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Wearable Sweat Sensors for Analyte Detection: A Review

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Abstract. Wearable technologies have rapidly advanced in recent years; as their availability increases, individuals are increasingly inclined to select non-invasive and portable for monitoring their physical health. Sweat can indicate an individual's health status by various essential biomarkers present. Research indicates that various types of wearable devices concentrate on distinct aspects; thus, thorough experimentation is essential to enhance the sensitivity, specificity, comprehensiveness, and stability of data. In October 2024, we examined three databases containing 624 records. Our analysis encompassed ten publications that detailed various wearable devices, such as patch-type and electrochemical devices, capable of continuously collecting and monitoring sweat samples by integrating microfluidic channels and reservoirs. The data acquired from these devices demonstrated authenticity and dependability since all publications highlighted the capacity to collect sweat in a regulated manner, hence minimizing contamination and preserving sample integrity.

Keywords: sweat, wearable sensor, vitamin, mineral, analyte.

1. Introduction

Sweating can have various causes, including temperature, emotions, stress, and medical conditions. Sweat is an essential biological metric that plays a crucial function in human life and cannot be overlooked. Occasionally, perspiration might remain on an individual's skin for an extended duration, while at other times, it dissipates rapidly, influenced by variations in both physical and mental conditions. In light of this, wearable technologies demonstrate the necessity for their design to prioritize convenience and timeliness while limiting the influence on individuals' physical conditions, which is crucial for subsequent studies. In recent years, an increasing number of studies have commenced experiments on sweat, such as analyzing vitamin concentration, which is an essential organic compound for the human body that plays a critical role in sustaining normal physiological functions and prompting individuals to take measures to ensure adequate vitamin levels within the body. Furthermore, the mineral composition of sweat provides critical information; electrolytes such as sodium, potassium, and calcium are essential for maintaining electrolyte balance. Timely and precise sweat analysis is instrumental in identifying potential health risks early and offering insights into an individual's nutritional status. Our findings indicate that numerous studies enhanced the materials used in experiments, rendering them cost-effective and facile to

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synthesize. Continuous data collection and monitoring are imperative to uphold the authenticity and reliability of the findings. Nevertheless, many studies need more data or more methodological detail and should be considered. Given that our perspective excludes clinical conditions, we must select the studies that best adhere to the established standards. The subsequent section will demonstrate the methodology employed by these researchers to achieve dependable outcomes in their experiments.

2. Methods

This review primarily aims to assess the medical uses of sweat sensors, particularly in detecting vitamins, minerals, and other analytes in sweat. This review aims to thoroughly examine the present research landscape, emphasizing the clinical applicability, precision, and dependability of diverse sweat sensors in health status monitoring.

2.1. Search strategy

A comprehensive literature review was performed across three principal databases: PubMed, IEEE Xplore, and ACM Digital Library. The search approach was carefully crafted to encompass a broad spectrum of papers about wearable sweat sensors and their medicinal applications. The subsequent search phrases utilized were: (Wearable OR "Wearable devices" OR "sweat sensor") AND ("vitamin" OR "mineral" OR "analyte"). The search was limited to articles published in peer-reviewed journals and conference proceedings to guarantee the inclusion of high-quality research.

The search procedure encompassed multiple processes to guarantee a thorough and methodical approach. The search criteria were applied to each database, and then the results were aggregated. The search was performed without date limitations to encompass the entire breadth of research in this domain. The search results were subsequently loaded into reference management software to enable the elimination of duplicates and the systematic structuring of records.

2.2. Inclusion and exclusion criteria

Establishing the inclusion and exclusion criteria guarantees the pertinence of studies on the medical utilization of sweat sensors. The research was methodically vetted by classifying the criteria into inclusion and exclusion groups.

A thorough literature analysis is performed to ascertain the present status of research on sweat sensors and their medical applications, thereby identifying key subjects, technologies, and analytes of interest. This crucial step outlines the attributes of clinical relevance, categories of sensors, particular analytes, technology integration, and research methodology. A preliminary version of the inclusion and exclusion criteria is established and evaluated throughout our initial search through an iterative refinement process. This phase guarantees that the criteria adequately filter pertinent research and that adjustments are implemented depending on input and outcomes. The inclusion criteria, employing specialized sensors, are designed to ensure that the research concentrates on detecting vitamins, minerals, and other analytes in sweat for medical purposes, hence promoting technological integration and breakthroughs. The exclusion criteria aim to exclude studies predominantly centered on material science with limited medical relevance, non-medical applications, inadequate technology integration, and those lacking sufficient data. The concluding phase of this procedure entails meeting the criteria, guaranteeing their thoroughness and conformity with the aims of the systematic review. This methodology enables the incorporation of high-quality,

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pertinent studies that offer insightful evaluations of the therapeutic uses of sweat sensors, thus progressing this field.

The inclusion and exclusion criteria were implemented sequentially to provide a stringent screening procedure. Initially, the titles and abstracts of all discovered records were reviewed to eliminate unrelated research. Subsequently, full-text articles were obtained for the remaining data and evaluated for eligibility according to the established criteria.

Inclusion Criteria	Exclusion Criteria
1. Clinical Relevance: - Studies that focus on the detection of vitamins, minerals, and other analytes in sweat for medical applications. - Research that discusses the clinical utility, accuracy, and reliability of sweat sensors in monitoring health conditions. 2. Type of Sensor: - Electrochemical sensors designed for sweat analysis. - Optical sensors used for detecting analytes in sweat. - Microfluidic sensors that collect and analyze sweat. 3. Analytes of Interest: - Studies that detect specific vitamins (e.g., Vitamin C, Vitamin D). - Papers focusing on other relevant analytes (e.g., glucose, calcium). 4. Technological Integration: - Papers discussing the integration of biosensing technologies for accurate and continuous monitoring. - Studies that include advancements in sensor technology, such as improved sensitivity, specificity, and real-time data transmission. 5. Study Design: - Reliable and authoritative papers.	1. Material Research Focus: - Studies primarily focused on the material science aspects of sweat sensors without significant discussion on medical applications. 2. Non-Medical Applications: - Research on sweat sensors used for non-medical purposes, such as sports performance monitoring without health implications. 3. Lack of Technological Integration: - Papers that do not discuss the integration of biosensing technologies or advancements in sensor technology. 4. Insufficient Data: - Studies with incomplete data or lacking detailed methodology and results.

Figure 1. Inclusion and exclusion criterias

2.3. Data extraction

The data extraction procedure encompassed multiple stages to guarantee the incorporation of pertinent studies and precise data extraction. The data extraction procedure utilized a standardized form to guarantee uniformity and precision. The form comprised sections for study characteristics, sensor characteristics, and outcomes. The subsequent steps were executed:

3. Results

This study includes a variety of technologies and approaches for detecting vitamins, minerals, and other analytes in sweat through wearable sensors. We thoroughly investigated both qualitative and quantitative methodologies, concentrating on sensor types, discovered analytes, clinical applications, and technical innovations.

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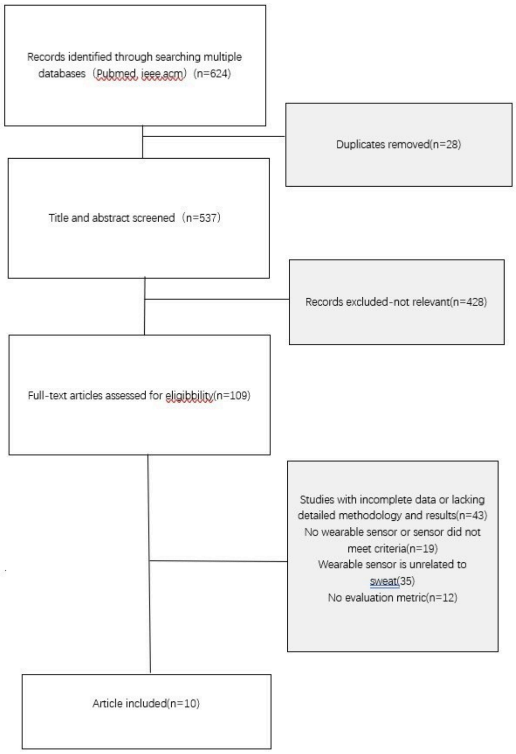

Figure 2. Flow chart

3.1. Qualitative analysis

3.1.1. Types of sensors

The research employed many sensor modalities, encompassing electrochemical, optical, and microfluidic sensors. Polat et al. [1] examined transducer technologies for biosensors, emphasizing the adaptability of electrochemical sensors. Mogera et al. [2] concentrated on wearable plasmonic paper-based microfluidics for ongoing sweat analysis, whereas Zhao et al. [5] created a thread/fabric-based band for sweat detection.

3.1.2. Detected analytes

The research encompassed various analytes, such as vitamins, minerals, and other biomarkers. Song et al. [8] created a comprehensive carbon-based method for detecting UV radiation and vitamin C. Kim et al. [9] designed a miniaturized microfluidic system for colorimetric measurements of nutrients in sweat, including vitamins. Garg et al. [6] used molecularly imprinted sensors for real-time sweat biomarker analysis.

3.1.3. Clinical applications

The clinical applications encompassed the monitoring of dehydration and electrolyte imbalances, the detection of metabolic diseases, and dietary shortages. Vaquer et al. [4] developed dissolvable polymer valves for sweat chrono-sampling, useful for longitudinal monitoring. Mishra et al. [7] created a wearable microfluidic patch for on-demand, multianalyte sweat sensing, providing a versatile tool for continuous health monitoring.

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3.1.4. Technological advancements

The research emphasized enhancements like increased sensitivity, specificity, and real-time data transfer. Mogera et al. [2] demonstrated high sensitivity and specificity with plasmonic paper-based microfluidics. Kim et al. [9] integrated a microfluidic system with colorimetric measurements for real-time monitoring and nutrient delivery. Mishra et al. [7] incorporated finger-actuated pumps and valves for on-demand sampling.

3.2. Quantitative analysis

3.2.1. Accuracy and reliability

The accuracy and reliability of the sensors were assessed according to sensitivity, specificity, and detection thresholds. Polat et al. [1] reported high sensitivity and specificity for electrochemical sensors. Mogera et al. [2] demonstrated high sensitivity with plasmonic microfluidics. Kim et al. [9] achieved accurate colorimetric measurements with their microfluidic system.

3.2.2. Clinical utility

The clinical utility was assessed based on the sensors' ability to monitor health conditions. Vaquer et al. [4] showed that their polymer valves could monitor hydration and electrolyte balance. Mishra et al. [7] demonstrated that their microfluidic patch could monitor multiple analytes, offering comprehensive health monitoring. Garg et al. [6] highlighted the potential of their sensors for real-time biomarker analysis.

3.2.3. Technological integration

The integration of biosensing technologies with wearable devices was a key focus. Mogera et al. [2] integrated plasmonic microfluidics with wearable devices for continuous analysis. Kim et al. [9] combined a microfluidic system with colorimetric measurements and nutrient delivery. Mishra et al. [7] incorporated pumps and valves for on-demand sampling, enhancing device versatility.

3.3. Synthesis of findings

The summary of findings offers a thorough picture of the present research landscape for medical sweat sensors. The research indicates that sweat sensors can precisely identify several analytes, underscoring their potential for medical use. Technological developments improve sensitivity, specificity, and real-time data transfer, augmenting their potential. The clinical efficacy of sweat sensors in health condition monitoring is apparent, as continuous observation and real-time data yield significant health insights. Subsequent investigations should focus on more extensive clinical studies, innovative sensor technologies, and the amalgamation of additional wearable devices to fully exploit the capabilities of sweat sensors in medical applications.

4. Conclusion

Our review concentrates on wearable devices capable of measuring vitamins, minerals, and analytes in human sweat; these sensors provide significant promise of delivering timely and precise data. Future wearable applications are anticipated to monitor several critical parameters continuously and

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noninvasively. During that period, individuals can choose their desired type of wearable gadgets, remain conveniently informed about their health status, and make timely adjustments.

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