Early Detection of Diabetic Foot Ulceration: A Review of Current Practices and Future Directions

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Abstract - Diabetes is a prevalent chronic health condition impacting millions globally. One of the most critical complications of managing diabetes is the development of diabetic foot ulceration, which if not detected early, can lead to severe consequences such as amputation. This review paper provides an extensive analysis of current practices in early detection of diabetic foot ulceration, ranging from clinical examinations to imaging techniques, highlighting their strengths and limitations. The review also explores emerging technologies, with a particular focus on the integration of machine learning methodologies, showcasing their potential to revolutionize the field. By synthesizing the existing literature, the review presents a dynamic landscape of advancements, demonstrating how artificial intelligence can enhance the accuracy and timeliness of early detection. Additionally, the review delves into the challenges and gaps in current approaches, paving the way for future discussions on potential directions. By providing a comprehensive evaluation of the state-of-the-art in early detection, this review aims to inspire medical professionals to adopt innovative technologies and practices, leading to improved outcomes in diabetic foot care.

Key Words: Diabetic foot ulceration, Convolutional Neural Network, Machine Learning, Amputation, Prediction.

1.INTRODUCTION:

Diabetes mellitus stands as a chronic metabolic disorder, posing a significant global health challenge beyond glycaemic control with complications like diabetic foot ulceration (DFU) carrying risks of chronicity, infection, and lower extremity amputations. Timely DFU detection is crucial for preventing adverse outcomes and enhancing patient quality of life. Diabetes, a major ailment affecting around 537 million people and projected to rise to 783 million by 2045, leads to severe complications, including heart disease, stroke, renal failure, blindness, and DFUs with amputations. The COVID-19 pandemic has reshaped healthcare, impacting DFU patient care with a focus on emergencies that have reduced both inpatient and outpatient services, exposing DFU patients to heightened vulnerability. The presence of common comorbidities in DFU patients raises the risk, coinciding with data indicating increased mortality in COVID-19 patients [1]. An insight into the critical issue of diabetic foot complications, emphasizing their substantial economic burden, impact on quality of life, and elevated mortality rates. It introduces once-daily foot temperature monitoring as a highly effective preventive measure, citing significant reductions in diabetic foot ulcer (DFU) incidence through temperature-based interventions. The text highlights a recent advancement in this approach—a telemedicine foot temperature monitoring mat. A multicentred investigation evaluated its accuracy, demonstrating a remarkable 97% detection rate for non-traumatic plantar DFUs before clinical manifestation. Despite its proven effectiveness, concerns persist regarding its applicability to patients with recent wounds or partial foot amputations, prompting a nuanced analysis to address these potential limitations [2]. Diabetic foot ulcers (DFUs) emerge as a serious consequence of diabetes, presenting a significant global healthcare challenge marked by substantial economic repercussions and mortality risks. Successful management of DFUs relies on the identification of crucial factors such as infection and ischemia, which are pivotal for predicting the succession of healing and minimizing the threat of amputation. Ischemia, stemming from vascular complications linked with diabetes, has the potential to advance to gangrene, necessitating immediate intervention to avert limb loss. Given that around 56% of DFUs succumb to infections and 20% result in amputations, a comprehensive understanding of these dynamics becomes imperative. This introduction emphasizes the need for holistic care strategies and underscores the intricate interplay between vascular health, infection, and for the risk of severe complications in cases of DFUs.

2. LITERATURE REVIEW

Katherine Ogurtsova at al; The paper proposes a new computer vision technique and dataset for identifying infection and ischemia in diabetic foot ulcers (DFU), showcasing superior performance in classifying ischemia compared to infection. The main contribution lies in the introduction of innovative methods for DFU image classification, potentially advancing medical diagnostics.

However, limitations include the absence of clinical meta-data, the necessity for a larger and more balanced dataset, evaluation of algorithm performance across different capturing devices, and the challenge of predicting wound depth and size. Despite these limitations, the study marks a significant step forward in leveraging computer vision for DFU analysis

Manu Goyal at al ; The study proposes a mobile and cloud-based framework for the automatic detection of diabetic foot ulcers and evaluates its usability and reliability in real-world settings. The research contributes to the field by introducing an innovative framework that leverages mobile and cloud technologies for the automated detection of diabetic foot ulcers. The study's main findings underscore the potential of the proposed framework in enhancing accessibility and efficiency in diabetic foot ulcer detection. However, the limitations include the early stage of exploration in serverless cloud computing, the need for further research in larger real-world settings, the requirement for retraining the existing model, potential unknown limitations as the system are further developed, and the need for validation in clinical practice. Despite these challenges, the study opens avenues for advancements in diabetic foot care through technology-driven solutions

Bill Cassidy at al; The paper presents an artificial intelligence (AI) algorithm for detecting diabetic foot ulcers, showcasing high sensitivity and specificity (0.92 and 0.89, respectively), with a post-processing improvement to 0.93. The study highlights the advantages, including accurate automated detection using AI, enhanced engagement with health apps, and excellent reliability of the algorithm. However, limitations such as small sample sizes, lack of rigorous evaluations, and slightly lower specificity are acknowledged. The conclusion emphasizes the potential of low-end smartphones and AI for precise diabetic foot ulcer detection, aiming to complement medical expertise and alleviate strain on healthcare systems.

Marco Meloni at al; The study delves into the characteristics of the study group, evaluating the effectiveness of a triage pathway for managing diabetic foot ulcers (DFUs) during the COVID-19 pandemic. Positive outcomes include a reduction in

major amputations and mortality, coupled with no hospital-acquired COVID-19infections. Acknowledging its strengths, the paper emphasizes the significance of a tailored triage pathway that considers ulcer features and patients' clinical history. Despite these advantages, the study is constrained by single-center data, prompting the need for future analyses to assess the long-term efficacy of the proposed approach. The overall thrust is to establish a nuanced triage pathway that optimizes care for individuals with diabetes and foot ulcers during the COVID-19 crisis, minimizing hospital admissions and COVID-19 exposure risks.

Ian L. Gordon at al; The paper proposes a mobile and cloud-based framework for the automatic detection of diabetic foot ulcers and evaluates its usability and reliability in real-world settings. The study's main findings center around the introduction of an innovative DFI-SIAM model for DFU image classification, showcasing its superior performance compared to other models. The paper contributes to advancements in the medical field by addressing the critical need for accurate and efficient diabetic foot ulcer detection. However, the study acknowledges limitations, including the early stage of exploration of serverless cloud computing, the necessity for further research in a larger real-world setting, the requirement for retraining the existing model, potential unknown limitations as the system is further developed, and the need for validation of the system in clinical practice. Despite these limitations, the research underscores the potential of the proposed framework in enhancing diabetic foot ulcer detection through mobile and cloud-based solutions.

Amith Khandaka at et al; The study compared a machine learning-based scoring technique and state-of-the-art Convolutional Neural Networks (CNNs) for early diabetic foot ulcer detection using thermogram images. Advantages include high accuracy with a shallow CNN model and potential use as a smartphone application. Limitations include challenges in quantifying temperature distribution and dataset size. The conclusion highlights contributions like comparing CNN models and proposing a smartphone-based application for clinical validation

Bill Cassidy at al ;The proposed paper introduces a mobile and cloud-based framework for the automatic detection of diabetic foot ulcers (DFUs) and assesses its usability and reliability in real-world scenarios. The system offers advantages such as potential self-monitoring by patients, up to 80% preventability of DFUs through early detection, significant cost savings for healthcare systems, and access to substantial processing power via cloud computing.
Mohammud Shaad Ally Toofanee at al; The study introduces the DFI-SIAM model for diabetic foot ulcer (DFU) image classification, highlighting its superior performance over other models. Advantages include the use of advanced neural network architectures for accurate classification, with remarkable results on both validation and test data. Limitations are acknowledged, particularly regarding class imbalance in the dataset, with suggestions for addressing these in future work. The conclusion underscores the novelty of using SNN architecture and LMCot for DFU classification, emphasizing the outperformance of the proposed DFI-SIAM model compared to other discussed models in related works.

Moi Hoon Yap at et al; The study explores the effectiveness of the Deformable Convolution variant of Faster R-CNN in detecting diabetic foot ulcers (DFU), emphasizing its potential impact on diabetic foot care and implications for future research.
Advantages include a comprehensive dataset for training and testing DFU detection algorithms, the transformative potential of technologies in diabetic foot care, and the goal of fostering wider participation for improved diagnosis and

monitoring. However, limitations include a small dataset, reliance on visual assessment for DFU detection, and the presence of artifacts posing challenges. The conclusion underscores the challenges in automated DFU detection and encourages future research to build upon the presented data and methods.

Firomsa Bekelea at al; The study reveals that predictors of amputation among diabetic foot ulcer (DFU) patients include elevated blood glucose levels, higher BMI, inappropriate antibiotic use, neuropathy, and advanced ulcer grade. Advantages include identifying significant predictors like obesity, advanced ulcers, neuropathy, and antibiotic misuse. Limitations involve a short follow-up period, the use of fasting plasma glucose instead of HbA1c, and the absence of culture tests for pathogen identification. Independent predictors of amputation include blood glucose level, BMI, inappropriate antibiotic use, neuropathy, and advanced ulcer grade

SL.NO	METHOD NAME	LIMITATION	ACCURACY
1	Foot thermogram images	Difficulty in quantifying temperature distribution, limited generalizability due to a small dataset, and unclear recruitment bias	95%
2	AI algorithm to detect diabetic foot ulcers	Small sample, limited prior studies, and slightly lower specificity observed	80% - 99%
3	Characteristics observed within the study group.	Single-center data limits study; future analyses needed for long-term effectiveness	80% to 95%
4	Incidence and timing of DFU recurrence at various follow-up periods	Low sample size, varied ulcer healing definitions are study limitations.	92%
5	Vision techniques and a dataset for discerning infection and ischaemia in Diabetic Foot Ulcers (DFU)	Study lacks clinical metadata, needs larger, diverse dataset, predicts wound characteristics	88%
6	Once-daily foot temperature monitoring	Secondary analysis, low statistical power, inherited source study weaknesses.	97%
7	DFI-SIAM model	Class imbalance, proposes solutions for future dataset work.	98%
8	Mobile and cloud-based framework	Early exploration of serverless computing, needs larger real-world validation	88%
9	Early exploration of serverless computing, needs larger real-world validation	Small dataset, visual assessment reliance, artifacts challenge accurate detection.	95%-99%
10	By identifying predictors of amputation	Short follow-up, fasting glucose (not HbA1c), no pathogen strain	85%-95%

Table 1 : Comparison of different research papers

3. SUBJECTS, MATERAILS & METHODS:

3.1. AI algorithm development

A deep learning model was utilized, characterized as a singular classifier localization model. This model incorporated the Faster R-CNN and Inception-ResNetV2 architectures for feature extraction and object localization. The process included transfer learning from the MS COCO dataset, and subsequent model training utilized 1775 photographs of diabetic foot ulcers (DFUs) along with expert labels acquired from Lancashire Teaching Hospitals.

3.2. Medical features

Ischemic heart disease (IHD) was defined by a history of acute coronary syndrome, coronary revascularization, angina, and specific electrocardiographic changes. Cerebrovascular disease was considered in cases of prior cerebrovascular ischemia, carotid revascularization, or significant carotid artery disease. Hypertension was characterized by persistent blood pressure exceeding 130/80 mmHg or current antihypertensive therapy. Hypercholesterolemia was identified by LDL levels exceeding 70 mg/dl or the need for statins. Heart failure (HF) was diagnosed based on typical symptoms and reduced left ventricular ejection fraction (LVEF $\leq$ 35%) without dilated left ventricle (LV) but associated with structural abnormalities. End-stage renal disease (ESRD) requiring dialysis was determined by chronic renal replacement therapy

3.3. Analysis approach

We divided participants into four groups: 1. The full study cohort. 2. A control group without partial foot amputations or recent wounds. 3. Those with a recent DFU (epithelialized in the last six months) are at higher risk for recurrence. 4. Participants with a history of partial foot amputation. Cohorts 3 and 4 may overlap, and Cohort 2 serves as a control, excluding potential challenges for daily temperature monitoring. Descriptive statistics were reported for each cohort. Receiver operator characteristic analysis evaluated predictive accuracy, with comparisons made using t-tests, Kolmogorov-Smirnov tests, and Fisher exact tests. Clinical parameters were reported, and challenging cohorts were compared to the control using the area under the ROC curve. A case series highlighted key clinical considerations for once-daily foot temperature monitoring in perceived challenging subgroups [2].

3.4. DFU detection methods

This section details the methods for detecting diabetic foot ulcers (DFUs), categorized by popular deep-learning object detection algorithms, including Faster R-CNN, YOLOv3, YOLOv5, and EfficientDet. The introduction of ensemble methods and the innovative Cascade Attention DetNet (CA-DetNet) are also presented [3]. Specifically focusing on Faster R-CNN, a two-stage model, it generates candidate object locations through a Region Pooling Network (RPN) based on shared feature maps, categorizing each proposal as foreground or background. To address misalignments, the RoI pooling layer is replaced by a RoIAlign layer. The Feature Pyramid Network (FPN) serves as the backbone, extracting RoI features from various pyramid levels. For robust predictions, data augmentation techniques include HSV and RGB shifts, blurring, affine transformations, and brightness adjustments. Model training involves fine-tuning MS-COCO using stochastic gradient descent with warm-up learning rate scheduling. Various faster R-CNN variants, like cascade R-CNN, deformable convolution, and prime sample attention, are explored. Post-processing includes soft NMS and a Weighted box Fusion ensemble method, enhancing prediction accuracy by combining outputs from Faster R-CNN, Cascade R-CNN, Faster R-CNN with Deformable Convolution, and Faster R-CNN with Prime Sample Attention.

3.5. Thermogram Analysis

Hernandez-Contreras et al. released a database featuring age, gender, height, weight, and 167-foot pair thermograms from 122 individuals with diabetes and 45 controls. The study analyzed continuous variables, reporting missing data, medians, means, and quartiles for both groups. Statistical tests, including chi-square for gender and rank-sum for other features, were conducted with a significant threshold of $p<0.05$. Thermogram images were segmented to remove backgrounds and divided into four angiosomes. Clear distinctions were observed between control and diabetic groups in temperature distribution patterns. The control group exhibited a unique butterfly pattern, while the diabetic group showed consistently higher temperatures across the foot. Angiosome-related information not only identified arteries associated with ulceration risk but also depicted local temperatures. The dataset included pixelated temperature readings for the entire foot and the four angiosomes in both feet, addressing challenges in two dimensions: pixelated temperature and 2D thermogram images.

3.6. Risk Factors

Clinical experts identified key factors from previous research to consider as potential covariates. These include basic details like age, sex, living arrangements, and distance to the study center. Diabetes-related factors such as the type and duration of diabetes and the treatment method (oral medication or insulin) were also considered. Other factors, like a history of heart disease, stroke, kidney issues, neuropathy, and foot-related conditions, were considered. The history of diabetic foot ulcers, whether it is the first occurrence or a recurring episode, and information about past amputations were also included as relevant factors for analysis [4].

4. DISCUSSION & FINDINGS:

In this extensive analysis, the performance of various object detection methods in the context of diabetic foot ulcer (DFU) detection is comprehensively discussed. Despite achieving F1-Scores surpassing 70%, the implementation of deep learning algorithms in real-world settings poses significant challenges. Notably, faster R-CNN-based approaches exhibited high mean average precision (mAP) and F1-scores in the DFUC2020 testing set [7]. Variants of Faster R-CNN further improved performance, but ensembling results from multiple models while reducing false positives showed an overall performance less impressive than individual variants. Future work is suggested to include a one-stage object detection method, like CenterNet, in the ensemble to enhance accuracy. The YOLOv3 algorithm secured a third-place ranking in both mAP and F1-Score, with postprocessing and the addition of healthy foot images proving beneficial. YOLOv5 showcased reliable detection, and improvements through duplicate cleansing and bounding box merging were explored. The EfficientDet algorithm demonstrated high recall, and future work will explore larger network architectures. Cascade Attention DetNet exhibited competitive but unsatisfactory performance, prompting further investigation into overfitting and potential solutions through ensemble learning and robust data augmentation. Ensembling methods and combining different backbones substantially reduced the number of predicted bounding boxes, emphasizing the need to focus on true positives in future research. The study highlights the limitations of current clinical practices in DFU detection, emphasizing the potential of accurate, automated methods to revolutionize wound assessment and analysis. However, the variability in DFU features presents a complex challenge, and this study underscores the diverse deep learning-based solutions developed to address the intricacies of accurate DFU detection.

DFU-SIAM introduces a pioneering model for Diabetic Foot Ulcer (DFU) classification, featuring a distinctive Siamese Neural Network (SNN) architecture and leveraging the innovative Large Margin Cotangent Loss (LMCot) approach [5]. In comparison to existing models that rely on convolutional neural networks (CNNs), vision transformers (ViTs), and ensemble strategies with pseudo-labelling, DFU-SIAM excels. The model strategically integrates the EfficientNetV2S and BEiT models, harnessing their complementary strengths. Unlike some counterparts, DFU-SIAM adopts a nuanced approach, concentrating on training only the last 10 layers of the BEiT transformer for enhanced computational efficiency. Amidst acknowledging challenges associated with imbalanced data, DFUSIAM not only achieves unprecedented performance but also underscores the significance of privacy preserving methodologies such as federated learning. This emphasis ensures the secure amalgamation of diverse datasets, addressing potential limitations in data sharing among clinics and medical centers. The exploration of federated learning emerges as a pivotal aspect, offering a decentralized solution to preserve patient privacy while enhancing the robustness of deep learning models in the context of DFU classification.

The Australian guidelines for Diabetic Foot Ulcer prevention present evidence-based recommendations, uniquely addressing the country's healthcare context. These guidelines offer simplified pathways for health professionals, aiming to enhance prevention outcomes and alleviate the national burden of Diabetic Foot Ulcers in Australia [10].

The experimental findings reveal significant insights into diabetic foot ulcer (DFU) detection, employing a combination of deep convolutional neural network (CNN) models and traditional machine learning approaches. The study systematically explores the impact of image enhancement techniques on thermogram classification, considering different CNN architectures with transfer learning over pretrained networks. The investigation includes the effects of single and dual-foot input for binary classification. Among the deep CNN models studied, DenseNet201 emerges as the top performer, showcasing an overall sensitivity of 94.01% for DFU detection, with distinct sensitivities of 95.9% and 88.89% for diabetic and control groups, respectively. Surprisingly, the original thermograms outperform enhanced images, and the incorporation of demographic information, such as age, enhances feature-based classification. Additionally, the study introduces the Adaboost classifier with random forest feature selection as a formidable contender, surpassing CNN models in certain scenarios and demonstrating deployability on smartphones for real-time detection in clinical and home settings. Moreover, the research underscores the effectiveness of gamma correction for enhanced discrimination in dual foot thermogram analysis, further emphasizing the nuanced interplay between image enhancement techniques and classification performance. The study, conducted by focusing on automatically identifying ischemia and infection conditions in diabetic foot ulcers (DFU), explores the application of machine learning for automated identification of ischemia and infection in diabetic foot ulcers (DFU). The research highlights successful ischemia classification and emphasizes challenges in recognizing infections, emphasizing the need for more sensitive ground truth determination in DFU analysis [8].

The amalgamation of infrared thermography and machine learning presents a pivotal stride in enhancing early diabetic foot ulcer detection.

In a study comparing two cohorts from diabetes centers in Germany and the Czech Republic, it was found that approximately 70% of patients experienced recurrent diabetic foot ulcers (DFUs) within 15 years. The risk factors for recurrence varied between the cohorts, with factors such as renal replacement therapy and no history of DFU associated with shorter time to recurrence in the German cohort, while type 2 diabetes and minor amputation for index ulcer treatment were linked to shorter time to recurrence in the Czech cohort [6].

6. RESULT:

A comprehensive examination of diverse diagnostic methodologies, including infrared thermography, deep convolutional neural network models, and classical machine learning algorithms, reveals a multifaceted and promising strategy for the early detection of diabetic foot ulcers. In conclusion, the developed cross-platform mobile app and cloud-based deep learning framework for automatic DFU detection, assessed for high usability, present a groundbreaking approach with potential applications in patient self-monitoring and assisting medical experts, marking a significant advancement in DFU diagnosis and monitoring technology [9]. These studies collectively underscore the potential synergy of leveraging technological advancements, sophisticated image processing techniques, and traditional feature-based analyses to enhance the accuracy and efficiency of diabetic foot ulcer detection, thereby offering valuable insights into current practices and future directions in this critical domain of healthcare.

7. CONCLUSION:

In conclusion, the early detection of diabetic foot ulceration remains a critical aspect of diabetes management, with various studies emphasizing the significance of timely intervention to prevent severe complications. While traditional clinical assessments continue to play a vital role, emerging technologies, including infrared thermography and artificial intelligence-based approaches, show promising potential in enhancing early detection capabilities. The integration of classical machine learning frameworks for feature optimization, as demonstrated in recent studies, presents a valuable alternative to 2D image-based deep learning techniques. These advancements not only contribute to improved diagnostic accuracy but also offer the feasibility of smartphone-based applications for convenient and widespread use. As healthcare continues to evolve, further research and clinical trials are essential to validate the effectiveness of these approaches and establish robust practices for the early detection of diabetic foot ulceration.

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