METABOLIC DISEASES

Review

Personalized and predictive strategies for diabetic foot ulcer prevention and therapeutic management: potential improvements through introducing Artificial Intelligence and wearable technology

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Abstract

Diabetic foot ulcers represent a serious and costly complication of diabetes, with significant morbidity and mortality. The purpose of this study was to explore advancements in Artificial Intelligence, and wearable technologies for the prevention and management of diabetic foot ulcers. Key findings indicate that Artificial Intelligence-driven predictive analytics can identify early signs of diabetic foot ulcers, enabling timely interventions. Wearable technologies, such as continuous glucose monitors, smart insoles, and temperature sensors, provide real-time monitoring and early warnings. These technologies promise to revolutionize diabetic foot ulcer prevention by offering personalized care plans and fostering a participatory healthcare model. However, the review also highlights challenges such as patient adherence, socioeconomic barriers, and the need for further research to validate these technologies’ effectiveness. The integration of artificial intelligence and wearable technologies holds the potential to significantly improve diabetic foot ulcer outcomes, reduce healthcare costs, and provide a more proactive and personalized approach to diabetic care. Further investments in digital infrastructure, healthcare provider training, and addressing ethical considerations are essential for successful implementation.

Keywords: diabetic foot ulcers, artificial intelligence, wearable technology, personalized medicine

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Introduction

Diabetic foot ulcers (DFUs) are a severe and costly complication of diabetes mellitus, significantly impacting patient morbidity and mortality. With the global prevalence of diabetes projected to reach 1.3 billion by 2050, the incidence of DFUs is expected to rise proportionately [1]. Currently, up to one-third of individuals with diabetes will develop a foot ulcer in their lifetime, highlighting the urgent need for effective prevention, management strategies, and surgical interventions [2].

DFUs often result in serious consequences, including a high risk of amputation. More than 80% of non-traumatic lower extremity amputations in diabetic patients are preceded by DFUs [3]. Amputations are categorized as minor (involving toes or parts of the foot) or major (removal of the limb below or above the knee), with increased risk correlated to ulcer duration, severity, infection, and inadequate glycemic control [4]. The associated 5-year mortality rate for DFUs is 45-55%, exceeding that of many cancers [2,5], due to complications like infections and cardiovascular diseases, and the added stress of amputation [6].

Economically, DFU management imposes a significant burden. In the United States, annual healthcare costs for DFU treatment range from $9 to $13 billion, not including additional costs related to hospitalization, rehabilitation, and long-term care [7]. Indirect costs, such as productivity loss and disability care, further exacerbate this economic strain [8].

Addressing DFUs necessitates a multidisciplinary approach, including diabetes management, patient education, regular foot examinations, and preventive actions to reduce DFU incidence and improve outcomes [9-11]. The rapid development of healthcare technology, particularly AI and wearable devices, offers new possibilities in DFU prevention and management. AI's application of machine learning and algorithm-based decision-making enhances diagnostic accuracy and treatment efficacy, revolutionizing patient care [12,13].

This paper reviews advancements in AI and wearable technologies, assessing their potential to improve healthcare delivery, provider training, patient outcomes, and system efficiencies in DFU management.

Methods

This narrative review aims to explore the advancements in AI, and wearable technologies, alongside their potential applications in the prevention and management of DFUs.

Search strategy

A systematic search of the literature was conducted using online databases, including PubMed, Google Scholar, IEEE Xplore, and Web of Science. The search terms included combinations of keywords such as "diabetic foot ulcers", "artificial intelligence", "wearable technology", "continuous glucose monitoring", "predictive analytics", "preventive care", "personalized medicine", "foot health monitoring", and "patient engagement tools". Articles published between 2010 and 2024 were considered to ensure a comprehensive inclusion of the most recent and relevant studies.

Inclusion and exclusion criteria

Inclusion criteria:

1. Studies about application of AI and wearables in diabetic foot care.
2. Publications in English.

Exclusion criteria:

1. Articles not relevant to the core themes of AI, wearables and DFU.

Data extraction involved identifying and summarizing key information from each selected study, focusing on the following aspects:

- The types of technologies and their applications in DFU prevention and management.
- The effectiveness of these technologies in preventing DFUs and improving patient outcomes.
- The benefits and challenges associated with the integration of AI and wearable technology in diabetic foot care.

Limitations

The narrative review acknowledges certain limitations:

1. Potential publication bias due to the selective inclusion of articles.
2. The rapid evolution of AI, and wearable technologies may result in some studies becoming outdated quickly.

Where are we now in the prevention and management of DFUs?

There is an urgent need to shift from a generalized to a personalized approach in preventing and managing diabetic foot ulcers (DFUs) [14]. Traditional healthcare methods, which categorize patients into broad risk groups, fall short in effectively preventing this complication. A move towards personalized medicine is needed to tailor interventions to each patient's unique characteristics [14]. Van Netten and colleagues stress that DFUs significantly increase morbidity and healthcare costs [14]. Current prevention strategies often overlook complex factors like neuropathy and foot deformities, and stratified care lacks the precision to address individual risks. Additionally, preventive strategies are less prioritized, as indicated by a study revealing a 1 to 36 ratio of papers on prevention versus treatment from 2015 to 2019 [14].

Knowledge of ulcer development remains limited, with outdated or narrow research focusing mainly on non-modifiable factors [15]. The International Working Group on the Diabetic Foot's (IWGDF) risk stratification oversimplifies risk categories, failing to distinguish between different ulcer histories [16]. Enhanced understanding of ulceration pathways is crucial for improving prevention. Furthermore, the disease's nature complicates involvement from patients and primary care professionals, while most studies are conducted in tertiary centers lacking training programs for handling DFUs.

AI and wearable technology working for the DFU patient

The integration of advanced technologies into diabetic foot care has been proposed, utilizing AI and machine learning to analyze large datasets and predict ulcer development more accurately than traditional methods [14,17,18]. Patients can input health data into an app, receive tailored feedback, and track improvements, motivating continued use and adherence to instructions [19].

AI-driven medical technologies enhance clinical practice by providing patients with autonomy and giving clinicians advanced tools for disease prediction, detection, monitoring, and treatment. AI's role in diagnostics includes analyzing complex medical data, improving early detection of conditions like cancer and diabetes [20-22]. This approach facilitates predictive, preventive, personalized, and participatory healthcare, aligning with the 4P model [23,24]. AI-powered technologies are transforming healthcare by aligning with the 4P model: Predictive, Preventive, Personalized, and Participatory practices.

Predictive medicine leverages AI's capabilities to analyze vast datasets from electronic health records and genetic information to identify risk factors and forecast potential health issues. This proactive approach aims to prevent diseases and reduces the burden on healthcare systems, particularly in diabetes mellitus (DM) and diabetic foot ulcers (DFU) [25].

Preventive measures focus on forestalling diseases rather than treating them post-diagnosis. Continuous monitoring and real-time data analysis by AI enable early detection of anomalies, significantly reducing the likelihood of severe complications and costly medical interventions [26,27].

Personalized healthcare proposes treatments to individual patients based on their genetic background, lifestyle, and medical history. AI's ability to analyze complex medical data at an individual level enhances the efficacy of treatments, minimizing adverse drug reactions and optimizing patient outcomes [13,28].

Participatory medicine empowers patients to manage their health actively. Smartphones and wearable biosensors facilitate the management of electronic health records and monitor vital functions, encouraging therapeutic compliance and a patient-centric healthcare journey [26,29-32].

Wearable technologies play a role in monitoring foot health in real-time by tracking parameters like plantar pressure, temperature, and movement. These devices provide early warnings of potential issues, allowing timely interventions and improving patient outcomes in DFU prevention [14,18,26,33].

Patient education for prevention of DFUs

There are papers that address the persistent issue of DFUs and the inadequacy of current preventive strategies, particularly focusing on patient education, highlighting that, despite extensive educational efforts, a significant proportion of patients with diabetes do not adequately respond to education about foot care, resulting in poor self-management and a high incidence of DFUs [34].

The reasons for this lack of response to education followed interventions that often failed to account for the individual differences in patients' cognitive and emotional capacities, cultural background, and socioeconomic status. These factors can significantly impact a patient's ability to understand and implement recommended foot care practices [34,35]. For example, patients with lower health literacy, cultural differences or those from disadvantaged backgrounds may struggle more with following complex care instructions [36].

Even when patients understood the importance of foot care, they might lack the motivation or resources to apply this knowledge consistently. Factors such as depression, which is prevalent among people with chronic illnesses like diabetes, can further diminish the effectiveness of educational interventions and increase amputation and mortality among people with DM and DFU [37,38]. Additionally, practical barriers, such as the inability to afford proper footwear or the lack of access to regular medical check-ups, undermine the impact of education [34].

Without any doubt while patient education is crucial as a first line of preventive measures against DFU in patients with DM, it is insufficient on its own to prevent DFUs effectively. A shift towards more individualized and supportive interventions is necessary to enhance patient adherence to foot care practices and ultimately reduce the incidence of DFUs and this could be achieved with smart applications and Artificial Intelligence monitoring and intervening [34].

What are the flaws of the current risk assessments for DFU patients ?

Beulens et al. conducted a systematic review identifying 34 models predicting diabetic foot ulcer (DFU) development and amputation in patients with diabetes, involving 37 variables categorized into seven groups: demographics (age, sex, ethnicity), diabetes-related factors (type, duration, HbA1c), health behaviors (smoking, BMI), clinical measures (lipids, blood pressure, foot sensitivity), medical history (prior ulcers, kidney function loss), medication/treatment, and physical/functional status [39]. While many variables are integrated into current prediction scores, several, such as fasting glucose variations, foot temperature, and foot sensitivity, are subject to continuous change. Evaluating these factors requires multiple healthcare visits, often causing patient dissatisfaction, low compliance, and increased costs, especially outside specialized, multidisciplinary centers. Additionally, the review noted some variables, such as physical activity, psychiatric disorders (e.g., depression), plantar pressure, and gait, were not adequately assessed. Furthermore, more than half of the identified risk factors are non-modifiable, highlighting the need to focus on modifiable factors and research new potential variables that could be targeted for intervention. This emphasizes the importance of a more dynamic, patient-centric approach to DFU risk management to improve outcomes and reduce healthcare burdens [38,39].

The 2023 IWGDF guidelines provide a framework for preventing DFUs through patient risk stratification and recommended frequencies for doctor appointments. These guidelines aim to optimize preventive care and early intervention based on the patient's risk level [40].

AI and wearable technology as game changers in DFUs – what has been done

Nowadays we have the option to record and integrate most of these variables in mobile applications connected to smart wearable sensors, applications which could have the options for the patients to fill in certain health results after blood tests for example, the height or the weight. This could transform the proposed visits to the footcare facilities into events driven by certain modifications discovered through smart applications and AI. We are going to evaluate some of the actual sensors and applications on the market based upon studies that proved their efficacy, trying to prove the feasibility of this idea.

Mobile health applications

Mobile health applications for diabetic foot care offer educational resources, interactive tools, and personalized support, helping patients manage their foot health daily. Accessible via smartphones and tablets, these apps incorporate key features such as interactive learning modules, daily reminders, personalized care plans, telemedicine integration, tracking, and community support.

Interactive modules in apps like MySugr and Glucose Buddy use videos, animations, and quizzes to educate patients on foot inspection, footwear, nail care, and blood glucose maintenance, enhancing information retention [41,42]. Daily reminders prompt patients to check for foot issues, customize alerts for doctor appointments, and medication schedules to promote consistency. Personalized care plans are generated based on user inputs, such as neuropathy and ulcer history, providing tailored advice [43].

Telemedicine features enable direct consultations with healthcare providers through video calls and chat functions, improving access for patients with mobility issues or in remote areas. Apps also track patient foot care activities and health metrics, sharing data with providers for ongoing monitoring and timely intervention. Community features, found in apps like Diabetes Connect, foster peer support, enhancing motivation for foot care [44,45].

These apps empower patients to prevent DFUs and reduce healthcare costs, offering an accessible solution for continuous education and engagement [46]. However, they currently lack integration with wearable sensors, electronic health records, and personalized medical feedback.

Foot temperature monitoring

Monitoring foot temperature has emerged as a vital strategy for early detection of potential ulceration in diabetic patients. Elevated local skin temperatures in one foot, compared to the corresponding area of the other foot, may indicate inflammation or infection, both precursors to ulcer development. Early identification of these anomalies allows for interventions before ulcers form, reducing the incidence of DFUs [47,48].

Several wearable devices have been developed to monitor foot temperature continuously. These devices, often in the form of insoles or socks embedded with sensors, measure temperature in various foot areas, transmitting data to a mobile app or central system for analysis [47]. Notable examples include the Podimetrics SmartMat and SurroSense Rx by Orpyx Medical Technologies, which detect temperature differences across the feet [49,50]. The Podimetrics SmartMat, used daily at home, alerts patients and healthcare providers to significant temperature differences, enabling early intervention. Clinical studies show that it significantly reduces foot ulcer incidence, with a sensitivity of 97% and specificity of 86% in detecting early ulceration signs [51].

Similarly, smart socks like the Siren Diabetic Socks incorporate temperature sensors within the fabric, continuously monitoring foot temperature and wirelessly transmitting data to an app. Upon detecting abnormalities, the app alerts the user and their healthcare team, prompting early intervention and reducing ulcer progression risk [47,52,53].

Despite the benefits, challenges such as the initial cost, patient adherence, data management, and privacy concerns affect the widespread adoption of these devices. However, the potential long-term savings from preventing complications support the cost-effectiveness of this technology [54].

Plantar pressure monitoring

Plantar pressure is a key factor in the development of diabetic foot ulcers (DFUs). Elevated pressure points can cause skin breakdown, especially in neuropathic patients who lack pain sensation. Monitoring plantar pressure enables early detection of high-risk areas, allowing for timely interventions to redistribute pressure and prevent ulcers. Golledge et al. emphasize that wearable sensors can provide real-time data, crucial for proactive foot care [55].

Tang et al. present a wearable insole system that measures both plantar pressure and shear stress, offering a comprehensive view of mechanical forces on the foot. This dual measurement is important as shear stress can exacerbate tissue damage, contributing to ulcer formation [56]. Clinical evidence supports the effectiveness of these devices; patients using pressure-sensing insoles experienced 86% fewer ulcer recurrences [57]. These smart technologies alert patients and clinicians to abnormal pressure patterns, prompting corrective actions like footwear adjustments or custom orthotics, extending ulcer-free periods [58].

Integrating pressure sensors with telehealth platforms further enhances patient outcomes. Real-time pressure data transmission enables continuous monitoring, timely treatment adjustments, and offloading alerts, reducing the need for frequent in-person visits and lowering healthcare costs [59]. Incorporating these data into large databases and using AI could further reduce costs and reaction times for interventions.

While pressure-sensing technologies improve foot health outcomes [60,61], challenges include ensuring patient compliance and the cost of devices, despite their potential long-term savings [62,63]. Integrating these devices into healthcare workflows requires provider training in data interpretation and secure transmission of health information to protect patient privacy [64,65].

Continuous glucose monitoring

Poor glycemic control is a trigger for distal neuropathy, a significant risk factor for DFUs. CGM systems are wearable devices that track glucose levels in the interstitial fluid, providing real-time feedback to patients and healthcare providers. Devices like the Dexcom G6 and Abbott's FreeStyle Libre have enhanced diabetes management by offering detailed insights into glucose fluctuations, helping patients make informed decisions regarding diet, activity, and medication [66]. These systems alert users to hyperglycemia or hypoglycemia, facilitating immediate corrective actions that are critical for preventing neuropathy and ulceration [67].

The integration of CGMs with smartphone applications enhances their utility. These apps analyze trends, offer personalized recommendations, and remind patients to check their feet, modify diets, or take medications. AI and ML incorporated into these apps predict glucose trends and potential complications, promoting proactive diabetes management. Additionally, implantable drug delivery systems represent another frontier by automatically delivering insulin based on real-time glucose readings, which can reduce the burden of diabetes management and minimize DFU risks [68].

Multi-parameter sensors that monitor glucose alongside heart rate, temperature, and activity provide a comprehensive health overview, aiding early detection of DFU risks [69]. Non-invasive technologies, such as sweat glucose sensors, offer a painless alternative, increasing patient compliance [70].

These technologies facilitate optimal glycemic control, reducing the risk of neuropathy and poor wound healing, key contributors to DFUs [71]. Advances in closed-loop artificial pancreas systems, with automated insulin delivery and predictive algorithms, further enhance glycemic control and reduce patient monitoring burdens [72-76]. Ongoing challenges like sensor accuracy and user calibration are areas for future research [77,78].

Other sensors and wearables

Wearable technology has transformed cardiovascular health monitoring, providing real-time data on metrics like heart rate, arrhythmias, and blood pressure [64]. Advanced algorithms analyze this data to identify trends and potential health issues [79].

Modern wearables also detect heart arrhythmias, such as. Early detection of atrial fibrillation through these devices is crucial for timely medical intervention [80].

Blood pressure monitoring has become more accessible via optical sensors that estimate blood pressure using pulse wave velocity [81].

The future starts today – the transformative potential of AI and machine learning

AI and machine learning (ML) have the potential to significantly advance the management of diabetic foot ulcers (DFUs), improving the precision and effectiveness of screening, diagnosis, and patient monitoring. AI uses complex algorithms to analyze vast datasets, including clinical information, imaging results, and patient histories, to predict ulcer development risks. By integrating data from electronic health records (EHRs) and wearable devices, AI systems could enable personalized risk assessments, allowing for early intervention [82].

ML, a subset of AI, is trained on extensive datasets to identify patterns and make predictions. In diabetic foot care, ML algorithms process patient demographics, medical history, lab results, and imaging data to identify those at high risk of developing DFUs. These models analyze factors such as blood glucose levels, neuropathy severity, and foot pressure distribution to predict ulcer formation more accurately than traditional methods [83,84].

AI and ML also enhance patient monitoring through continuous monitoring devices like smart insoles and wearable sensors that track foot temperature, pressure, and movement [85]. AI algorithms analyze this data in real-time, detecting abnormal patterns indicative of ulcer development and alerting patients and healthcare providers for timely intervention. This proactive approach helps optimize treatment protocols tailored to individual risk profiles [86].

In addition, AI-driven decision support systems recommend specific wound care products, offloading devices, or surgical interventions based on the ulcer's characteristics and the patient's health status, enhancing treatment effectiveness [87]. Furthermore, large-scale data analysis facilitated by AI uncovers new insights into DFU progression, guiding future research and clinical practices.

Challenges in adopting these technologies include ensuring model accuracy, integrating them into clinical workflows, and maintaining data privacy [88]. However, AI and ML hold significant promise for improving DFU outcomes and reducing healthcare burdens [89].

Discussion

This review explores the role of Artificial Intelligence (AI), machine learning (ML), and wearable technologies in the prevention and management of diabetic foot ulcers (DFUs). It emphasizes the advancements in these technologies and their transformative potential for patient care, especially in tackling the complex and costly complications associated with DFUs. Traditional methods have often struggled to provide effective prevention, highlighting the need for innovative strategies to improve outcomes.

AI has become integral in identifying DFU risk through predictive analytics. By processing large datasets, AI algorithms analyze patterns in electronic health records (EHRs), lifestyle factors, biometric information, and clinical data to predict ulcer development risks. This possible early identification could allow timely interventions and personalized prevention strategies, enhancing the accuracy of risk assessments. For instance, AI systems can alert healthcare providers and patients to potential issues before they escalate into serious complications, enabling proactive patient education and modifications in care plans [82,90].

Machine learning (ML), a subset of AI, uses past patient data, including demographics, medical history, lab results, and imaging data, to detect subtle trends and correlations that may go unnoticed by traditional methods. ML algorithms can predict the likelihood of ulcer formation based on various factors such as blood glucose levels, neuropathy severity, and foot pressure distribution [83,84]. This capability helps in creating tailored interventions and managing individual patient needs more effectively.

Wearable technologies like continuous glucose monitors (CGMs), smart insoles, and temperature sensors provide real-time monitoring of foot health. CGMs track blood glucose levels continuously, assisting in maintaining better glycemic control and thereby reducing the risk of neuropathy, a critical factor in DFU development [91]. Smart insoles detect abnormal pressure points, while temperature sensors identify elevated skin temperatures—both early indicators of potential ulceration. These devices collect data and send alerts to patients and healthcare providers when signs of potential problems are detected [55]. Immediate corrective actions, such as adjusting footwear or reducing pressure, can be taken to prevent the progression of minor issues into severe ulcers [92,93].

Mobile health applications offer another dimension to DFU care by enhancing patient engagement and education. These apps provide personalized foot care plans, daily reminders for foot inspections, and guidance on footwear, allowing patients to manage their foot health proactively. By sending alerts for abnormal readings from wearable devices and offering educational resources, they improve patient adherence to preventive measures and empower users to take an active role in their care [94].

AI, through its ability to analyze large datasets, can identify subtle patterns and correlations that may not be apparent through conventional methods [95]. By linking data from CGMs, smart insoles, and temperature sensors with telemedicine platforms, healthcare providers can monitor patients remotely, especially those in underserved or rural areas [96,97]. This real-time flow of information enables timely interventions, reducing the need for frequent in-person visits and improving access to specialized care. AI-driven analytics within these platforms ensure that alerts and recommendations are based on current, comprehensive data, enhancing the effectiveness of remote care.

Despite the benefits, challenges remain in ensuring patient adherence to wearable devices, integrating new technologies into clinical workflows, and maintaining data privacy [98]. Socioeconomic factors also affect access to these technologies. The rapid acceptance of telemedicine during the COVID-19 pandemic demonstrates a promising future for remote DFU management, but ongoing research, refinement, and support are needed to overcome existing barriers and fully realize the potential of AI, ML, and wearable technologies in improving DFU outcomes.

Conclusions

In conclusion, the integration of AI, ML, and wearable technologies offers a promising approach to improving the prevention and management of diabetic foot ulcers. These advancements could lead to better patient outcomes, reduced healthcare costs, and a more proactive and personalized approach to diabetic care. However, ongoing research, strategic planning, and careful implementation will be essential to fully realize the potential benefits of these innovative technologies, especially in the prevention of diabetic foot ulcers.

Future directions

Artificial intelligence (AI) enhances clinical decision-making and patient engagement, significantly improving diabetic foot ulcer (DFU) prevention and management. Patient engagement tools, like mobile health applications, empower individuals to take an active role in their care, promoting a proactive approach to foot health. Remote monitoring and telemedicine expand access to care, ensuring timely treatment regardless of location. Together, these innovations offer a comprehensive approach to DFU management, potentially improving patient outcomes and reducing healthcare costs.

Integrating AI and wearable technologies into DFU care can address some limitations of traditional methods. AI-driven health applications, connected to sensors, utilize the 4P principles (Predictive, Preventive, Personalized, and Participatory) to monitor foot temperature, pressure, and movement, providing real-time insights. Predictive analytics can identify early signs of potential ulcers, allowing for timely interventions before complications arise. While promising, these advancements require cautious interpretation. Continuous monitoring and personalized interventions appear effective in preventing DFUs, yet more research is needed to fully understand their potential.

The adoption of these technologies necessitates shifts in healthcare infrastructure, including investments in digital systems and training professionals to work alongside AI tools. Ethical considerations, such as data privacy and potential AI bias, must also be addressed to ensure equitable healthcare delivery [17,99].

Wearable technology provides numerous benefits by enabling continuous data collection, which helps detect subtle health changes before they become severe. Patients can share health data with providers, facilitating personalized care. Despite their convenience, the accuracy and reliability of wearables remain a concern, emphasizing the need for corroboration with clinical-grade equipment. Ongoing advancements in sensor technology and algorithms are expected to enhance the precision of these health monitors [64,100].

Leveraging AI and wearable technologies in DFU care shows potential for improved patient outcomes and proactive health management. However, strategic planning, investment, and ongoing evaluation are crucial for maximizing benefits and minimizing risks.

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