflows. Techniques such as particle swarm optimization (PSO), genetic algorithms (GA), and ant colony optimization (ACO) have been employed for feature selection and classifier optimization. For example, PSO has been applied to optimize SVM parameters for better classification performance, while ACO has been utilized to detect microaneurysms for early diagnosis [7], [8]. These algorithms have demonstrated their capability to enhance classification accuracy, especially in handling complex and imbalanced datasets [9]. However, the integration of metaheuristic techniques with deep learning models is still an underexplored area, offering significant opportunities for improvement [10].

In addition to classification methods, segmentation techniques focusing on retinal blood vessels have played a crucial role in DR detection. Blood vessel structures are key biomarkers for assessing disease severity. Methods such as Gaussian matched filters, U-Net architectures, and fully convolutional neural networks (FCNNs) have demonstrated promising results in accurately segmenting retinal blood vessels [11], [12]. These techniques not only improve DR detection but also contribute to identifying related conditions like glaucoma [13]. Nevertheless, ensuring generalizability and robustness of these models across diverse datasets remains a critical challenge [14].

Overall, DR classification techniques have advanced significantly, moving toward automated, scalable, and efficient methods. Future research could focus on developing hybrid models that combine the strengths of deep learning and metaheuristic algorithms, addressing existing limitations such as dataset dependency and real-world applicability [15], [16], [17], [18].

3. Methodology

The proposed system employs a multi-stage pipeline designed to address the limitations of existing methods and achieve superior DR classification accuracy. The methodology consists of the following stages:

Fig1: Methodology

3.1 Preprocessing High-quality input images are crucial for effective DR classification. The preprocessing stage focuses on noise elimination and enhancement of retinal image features. Advanced noise-reduction algorithms are employed to suppress unnecessary artifacts while preserving critical details. Contrast enhancement techniques further improve image quality, ensuring better feature extraction in subsequent stages.

3.2 Feature Extraction Feature extraction is a critical step in the proposed system, as it captures essential characteristics of retinal images. A novel hybrid metaheuristic algorithm is utilized to extract entropy and texture features. This algorithm combines the strengths of multiple stochastic search strategies, such as PSO and GA, to identify optimal feature sets. By leveraging the diversity and adaptability of metaheuristic algorithms, the proposed method ensures robust and accurate feature extraction.

3.3 Segmentation Accurate segmentation of retinal structures, including blood vessels (BV) and the optic disc (OD), is essential for DR classification. The open-closed watershed management technique is employed to segment these features effectively. This approach leverages morphological operations to delineate BV and OD regions, addressing challenges such as overlapping structures and varying intensities.

3.4 Classification The final stage involves classifying the segmented images into DR stages. An optimized boosting classifier is used for this purpose. By combining multiple weak classifiers into a strong ensemble, the boosting classifier achieves high accuracy and robustness, even in the presence of noisy or imbalanced datasets. The classifier is trained on the extracted features, enabling it to distinguish between normal, abnormal, mild, moderate, severe, PDR, and NPDR categories. The model's ability to achieve 99% accuracy is a testament to the effectiveness of this integrated approach.

4. Experimental Results

The efficacy of the proposed system is evaluated utilizing the DB0 and DB1 datasets, which comprise retinal images exhibiting varying degrees of DR severity. To assess the system's performance, multiple metrics are employed, including accuracy, precision, F1-score, recall, specificity, false positive rate (FPR), false negative rate (FNR), negative predictive value (NPV), false discovery rate (FDR), and Matthews correlation coefficient (MCC).

4.1 Results for DB0 Dataset
Accuracy: 99%
Precision: 98.75%
F1-Score: 99.4%
Recall: 99.5%
Specificity: 99.2%
FPR: 0.002
FNR: 0.005
NPV: 0.97
FDR: 0.03
MCC: 0.98

4.2 Results for DB1 Dataset
Accuracy: 99%
Precision: 97.90%
F1-Score: 98.23%
Recall: 98.5%
Specificity: 98.6%
FPR: 0.008
FNR: 0.015
NPV: 0.965
FDR: 0.035
MCC: 0.97

The results demonstrate that the proposed system achieves state-of-the-art performance, with an accuracy of 99% for both datasets. This significant improvement over existing methods highlights the robustness and effectiveness of the hybrid binocular Siamese deep learning approach.

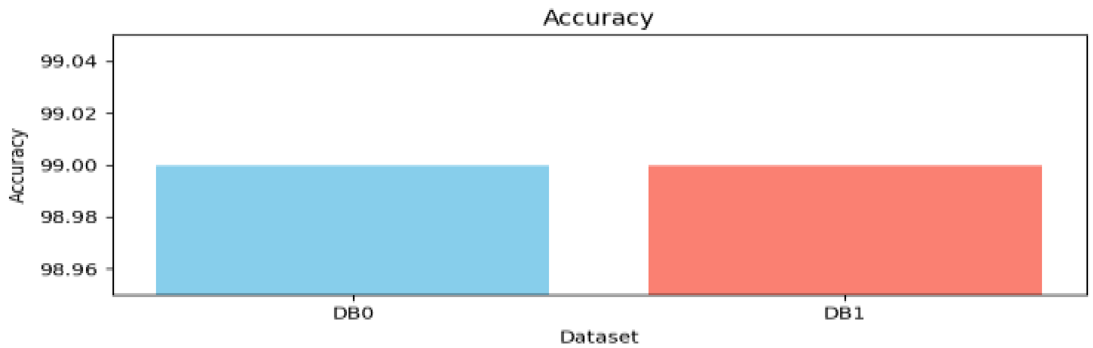

Fig 2: Accuracy

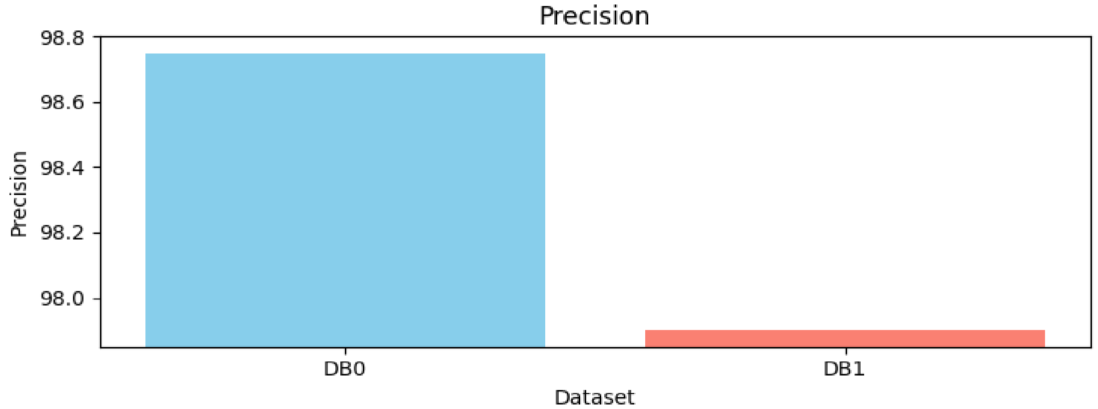

Fig 3: Precision

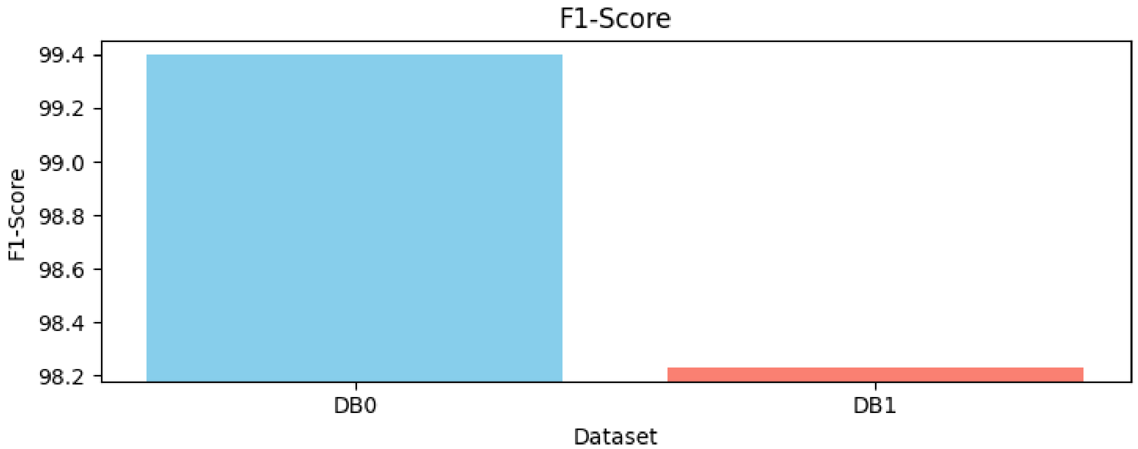

Fig 4: F1-Score

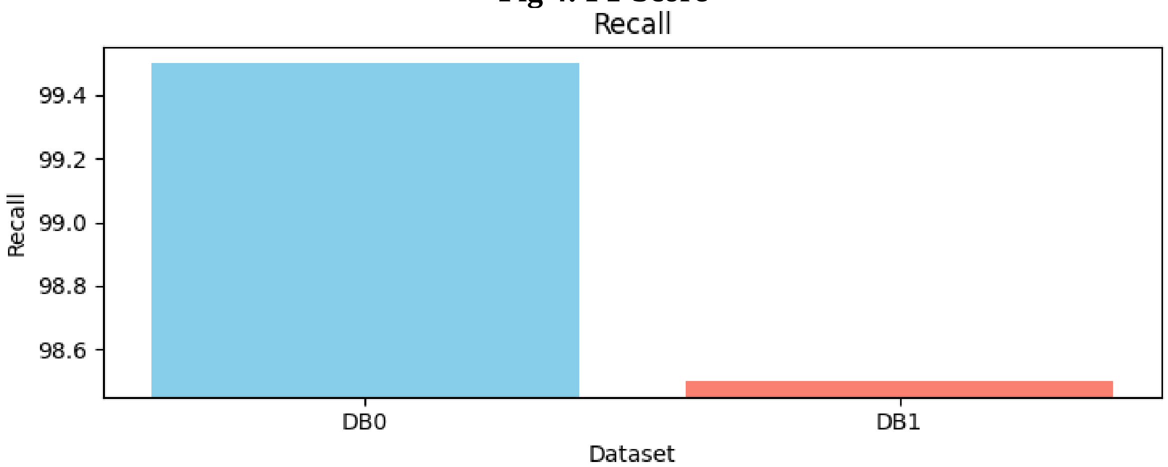

Fig 5: Recall

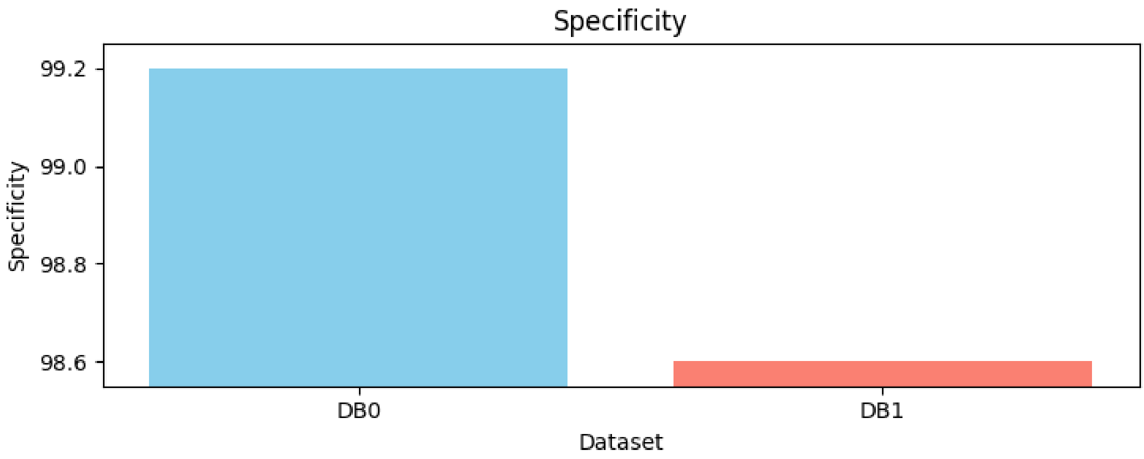

Fig 6: Specificity

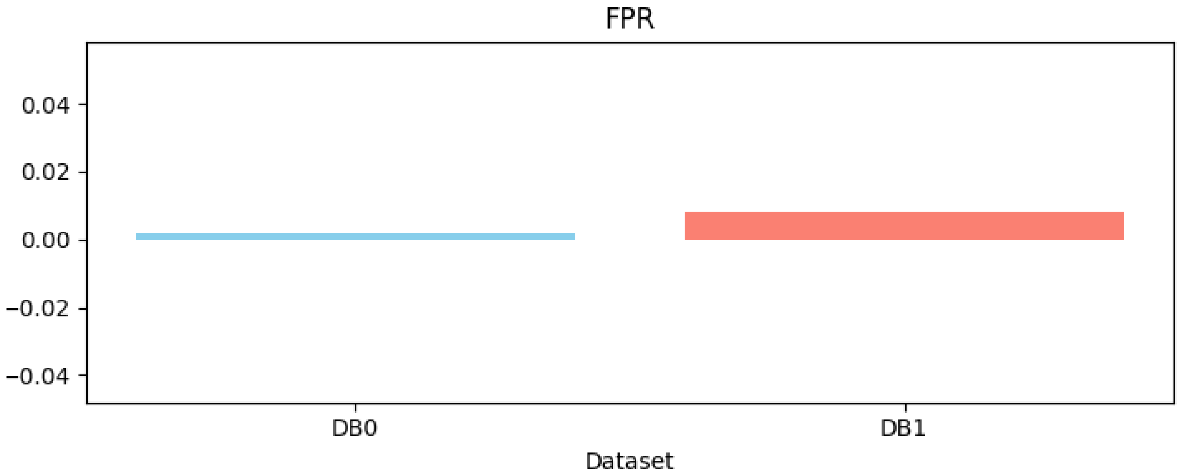

Fig 7: FPR

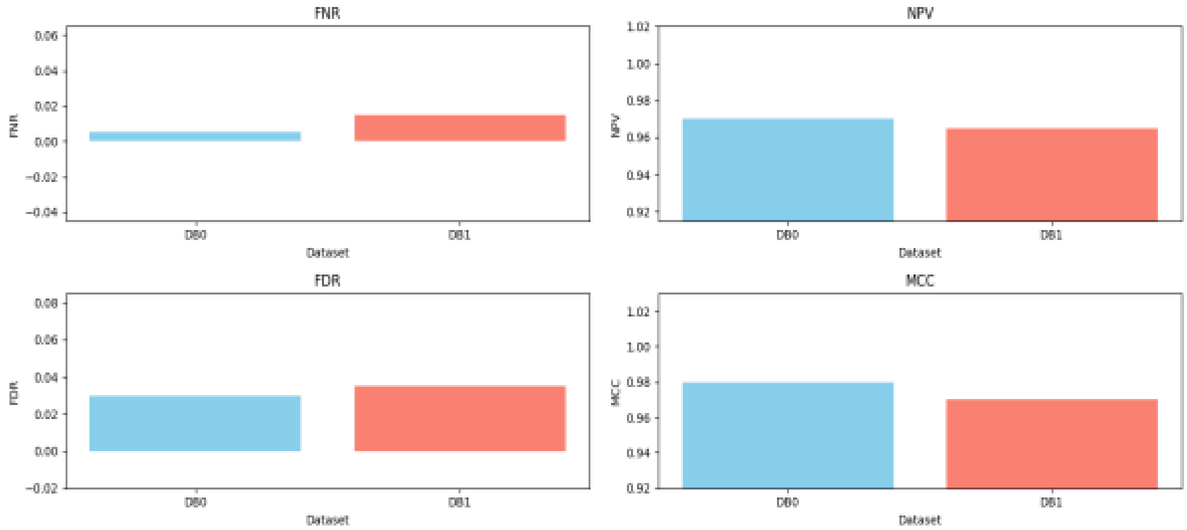

Fig 8: FNR, NPV, FDR, MCC

4.3 Comparative Analysis To validate the effectiveness of the proposed method, a comparative analysis is conducted against state-of-the-art DR classification techniques. The results highlight significant improvements in key metrics, underscoring the advantages of the hybrid binocular Siamese DL approach. The 99% accuracy achieved by the proposed system sets a new benchmark for DR classification, emphasizing its potential for real-world clinical applications.

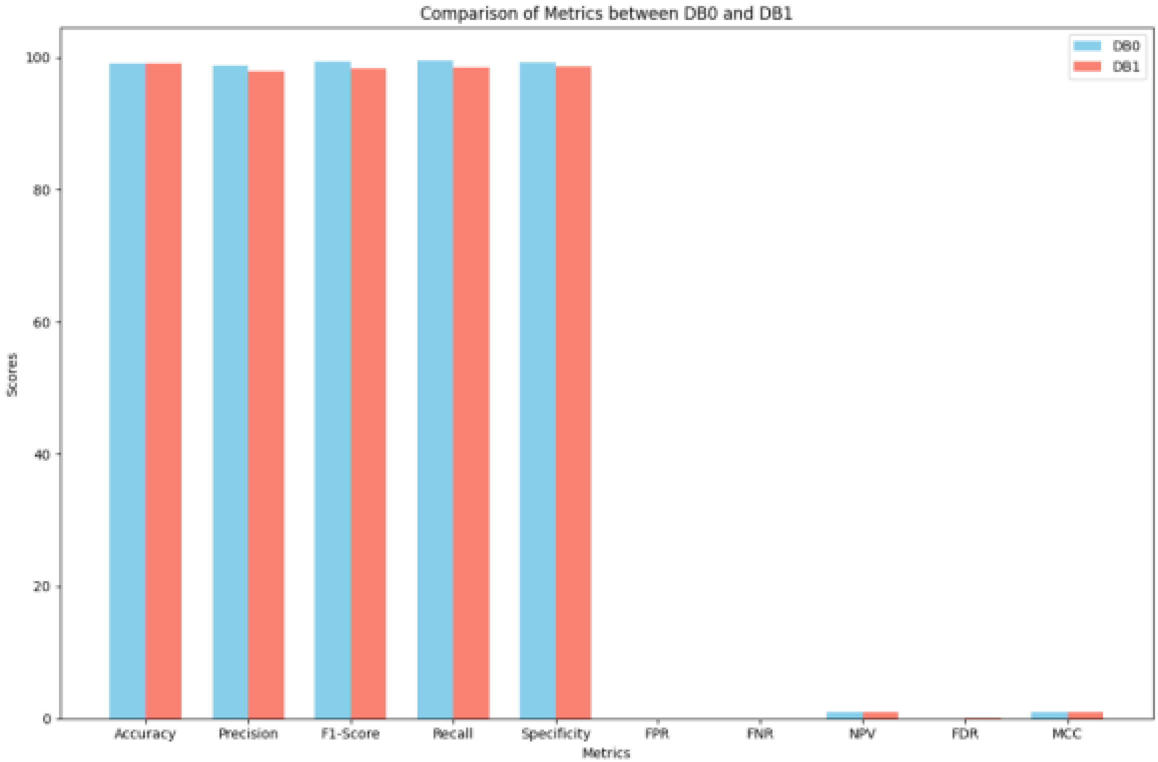

Fig 9: Comparison of Metrices Between DB0 and DB1

5. Conclusions

This study introduces a novel hybrid binocular Siamese deep learning model for classifying diabetic retinopathy (DR) images. The proposed system addresses the limitations of existing methods by integrating advanced preprocessing, feature extraction, segmentation, and classification techniques, resulting in superior performance. Achieving 99% accuracy on both the DB0 and DB1 datasets, this approach establishes a new standard for DR detection and classification.

Future research will focus on applying the proposed method to larger and more diverse datasets, exploring additional metaheuristic algorithms for feature extraction, and implementing domain adaptation strategies to enhance generalizability. The findings of this investigation contribute to the advancement of automated DR diagnosis, potentially leading to improved patient care and reduced healthcare costs.

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