Recent Advancements in Wearable Hydration Monitoring Technologies: A Scoping Review of Sensors, Trends, and Future Directions

Nazim Belabbaci, Raphael Anaadumba, Mohammad Arif Ul Alam

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Abstract

Background: Monitoring hydration is crucial for maintaining health and preventing dehydration-related is-sues. Wearable devices offer a promising method for continuously tracking hydration levels. Despite the popularity of wearable technology in health research, its application for hydration monitoring is not extensively studied, and clear design guidelines are lacking. This scoping review aims to fill this gap by analyzing existing research trends and the potential impact of wearable technologies for hydration monitoring.

Objective: This review comprehensively analyzes recent advancements in wearable hydration monitoring technologies, focusing on their capabilities, limitations, and research and prototype designs. It explores different sensors and technologies for tracking hydration, compares their ad-vantages and disadvantages, identifies trends in wearable hydration monitoring devices, assesses their accuracy and reliability compared to established benchmarks, and identifies commercially available products to bridge research findings with practical use.

Methods: Following PRISMA guidelines, a scoping review was conducted to explore the breadth and variety of technological approaches in hydration monitoring research. A systematic search across Pubmed, IEEE Xplore, and Google Scholar was performed using a versatile search syntax. Studies published since 2014 focusing on non-invasive, portable hydration monitoring systems utilizing physiological biomarkers were included.

Results: The review included 63 articles selected from 156 studies for synthesis analysis. The literature was categorized based on sensor types, including electrical, optical, thermal, microwave, and multimodal sensors. Most studies explored hydration's effects on physiological parameters, with some examining hydration status during physical activity or in various environmental conditions. Commercially available products from eight companies were also evaluated for technological features, functionalities, and applications.

The dominance of electrical sensors in re- search was noted, leveraging their ease of use and integration into wearables. While fewer in number, optical methods exhibited precision and provided molecular-level in-sights. The emergence of multimodal sensors indicated a trend toward combining technologies for better ac- curacy. Other sensors, such as thermal and microwave-based variants, found unique niches. The prevalence of optical-based wearables in the market suggests their growing acceptance due to cost-to-precision effectiveness.

Conclusions: Wearable hydration monitoring devices offer real-time hydration assessments, but challenges remain in reliability, accuracy, and applicability across diverse populations and conditions. Future directions include standardized protocols, extensive clinical studies, sensor miniaturization, and improved wearability. Multimodal systems combining various sensors with AI-driven analysis offer potential for personalized hydration management. This review provides detailed insights into sensor technologies' strengths and challenges, paving the way for practical solutions in skin hydration monitoring.

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Keywords: Wearable technology, Hydration monitoring, Sensors, Trends

II. Introduction

Water is a fundamental component of the human body. Constituting from 75% of body weight in infants to 55% in the elderly (1), and plays a crucial role in the functioning of various organs. This indispensability of water underscores the importance of maintaining proper hydration levels for overall health and well-being (2, 3). Ironically, both underhydration and overhydration pose risks, from impacting physical performance to causing severe medical conditions such as heart failure exacerbated by diuretics or im- proper blood circulation.

Given the complexities and the urgent need for non-invasive, real-time hydration monitoring systems, as highlighted by various studies (4), the recent advancements and widespread adoption of wearable technology present a promising solution. Over the past few years, wearables have not only become integral to daily life for many (5, 6, 7, 8), but their potential for scientific data collection and evaluation has also seen a significant increase. This is particularly evident in the realm of health and fitness monitoring, where wearables are being leveraged for a variety of metrics (8, 9, 10)

In the realm of wearable technology, a diverse array of devices, from sophisticated smartwatches (11, 12) to innovative smart clothing (13), is revolutionizing how we monitor health parameters. A particularly notable advancement is their ability to monitor hydration levels, an essential aspect of health often overlooked. These wearables employ cutting- edge methods, such as analyzing electrolyte variations in sweat or utilizing electrical and optical sensors for cellular-level hydration assessment. This technique exploits the optical properties of tissues to provide a nuanced understanding of hydration status.

The implications of these technological strides are profound. For the first time, continuous, non- invasive hydration monitoring is within our grasp, offering a potential safeguard for various at-risk populations. It heralds a new era in preventive health care, where risks associated with dehydration can be mitigated proactively, thereby enhancing quality of life.

However, this bright horizon is not without its shadows. Recent research in hydration monitoring, while promising, reveals significant gaps.

A notable shortfall is the paucity of robust clinical studies, particularly those focused on specific diseases or clinical problems (14, 15, 16). This limitation raises questions about the applicability and accuracy of these technologies in real- world scenarios, as the lack of targeted research hinders our understanding of their effectiveness in addressing particular medical challenges. Furthermore, another major shortfall is that most of the technology in wearables is still in its development phase(17, 18, 19), which adds another layer of uncertainty regarding their reliability and effectiveness in practical applications. In addition, the sample sizes in existing experiments often fall short of statistical significance, limiting the reliability of their findings. Additionally, much of the research is narrowly focused on specific population groups (20), which may not accurately represent the diverse needs of the broader population. This lack of inclusivity in research design could potentially skew the results and limit the universal applicability of these wearable technologies.

In this review, we aim to fill a notable gap in the current literature by providing an in-depth exploration of the latest developments in wear- able and portable solutions for hydration tracking. Our focus extends to populations at an elevated risk of dehydration, such as athletes, military personnel in extreme environments, individuals involved in infant and maternal health, and the elderly, detailing why these groups are particularly susceptible (21). This is because dehydration that exceeds 2% bodyweight loss may lead to heart-related injury risk (22) We will delve into the medical and operational causes and consequences of dehydration in these groups, examining both established and emerging monitoring techniques. This analysis is informed by recent advancements in wireless body sensor networks, as highlighted in studies like (23, 24), and pays special attention to technologies that enable real-time monitoring, emphasizing their critical role in timely health intervention and preventive care.

A. Research Objectives

The rationale behind this scoping review is to comprehensively explore the landscape of wearable hydration monitoring technologies, ad- dressing key questions to enhance understand-

ing and inform future research and development. Specifically, the objectives are as follows:

- To examine the various types of sensors and technologies utilized for hydration monitoring, providing insights into their functionalities, advantages, and limitations.
- To assess the trade-offs between different monitoring methods, shedding light on the optimal use cases for each sensor type and category.
- To identify trends and emerging techniques in wearable hydration monitoring, providing a forward-looking view on technology adoption and innovation.
- To evaluate the precision and reliability of wearable devices compared to gold standard methods, examining their performance across diverse populations and scenarios.
- To map commercial products in the market, analyzing their technological features, functionalities, and practical applications, bridging the gap between academic research and real-world implementations

III. Methods

The review concentrated on wearable or portable devices, seeking to provide a detailed overview of recent advancements in hydration monitoring technologies, including their capabilities and features. Additionally, it aimed to assess the overall direction of development, re- search, and prototype design in this area. This scoping review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and the PRISMA-ScR (Scoping Reviews) guidelines (25).

Information Sources: The search syntax, incorporating keyword variations like" hydration monitoring" and " wearable devices", was crafted for advanced search functions in PubMed and IEEE Xplore's "Title-Abstract" fields, and further extended to Google Scholar to ensure com- prehensive literature coverage. The final search string "(hydration monitoring OR hydration sensor) AND (wearable OR device)" targeted literature published after 2014.

Selection of Sources of Evidence: A total of 551 articles were identified initially; PubMed returned 408 articles, IEEE Xplore returned 107 articles, and articles from additional sources were included (36 papers, which were identified from Google Scholar search and references of the mentioned papers that did not appear in the initial search results). After excluding duplicates, a total of 546 articles remained. Screening based on titles and abstracts led to the inclusion of 156 studies for full-text analysis. If a paper couldn't be definitively accepted or rejected based on its title or abstract due to a lack of alignment with the study criteria, a thorough examination of the full text was conducted.

Eligibility Criteria: Inclusion criteria encompass studies focusing on wearable or portable hydration monitoring systems, excluding obtrusive or invasive methods. The criteria also re- quired direct addressing of body hydration, targeting biomedical applications, and reliance on physiological biomarkers rather than methods such as body motion tracking or monitoring fluid intake or extraction through smart bottles or toilets. Validation through tests on human sub- jects or comparisons with gold standards was an essential criterion. Out of the 156 studies pre-selected for a full-text screening, a total of 63 articles were retained for a synthesis analysis. The individual steps that were carried out is shown in Figure 1.

Data extraction: Data extraction involved summarizing prototype/device design, the technology utilized, the novelty of research, challenges, and limitations of each paper. Articles were saved and data was extracted using Mendeley, with annotations for each paper.

Commercial Product Search: In addition to academic research papers, we conducted a Google search to investigate commercial products in the field of hydration monitoring. Through online research, we identified several companies. Detailed evaluations were undertaken to compare the technological features, functionalities, and applications of these commercial products. This analysis offers valuable insights into practical implementations and advancements in the field, bridging the gap between academic re- search and real-world applications. Specifically, we identified and compared eight companies based on factors such as validation, FDA approval, and technology employed.

IV. Results

To organize the selected literature and facilitate comprehensive analysis, a classification

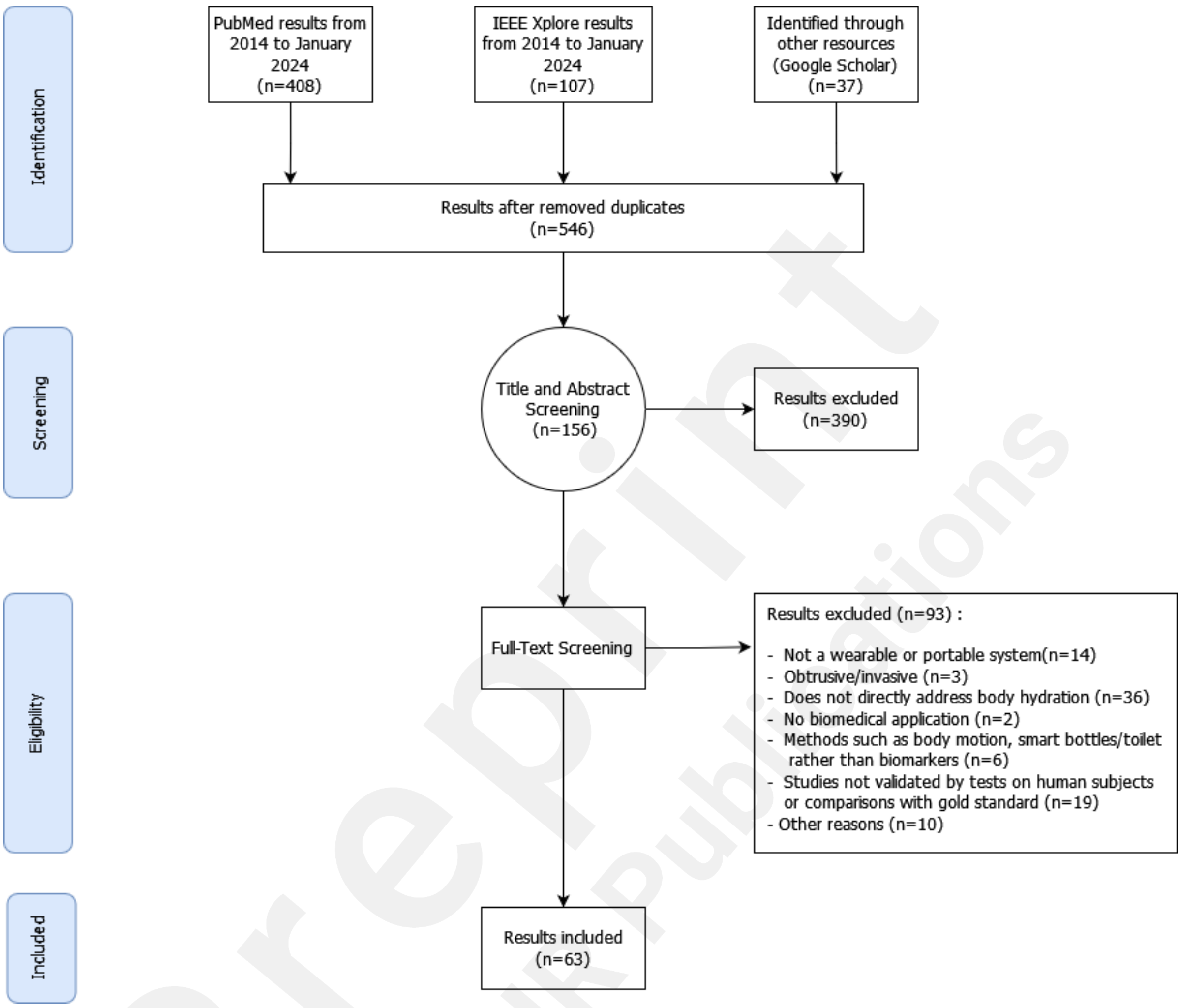

Fig. 1: Flow diagram of study selection for wearable and portable hydration monitoring systems.

taxonomy was developed based on the type of sensors used for hydration monitoring in wearable technologies. This taxonomy categorizes the gathered papers into the following groups: Electrical Sensors, Optical Sensors, Thermal Sensors, Microwave Sensors, Multi-Modal Sensors, and Commercial Products (see Figure 2). This classification allows for a structured review of the literature, highlighting the different sensor technologies utilized in hydration monitoring devices.

A. Electrical-Based Sensors

We explored a variety of wearable electrical sensors, including capacitance, conductance-based, impedance-based, and electrochemical-based systems.

1) Capacitance Method: In this category, we classify studies that monitor hydration by evaluating the skin's capacitance. This methods in- volves measuring changes in electrical proper- ties resulting from variations in skin moisture levels to assess and monitor hydration status as illustrated by Figure (supplement) 4.

Yao et. al. (26) introduced a wearable skin hydration sensor featuring silver nanowire electrodes. With its flexible and stretchable nature, this sensor can remain unaffected by humidity changes, contributing to consistent performance. Calibrated against the MMD (27) commercial skin hydration system, the sensor is packaged into a flexible wristband with an

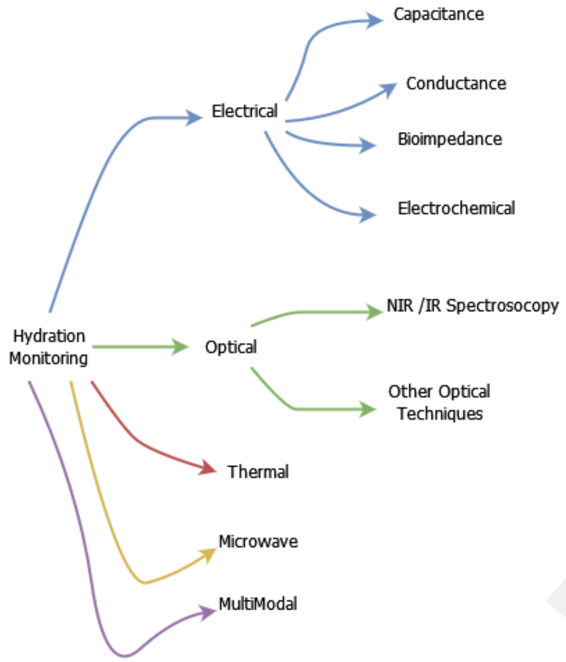

Fig. 2: Hydration monitoring systems categorized based on the type of sensors used.

ultralow-power MCU and Bluetooth capability. Further research should assess the adaptation to different skin layers and fully realize its potential for widespread use.

One study (28) introduced a ’Skin Hydration Sensor Patch’ integrating capacitive measurement and NFC data transmission with smart phones. The patch showed high correlation with Corneometer© results on various skin sites. A subsequent study with moderate dry skin on the face and forearm suggested upgrading the sensor probe calibration for enhanced sensitivity. Additionally, a potential future direction involves correlating changes in facial skin signs with variable skin hydration using an AI-driven system analyzing selfies.

Another study (29) developed capacitive textile sensors for continuous skin hydration monitoring, aiming for integration into everyday clothing textiles. The study emphasized the sensors’ ability to provide real-time health assessment and enhance patient comfort. Challenges regarding sensor absorption effects, long-term performance, and pressure during measurements were noted, suggesting that future research should prioritize addressing these issues to improve the reliability and appli of textile sensors.

2) Conductance Method: In this section, we explore papers focusing on the application of monitoring hydration using sensors that measure skin conductance. Conductance-based hydration measurement involves assessing skin moisture levels by measuring the ease of electrical current flow through the skin, with increased conductance indicating higher hydration.

Clarys et al. (30) conducted a comparative analysis to quantify the difference be- tween conductance-based and capacitance- based methods for hydration assessment. They investigated two instruments, the Corneometer 825 (capacitance-based) and Skicon-200 EX (conductance-based). In vitro and in vivo evaluations revealed that conductance measurements are influenced by electrolytes, whereas capacitance measurements remain unaffected. The capacitance method allows for probing deeper skin layers (up to 45 μm) compared to the conductance method (up to 15 μm). Both methods showed robust correlations between water con- tent and measurements.

Lu et al. (14) introduced a portable device for diagnosing dehydration and its potential link to chronic kidney disease through saliva conductivity analysis. It consists of a micro control unit (MCU), an analogue-to-digital converter (ADC), and an LCD display to show electric signals of saliva samples. The device capable of measuring saliva conductivity through the assessment of bioelectrical signals. The miniaturization of electrodes reduces its sample-contact area and the amount of saliva required for a test. Challenges include the significant variation in saliva conductivity among individuals due to factors such as diet, hydration status, and individual physiology, which could affect the device's accuracy and reliability.

Rizwan et al. (15) proposed Galvanic Skin Response (GSR) as a non-invasive marker for hydration, collecting and analyzing GSR data from individuals in different hydration states and body postures (Figure (supplement) 5). The paper demonstrated promising advancements in non-invasive hydration level monitoring, suggesting further research for algorithm refinement and addressing variability in GSR measurements.

Madhvapathy et al. (31) presented a versatile and cost-effective patch based on a flexible PCB for skin hydration monitoring and dermatological diagnosis. This platform utilizes a thermistor to measure skin conductivity and diffusivity, enabling the measurement of volumetric water con- tent up to approximately 1 mm in depth. The sensor wirelessly communicates with a smartphone using NFC technology. Some limitations include the lack of knowledge regarding the thickness of the epidermis, which cannot be easily inferred directly from thermal conductivity data.

Wang et. al. (32) introduced a wearable sweat sensor platform for simultaneous measurement of sweat rate and total electrolyte concentration without the need for calibration. The platform features a unique fluidic-controlled design to detect sweat and minimize dilution effects. Practical tests demonstrate its ability to measure regional sweat rate, sweat loss, and electrolyte concen particularly optimized for high sweat situations like spor platform may face challenges at low flow rates, impacting re detection and introducing potential bias. Addressing this lin could improve its accuracy and applicability in scenari varying sweat flow rates.

Responding to limitations in existing hydration t methods, Liaqat et al. (33) developed a novel system ba machine learning and deep learning techniques for acc estimating hydration levels using GSR data. The hybrid enhanced accuracy, making it valuable for sports, health, an being applications.

3) Bioelectrical Impedance Analysis (BIA): In this sect delve into studies that employ impedance-based sensors. Distin conductance-based tracking, which measures skin's e conductance, BIA examines impedance, including both resista capacitance as illustrated in Figure (supplement) 6. The working principle of bioimpedance hydration t involves two stages: an initial rapid impedance change caused by electrolyte solution filling skin voids, followed by a gradual change associated with water gradient equalization and structural skin barrier alterations (34).

Chua et. al. (35) introduced the i-Health Watch, an integrated wearable for continuous monitoring of heart rate (HR), hydration level, and blood glucose concentration using bioimpedance. The compact prototype incorporates 2 pairs of silver electrodes with conductive gel, enabling real-time tracking. The watch's face displays continuous readings and issues on-screen alerts for abnormalities. The novelty lies in a parallel signal processing approach, deriving three physiological readings from a single bioimpedance feed, streamlining the device. Initial testing on a single human subject demonstrates the potential for future integration into a smart telemonitoring health system.

Agcayazi et al. (36) designed a wearable bioimpedance analyzer for infant hydration monitoring. The system utilizes an Analog Devices 5933 impedance analyzer combined with an RFduino for Bluetooth communication with a smart- phone. Validation on two adult subjects using electrodes placed on specific body parts demonstrated a relative decrease in bioimpedance and an increase in hydration as subjects consumed water progressively. The system requires initial calibration based on an individual's height and weight, which may limit its applicability in certain scenarios.

Yang et al. (37) introduced a small, battery less wearable device for assessing skin hydration levels. The device combined sunlight exposure computation with skin impedance and temperature measurement, aiming to be incorporated into a bracelet or ring for simultaneous UV index, skin hydration, and temperature measurement, a feature does not present in current UV trackers. Despite its simplicity, affordability, and energy efficiency, the device is practically useful for detecting skin impedance variations due to water loss caused by sunlight exposure. Testing during the summer season is crucial to establish correlations between skin impedance changes and higher UV indexes.

Sunny et al. (38) developed a cost-effective bio-impedance sensor that uses four gel electrodes on the skin surface to mimic skin properties and detect hydration changes. Accuracy was validated under varying skin conditions. The sensor shows promise for detecting skin hydration changes in both phantom and human skin experiments. Future research could focus on enhancing the sensor's performance, usability in portable or wearable modes, and standardizing experimental setups.

Leonov et al. (39) introduced a sensor with significant sensitivity to hydration change, with a detection limit of 55 ml for sweat loss under

the worst-case scenario. Although it has shown sensitivity to hydration changes of approximately 700 ml, more refined protocols and improved devices are necessary to enhance reliability for practical daily life applications.

Matsukawa et al. (40) presented a method for continuous monitoring of skin hydration using nanomesh electrodes attached on the left ventral forearm. These electrodes adhere to the skin comfortably which offers water vapor permeability for extended wear and enables impedance measurements without applying pressure. Impedance results correlated with hydration levels measured by a Corneometer. Because intense sweating can lead to short- circuiting between electrodes due to the lack of an encapsulation layer, the research plan addresses this challenge by adding an encapsulation layer.

Veeralingam et al. (41) developed a novel 'Body Hydration Analysis System' to improve running performance by assessing skin hydration levels through impedance variations. The system utilizes the open-source QueSSence board and an AI-driven K-Nearest Neighbors (KNN) algorithm for efficient data analysis. The sensor, based on a semiconductor compound with high electronics properties, demonstrated high conductivity, ideal for wearable applications. The study's challenges include the need for further validation and integration of these technologies into user-friendly wearable devices for real-time monitoring during athletic activities.

Valentin et al. (20) created a wearable MCU-based BIA device for precise hydration measurements with low power consumption. The study involved placing electrodes below the right shoulder blade and on the left bottom of the belly. The protocol included an initial measurement, intake of 200 ml water, and another measurement after 15 minutes. The experiment resulted in an impedance recording accuracy below 2%, supporting future clinical applications. Further research should address limitations such as sample size and long-term monitoring to validate the method for clinical use.

Songkakul et al. (17) introduced a miniaturized wearable bioimpedance spectroscopy (BIS) system for continuous tissue hydration monitoring, emphasizing electrode optimizati advanced data processing. The system comprises Bluetooth analog front-end circuit integrated with conformable, flexible, and stretchable silver-nanowire electrodes. The system is powered by a lithium battery, providing 18 hours of operation. Configured with four-electrode, where two serve as the current source and sink, while voltage is measured across the other two electrodes. Further research is needed to validate the system in vivo to enhance its accuracy and usability in real-world applications.

AlDisi et al. (16) developed and tested two wrist-worn interdigitated electrode designs (IDEs) for assessing hydration levels using BIA. The study demonstrated IDEs' accuracy in measuring hydration without complex models, addressing classification challenges and impedance reading influences. The experiments involved six participants classified into severe dehydration, mild dehydration, and hydration states. While promising for hydration assessment without complex calibration, further clinical studies with a larger sample size are needed to establish robust classification criteria and address differences in readings between body sides and testing sessions.

Thomas et al. (18) introduced a MoSe2/PVA-based (molybdenum diselenide/ polyvinyl alcohol) wearable platform for pulse rate monitoring, skin hydration sensing. The PVA/MoSe2 com- pound can be visualized as a combination of resistance and capacitance in parallel and skin as resistance in parallel when the sensor is placed over it. Experiments involving moisturizer application and changes in relative humidity demonstrate the sensor's performance. The sensor exhibits low noise, cost-effectiveness, and reusability. While the fabrication process is described as simple and cost-effective, it still requires specialized techniques such as hydrothermal synthesis. This could limit scalability and accessibility for widespread adoption.

Jang et al. (42) presented a textile-based wearable sensor designed for stable and reliable monitoring of skin impedance changes related to hydration levels. The sensor can detect different hydration levels across various body parts while maintaining stable contact with the skin. Time- dependent monitoring of skin hydration on the hand demonstrates the sensor's ability to detect changes over time, with reliable results and fewer standard deviations compared to ground truth sensor. Future research could focus on designing more intricate electrodes to enhance sensing performance or adjust to different skin conditions.

Tonello et al. (19) described a multisensory wearable that integrates inkjet-printed flexible sensors on a bracelet-shaped substrate for temperature, body impedance, and skin hydration monitoring. The device measures total impedance from three sensors: RTD, BIA, and a hydration status sensor. This combination enables continuous non-invasive hydration level measurement through temperature measurement, local hydration monitoring, and global body composition analysis. Preliminary in-vivo validation on two volunteers demonstrated the sensors' capability to detect different hydration conditions. Future work will focus on refining sensor design and conducting reproducibi stability tests.

Finally, SkinUp® (43) measured skin moisture and oi using impedance, validated against the Corneometer® C offering a portable solution for skin hydration measu on different regions. SkinUp® can take skin hy measurements on the forearm, cheeks, and forehead.

Hereby, various techniques are employed to monit hydration levels, each with dis- tinct strengths and lim Capacitance- based sensors assess hydration through di properties, providing non-invasiveness but maybe less Conductance-based sensors gauge hydration through el conductivity, balancing accuracy and user-friendliness combines aspects of both, offering a com- prehensive asse but may limit long-term wear. Selection depends on app and user preferences, considering factors like precision, c and duration of use.

4) Eletrochemical Analysis: Electrochemical analysis employs various techniques to monitor electrolyte concentrations (44). These techniques include sweat sensors that utilize ion- selective electrodes (ISFETs) with microfluidics and low-noise electronics for precise electrolyte level monitoring (45, 46). Other approaches include waterproof, epidermal microfluidic devices for capturing and analyzing sweat underwater, as well as chemiresistors based sensors for monitoring sweat dynamics (47, 48).

In their investigation, Culver et al. (44) focused on monitoring electrolytes in sweat using a wear- able sweat sensor. The Objective of the study was to evaluate the sensor during a simulated special operations field event conducted at the U.S. Air Force Academy. While the study underscores the potential of the sensor for hydration monitoring, it also recognizes the challenge posed by limited sweat availability for detection. To overcome this hurdle, the study explored sensor placement on the lower back, a region known to produce more sodium-rich sweat for analysis. The device incorporates ion-selective electrodes with microfluidics and low-noise electronics, ensuring precise and reliable monitoring of Na^+ and K^+ levels in sweat (45). Challenges identified include the improvement of sensor shelf-life, and stability, as well as the reduction of sensor footprint.

Reeder et al. (47) introduced waterproof, epidermal microfluidic devices for capturing and analyzing sweat underwater. These devices, designed for athletics and fitness, allow real-time monitoring of fluid loss and electrolyte concentration in aquatic settings. Field trials demonstrate quantitative in situ measurements of sweat chloride concentration, local sweat loss, and skin temperature during physical activity. The devices are made of soft, waterproof materials and designed for seamless operation in extreme environments. Future research aims to explore the physiology of aquatic sweating using this platform and validate its utility.

Parrilla et al. (48) introduced a wearable paper-based chemiresistor for monitoring sweat dynamics, emphasizing sweat rate and loss. This sensor measures microliter-scale volumes of aqueous solution via resistance changes along a conducting paper substrate. The study outlines the sensor's analytical performance, sensing mechanism, and effectiveness in monitoring sweat loss during exercise. Challenges include optimizing sensitivity and reliability across various conditions.

Lafaye et al. (46) presented a real-time multi-sensing wearable platform for continuous sweat biomonitoring. One prototype uses an ISFET soft sensing Patch, while the second prototype uses silicon-based sensors and paper microfluidics. Both platforms integrate a multi-sensor array for measuring sodium, potassium, and pH in sweat. Initial results from prototypes placed on athletes during exercise demonstrate the platform's efficacy. Body water loss percentage (BWL%) was used as a quantitative indicator for the hydration status of the subjects. Machine learning algorithms predict BWL from biomarkers like HR and sweat sodium concentration across multiple subjects. Future work includes expanding experiments with more subjects, correlating sweat sensor recordings with other biomarkers.

Yang et al.(49) showcased a cost-effective wearable sweat sensor, utilizing screen printing technology for real-time monitoring of K+ and Na+ concentrations in human sweat. In a 10-day continuous monitoring experiment, a close relationship between K+ and Na+ concentrations and hydration status was observed. The fabricated sensors meet the requirements for sweat sensing applications, demonstrating sensitivity, linearity, repeatability, resistance to interference, and mechanical deformation resistance.

B. Optical-Based Sensors

Typically, noninvasive biomedical measurements involve directing light of a specific wave- length onto the skin to collect data. A sensor then detects the light that is either reflected, absorbed, or refracted. This data is utilized to quantify biomedical information. The wavelength of the light is critical for determining the depth of its penetration into the skin when transmitting an optical signal (Figure (supplement) 7). This aspect is what primarily distinguishes the techniques reviewed in this section. Furthermore, these methods enable researchers to evaluate the physiological condition of internal organs through the skin (50).

1) Near Infra-Red Spectroscopy (NIRS): In recent years, NIR spectroscopy has proven to be a potent tool for comprehensive skin hydration analysis within the optical range of 750–2500 nm. Chosen for its ability to capture absorption bands of water, proteins, lipids, and other skin constituents, NIR spectroscopy enables precise measurement of hydration levels. In 2013 Qassem et al. (51) employed NIR Spectroscopy to investigate the effects of sh skin water contact and subsequent moisturizer application o skin. The study involves in vivo measurements within th of 900-2100 nm, highlighting variations in peak values around water overtone and combination bands, providing insights into distinctions between skin types and moisturizer usage patterns.

Visser et al. (52) developed a portable proto- type that utilized an Arduino UNO32 MCU and two infrared LEDs emitting light at 1300 nm and 1480 nm. These wavelengths were chosen for their differing water absorption coefficients, with 1300 nm selected for maximum skin penetration depth and 1480 nm for sensitivity to water concentrations. The study noted greater variability in hydration status among adult patients compared to infants, highlighting the need for universal calibration and validation protocols. Further re- search and validation studies are required to address these limitations and ensure the sensor’s effectiveness across diverse demographic groups.

On another study, Visser et al. (53) investigated the use of optical sensors for prospectively assessing infant dehydration. An Infrared Spectrometry (ISP) sensor with infrared LEDs emitting light at 1300 nm and 1480 nm was employed to maximize skin penetration depth and sensitivity to water concentrations. The study, conducted on 10 infants with acute gastroenteritis, demonstrated promising results, showing high specificity and sensitivity of the ISP sensor in dehydration assessment. Challenges such as infant movement artifacts and data irregularities were mitigated using supplementary algorithms and repeated measurements. The study small sample size necessitates further evaluation on a larger population before clinical deployment.

Mamouei et al. (54) presented the development of a portable sensor for skin hydration monitoring, specifically targeting dermal water content. The focus lies on a multi- wavelength optical sensor designed for continuous and non- intrusive monitoring, utilizing four LEDs emitting at 940 nm, 970 nm, 1200 nm, and 1450 nm, three of which correspond to water absorption peaks in the NIR region of the optical spectrum. Validation includes benchmarking accuracy against a high- end, broad-band spectrophotometer. Future work will concentrate on establishing appropriate algorithms for sensor calibration in the absence of reference gravimetric data, addressing limitations, and enhancing the sensor’s accuracy and usability in practical settings.

Benavides et al. (55) introduced a novel wear- able medical device for continuous monitoring of UV exposure and hydration levels. The device uses IR spectroscopy, where an LED emits light at 940 nm against the skin, and a photodiode detects unabsorbed light to measure water ab- sorption in the skin, enabling real- time hydration assessments through a paired mobile application. Future work may focus on advanced data analytics within the app to provide users with insights into their UV exposure and hydration trends.

Volkova et al. (56) advanced Smartwatch capabilities for continuous monitoring of skin hydration and sweat loss by integrating multi- wavelength optical sensors. Using infrared light at 970 nm and 1450 nm, they identified key characteristics of photoplethysmography (PPG) signals corresponding to skin water content dynamics. Val including simulations and user studies with 19 s supports technology accuracy. Integrated into the S Galaxy Watch Active 2, the hardware effectively monito hydration and sweat loss. Challenges include motion artifa further investigation into sensing water loss due to insu intake. Table I summarizes the cited research, the bior used, and the specific wavelength

range for NIR spectroscopy.

2) *Other Optical-based Techniques:* Other optical are increasingly used for noninvasive hydration monitorin sensors employ various techniques such as spectroscopy on range of wavelengths, and photonics to analyze biomarkers or tissue.

Curto et al. (57) introduced a self-contained wearable d for real-time analysis of pH levels in sweat. The p incorporates a surface mount light-emitting diode (smLED photodiode controlled by a Lilypad Arduino MCU. D occurs through the photodiode and an smLED positioned above and below the sensing area, respectively. Replacing standard LEDs with smLEDs reduced the bulkiness of the system electronics. Challenges remain, including the need to refine sensitivity, specificity, and accuracy of the platform, as well as expanding the range of detectable analytes.

Ozana et al. (58) introduced a wearable optical sensor for noninvasive detection of glucose concentration and assessment of dehydration levels. The sensor uses two optical techniques,

remote vibration source extraction, and rotation of polarized light. It includes four LEDs emitting wavelengths from 600 nm to 1150 nm and a green laser (532 nm) and a camera connected to a computer, resembling a bracelet setup. De- hydration measurements were taken with sub- jects in a 50ºC chamber. Challenges include implementing a motion cancellation mechanism and developing a robust, automatic calibration process.

Perkov et al. (59) investigated optoacoustic (OA) monitoring as a method for assessing water content in tissue. Renowned for its optical contrast, ultrasound resolution, and significant penetration depth, the OA technique presents a promising avenue for such assessments in the skin. The analysis was performed across a wavelength range from 1370 nm to 1650 nm to optimize for water content assessment in skin tis- sues. Challenges identified in the study include the optimization of wavelengths to fully exploit the potential of OA monitoring for skin hydration.

The miniaturized CMOS spectrometer in the 650-900 nm wavelength range, presented in Figure 8, is designed for continuous monitoring of dermal skin hydration (60). Fabricated using a monolithically integrated filter process, the spectrometer ensures cost-effectiveness, low power consumption, and mass production capability. The study highlights the significance of specific wavelengths, such as the 970 nm water and the 930 nm fat absorption peaks, showing the potential of the device for wearable skin biomarker measurements and its versatility for applications beyond dermal hydration, such as HR and sub- dermal markers like glucose or lactate detection(60). However, this work focuses on a small sample size and lacks extensive validation across diverse populations or clinical conditions.

Sandys et al. (61) conducted a pilot-scale observational study to evaluate a wearable hydration monitor, the Sixty, in haemodialysis patients. The device, utilizing diffuse reflectance spectroscopy and machine learning, detected subdermal fluid levels. It combined photonics sensors and wavelengths from 530 to 950 nm to determine fluid status based on reflected light, correlating with tissue composition, particularly water concentration. The primary objective was to assess the device's accuracy compared to bioimpedance measurements during dialysis

Biomarkers	Wavelength Range	Authors
Water content	1300 nm and 1480 nm	Visser et al.(52)(53)
Water absorption peaks	940, 970, 1200, and 1450 nm	M. Mamouei et al.(54)
Water content	940 nm	R. Benavides et al.(55)
Water content and sweat	940 nm and 1450nm	Volkova et.al(56)

TABLE I: NIR Spectroscopy Biomarkers, Wavelength Range, and Authors

sessions and overnight for three weeks. Successful validation of the device's accuracy could lead to its integration into a comprehensive algorithm for managing fluid overload in interdialytic periods, providing patients with actionable insights.

Rockley (62) presented a silicon-photonics-based spectrophotometer for monitoring temperature and water content in tissue-simulating phantoms, utilizing semiconductor lasers. The spectrophotometer demonstrated the utility for temperature and water content tracking, exhibiting excellent agreement between predicted and reference values. However, variables might influence the precision of the spectrophotometer in real-world scenarios, especially when used with intricate substances like human tissue.

Table II summarizes the different optical techniques and corresponding biomarkers used for hydration tracking.

C. Thermal Methods

Thermal methods for assessing hydration involve measuring the skin's thermal properties, such as temperature and thermal transport, which can indicate hydration levels and blood flow dynamics.

Madhvapathy et al. (63) described the development of soft, skin-like thermal depth sensors to track hydration levels. The sensor measured the thermal properties of human skin at depths up to 6 mm beneath the skin's surface, addressing limitations of current methods confined to superficial layers in clinical environments.

Krishnan et al. (64) introduced a wireless, battery-free sensor system for measurement of skin's thermal properties. The device comprises a wireless power harvesting system, NFC-based data transmission, analog signal conditioning on a flexible printed circuit board, and a stretchable sensor with a temperature coefficient of resistance for temperature measurements. Human trials demonstrate cor monitoring of skin conditions over a week without interruption. Challenges involve ensuring the accuracy and reliability of data collected.

Kwon et al. (65) introduced a wireless, soft electronics platform designed for rapid measurements of hydration levels. Recent alternatives utilizing thermal measurements with soft wire- less devices have limitations such as a restricted operating range (1 cm) and sensitivity to environmental fluctuations. In response, this study presented innovative technologies to overcome these drawbacks, enabling high-speed, robust, automated measurements of thermal transport properties. The sensor module was controlled by a BLE system on a chip, with a smartphone interface.

Shin et al. (66) presented a novel wireless and soft skin hydration sensor (SHS) designed for rapid and accurate diagnostics of dermatological health. The SHS integrates a BLE system on a chip within a flex-PCB. Pilot trials involving over 200 patients in a dermatology clinic showcased the practical applicability conducted at three skin locations (forehead, lower leg, and lower arm) using both the SHS and a commercial system (Delfin). The SHS operates without applied pressure, adheres gently to soft and curved skin regions, and provides rapid and objective measurements. Future research could improve by tackling potential limitations, including scalability and long-term reliability and user comfort.

D. Microwave-Based Sensors

Microwave-based sensors utilize microwave or electromagnetic signals to measure various hydration-related parameters.

Butterworth et al. (67) presented a wearable wristband for hydration monitoring, employing non-contact dielectric spectroscopy in the microwave range (2-6 GHz). This technology lever- aged minute variations in wrist hydration, offering a unique approach to tracking overall hydration status. Potential areas for improvement include

Biomarkers	Technique Used	Authors
pH levels in sweat	smLED at visible light (300-700 nm)	F. Curto et al.(57)
Temporal changes in reflected speckles water content	600-1150 nm	N. Ozana et al.(58)
	Optoacoustic monitoring (1370-1650 nm)	Perkov et al. (59)
Localized percentage water content (PWC)	CMOS spectroscopy (650-900 nm) Photonic	R. Van Beers et al.(60)
Dermal fluid status	sensor (530-95 0nm)	V. Sandys et al.(61)
Temperature and water content	Photonic sensor (530-950 nm)	A. Bohman et al.(62)

TABLE II: Optical Techniques and Biomarkers for Hydration Tracking

further validation studies involving a larger and more diverse sample of participants.

Wang et al.'s paper (68) presented a wearable RF device for non-invasive real-time hydration monitoring, correlating received signal strength indicator (RSSI) with BWL%. The de- vice comprised nearfield antenna sensor nodes, an RF frontend, and digital processing units. Challenges involve further validation and refining accuracy and usability of the device.

Schiavoni et al. (69) investigated a time-domain reflectometry (TDR)-based wearable skin hydration sensing system, an electromagnetic (EM) technique showing accuracy, cost- effectiveness, and portability for potential medical applications. Challenges may involve ensuring reliability and connecting TDR measurements to physiological parameters.

Schiavoni et al.'s system (70) combined time-domain reflectometry (TDR) and frequency-domain (FD) data extraction in microwave reflectometry, developing calibration curves linking skin dielectric permittivity to FD-responses, showing promise for real-time skin hydration monitoring. Challenges may include system vali- dation, portability, and integration into wearables. Besler et al. (71) investigated microwave- based hydration assessment using fasting volunteers during Ramadan, employing a time-of- flight (TOF) permittivity estimation technique to measure hydration changes throughout the day. Challenges include improving sensitivity and precision in detecting subtle hydration changes.

Cataldo et al. (72) developed a flexible wear- able for skin hydration sensing. The sensor underwent redesign for enhanced wearability, sensitivity, and patient comfort, incorporating a flexible rubber substrate with a Kapton layer. Future efforts will focus on system improvement and systematic characterization, including solutions for Bluetooth data acquisition and local processing. Their goal is to further miniaturize the system for full wearability by re the

LCD screen.

Bing et al. (73) introduced a small, planar resonant loop sensor for water content monitoring based on electromagnetic resonance. Experiments on human hydration processes align well with simulations using documented skin permittivity properties. The wearable sensor, integrated on the human forearm, offers discrete and continuous measurements. It is crucial to note that the sensor's sensitivity is influenced by dielectric property changes due to water content variations.

E. Multi-Modal Sensors

This section explores research on multi-sensor systems designed to provide a holistic view of hydration levels, integrating diverse sensor types and combining various measurement techniques for a comprehensive assessment.

Krishnan et al. (74) introduced multimodal sensors for precise, quantitative in vivo monitoring of hydration levels in the near-surface skin regions. The mathematical model designed Encompass temperature, thermal conductivity, thermal diffusivity, volumetric heat capacity, and electrical impedance using simple analysis algorithm. Challenges involve evaluating device performance in real-world scenarios with varying temperature and humidity.

Salvo et al. (75) developed a wearable sensor for real-time sweat rate monitoring using the open-chamber method based on Fick's first law of diffusion. The cylindrical chamber within a 3D-printed adapter calculated sweat rate by measuring water vapor flow from the skin. The sensor, tested on thirteen participants during a cycling test, consisted of an Arduino Pro Mini and a PCB with a humidity and temperature sensor (SHT25), and was compared to a Dermalab® commercial device. Further testing in uncontrolled environments is needed to address factors like air movements and humidity that may affect the evaporation rate.

Bandodkar et al. (76) introduced a wearable sweat sensing platform combining battery-free, wireless electronic detection with integrated colorimetric assays (Figure (supplement) 9). This allowed simultaneous monitoring of multiple biomarkers, including pH, lactate, glucose, and chloride. Challenges include real-world optimization, accuracy assurance, and expanding the range of monitored biomarkers.

Lapadula et al. (77) presented a system for analyzing body hydration to enhance running performance. It combined BIA as a benchmark with data from a Garmin vivoactive® device and a custom mobile app. The Garmin recorded parameters like HR, speed, altitude, calories, distance, and steps, while saliva analysis using Cyclic Voltammetry (CV) was employed to extract hydration-related features. Challenges include the validation of measures and the integration of these technologies into user-friendly wearable hydration monitoring during athletic activities.

Kamran et al. (22) devised a data-driven method to measure hydration status using wear- able sens normal orthostatic movements. Logistic regression mode trained to estimate dehydration status based on HR respo postural movements, indicating that shorter orthostati achieved comparable accuracy to clinical tests. The study s that the sensor can accurately estimate mild dehydra athletes. Challenges include exploring a wider ra movements and addressing study limitations, such as a co exercise environment and specific postural movements.

Sabry et al. (78) utilized machine learning for or dehydration monitoring, integrating data from various w sensors such as accelerometer, magnetometer, gyroscope, g skin response, PPG, temperature, and barometric pressu study's focus on developing models suitable for m constrained wearable devices highlights its practical p Challenges include ensuring model accuracy and minimizing consumption.

Rodin et al. (79) assessed the real-world performanc wearable body hydration sensor, which integrates PP galvanic biosensors. The study involved 240 part performing treadmill exercises over 90 minutes, with inte rest periods, to evaluate the sensor's accuracy in monitoring water mass loss due to perspiration. The sensor, attached to a smart- watch, showed strong agreement with the gold- standard method (body mass change measured by a medical balance). Utilizing proprietary algorithms to estimate sweat volume and employing a galvanic contact system to estimate total BWL, the system shows promising potential as an accurate wearable hydration monitor in practical real-world scenarios.

Wang et al. (80) conducted a study on predicting hydration status based on single-subject experiments involving 32 moderate-intensity exercise sessions with and without fluid intake. Four noninvasive physiological and sweat biomarkers—heart rate, core temperature, sweat sodium concentration, and whole-body sweat rate were measured during exercise. Machine learning models were used to determine BWL percentage as an indicator of dehydration. The models revealed that whole-body sweat rate (WBSR) and HR achieved the highest accuracy, with sweat sodium concentration from the arms showing the best prediction accuracy. Challenges related to hydration's impact on biomarker relationships with %BWL highlight the need for future ex- tended studies with multiple subjects and intensity variations.

F. Commercial Products and Comparisons

In this section, we explore innovative hydration monitoring solutions from top companies. These products employ cutting-edge technology, providing personalized insights through wearable patches, wristbands, and electronic biosensor. Table III presents a comprehensive overview of various hydration monitoring products, each offering unique features and technologies.

1) Rockley's BioPtx: BioPtx is a non-invasive hydration monitoring wristband using silicon-photonics-based sensors, which respond to water concentration changes in the human body. Rockley's platform caters to athletes, health- conscious individuals, and those managing hydration-related conditions (81).

2) Sixty: Sixty offers a hydration monitoring solution with a simple design featuring LED indicators. Users can choose between continuous monitoring using a wrist or arm strap or occasional checking with the standalone monitor. This flexibility caters to both athletes needing

constant tracking and individuals seeking occasional hydration updates. The device can detect fluid loss as low as 30-40 ml, providing timely reminders well before the sensation of thirst, typically experienced after losing 300-400 ml of fluid. While Sixty acknowledges the challenge of ensuring precise accuracy across different phenotypes, it plans to gather extensive data for validation (82) (Figure (supplement) 11).

3) LVL: The LVL Wearable Hydration Monitor employs red light technology, penetrating deeper into the body compared to conventional fitness trackers with green light sensors. Tailored for individuals valuing comprehensive health monitoring, LVL calculates fluid requirements based on an individual's hydration status and sweat rates. The device emphasizes the connection between hydration and improved sleep quality, offering compatibility with devices through BLE technology (83) (Figure (supplement)

4) hDrop Gen 2: hDrop Gen 2 from hDropTech stands out rapid, direct skin contact readings for sweat rate, el concentration, and estimated sodium and potassium levels. primarily at athletes, this technology employs electrodes to personalized recommendations for fluid and electrolyte replen enhancing hydration management during workouts(84) (supplement) 13).

5) Hydrostasis Geca Sensor: The GecaTM sens optical-based wristband. The sensor undergoes rigorous ev including comparisons against known hydration and deh events, as well as urine specific gravity. Consumer pilot show the sensor's potential to accurately measure hydra dehydration changes. It demonstrates greater sensitivity in pr hydration levels associated with minimal total body weight ranging from 0.5% to 1%, outperforming conventional osmolality tests and standard physical assessme dehydration(85) (Figure (supplement) 14).

6) Aura Strap: The Aura Strap integrates smart functionality into an Apple Watch band to track hydration levels using bioimpedance analyses (BIA). It also provides insights into body composition, including body fat, muscle mass, minerals, and body water, when paired with user information like age, gender, and weight. Measurements are taken by placing the sensor on a specific part of the hand, with data transmitted to the Apple Watch and stored in the dedicated app. However, it offers spot measurements rather than continuous monitoring, and improvements in size and ease of use are needed. (86).

7) Epicore Gx Patch: Epicore Biosystems Gx Sweat Patch is a wearable technology aimed at athletes seeking personalized hydration insights and recovery guidance. This innovative skin- like patch pairs with the Gatorade Gx iOS app, utilizing microchannels to capture sweat data in real-time. The app provides athletes with personalized recommendations based on their sweat profiles, catering to their unique hydration and refueling needs(87). A paper was published and presented their wearable microfluidic-based system for real-time analysis of sweating rate and sweat chloride concentration, validated through studies involving 312 athletes(88) (Figure (supplement) 16).

8) Nix Hydration Biosensor: The Nix Hydration Biosensor is a lightweight and compact electronic device designed for durability and reusability. It attaches to a single use sweat patch and continuously transmits data to a smartphone, watch, or bike computer with a battery life of up to 36 hours, making it suitable for long training sessions. The Nix app offers essential analytics, including real-time data for monitoring fluid and electrolyte loss during work- outs, historical data to understand your sweat profile, and predictive data that calculates future hydration needs based on weather forecasts and past performance (89) (Figure (supplement) 17).

V. Discussion and Challenges

We discovered from the reviewed studies that several wearables were either in the prototype phase or tailored to a specific user group. Figure 3 provides a concise overview of the distribution of publications across various hydration tracking techniques, categorizing them into Electrical, Optical, thermal, microwave, and multimodal methods. This categorization sheds light on the current landscape of research in the field and

Category	Name	Features	ial Validated		Company	Technology
Wristband	BioPtx(90)	Hydration, Temperature, HR, HR variability, Respiratory rate, Blood saturation	No	No	Rockley	IR laser tech (36 wavelengths), PPG: green, red, infrared, Accelerometer
Wristband	Sixty(91)	Hydration, HR, activity levels, calories burnt, sleep tracking	No	No	Sixty	Optical spectrometry. Three LEDs shine green, red, and infrared light.
Wristband	LVL(83)	Hydration, tracking activity, sleep, mood and HR, calories.	No	No	BSX Athletics	Red light technology.
Wearable band	hDrop Gen2 (92)	Hydration and Body temperature.	No	Pre-Order	hDroptech	Electrode tracks sweat loss and rate, sweat, sodium, and potassium levels.
Smartwatch	Geca sensor(93)	Hydration.	Yes	Pre-Order	Hydrostasis	Optical spectroscopy, detect fluid concentration in the skin.
Smartwatch	Aura Strap(94)	HR, blood saturation, hydration.	No	No	Apple	Electrode measure electrolytes in sweat to monitor hydration.
Smartpatch	Gx Patch(95)	Hydration, sweat, electrolyte content, body temperature.	Yes	Yes	Epicore Biosystems	A thin microfluidic substrate on the skin that captures sweat.
Smartpatch	Hydration Biosensor(89)	Hydration	Yes	Yes	Nix	Electrodes detect electrochemical biomarkers in sweat.

TABLE III: Overview of Wearable Hydration monitoring system products

offers insights into potential trends and areas of interest.

A. *Electrical-based sensors*

Electrical-based sensors: Electrical-based methods for hydration tracking, particularly BIA, are at the forefront of current research with 31 publications highlighting their popularity. These methods have been favored for their direct correlation between the electrical characteristics of skin and its hydration levels, alongside benefits such as accuracy, user-friendliness, portability, and affordability.

However, these systems are not without their limitations. One significant drawback is their inability to effectively assess hydration levels in deeper layers of the skin. This limitation can impede the comprehensiveness of hydration analysis, potentially overlooking critical aspects of skin hydration that occur below the surface. Furthermore, the performance of electrical-based hydration tracking systems can be adversely affec external factors, including ambient environmental conditions and variations in skin temperature. Such dependencies may compromise the accuracy and reliability of hydration measurements, particularly in fluctuating or extreme conditions(96).

Electrochemical methods, which involve the extraction of fluids to monitor hydration, offer a different approach by focusing on the precise measurement of Na+ and K+ levels. While these methods can provide higher accuracy due to the specificity of electrolyte level monitoring, they face their own set of challenges. The lack of selectivity of ions, as well as problems related to electrode conditioning (97) presents a major is- sue, and enhancing the reliability and sensitivity of sensors under varying conditions and across diverse population groups remains a significant hurdle. Contribute to this challenge The variability in fluid extraction processes from one individual to another adds another layer of complexity to achieving consistent measurements.

B. Optical-based sensors

Optical-based hydration tracking techniques account for 13 publications. While fewer in number compared to electrical methods, they offer distinct advantages, particularly in their ability to provide detailed molecular information about skin hydration. The smaller number of publications in this area may be attributed to the relatively higher complexity and cost associated with advanced optical sensors. Recent advancements, such as the use of LED-based and semiconductor photonic sensors, have ad- dressed some of these challenges by offering smaller sizes and lower costs compared to traditional laser-based laboratory equipment. These developments in semiconductor miniaturization and photonics technology, with a wider range of wavelengths and improved absorption capabilities, present promising avenues for hydration monitoring.

While IR and NIR spectroscopy predominantly focus on water absorption at two main frequencies, notably 1300 nm for maximizing skin penetration depth and 1480 nm for sensitivity to water concentrations (Table I), some research has extended this range by including 940 nm to encompass sweat properties. Additional frequencies can lead to different coefficients and higher accuracy. Other optical techniques follow a similar principle; more frequencies may result in greater accuracy. By analyzing skin with a wider range of frequencies, studies have been able to identify pH levels, glucose concentrations, temperature, and other dermal properties (Table II).

Despite their innovative approach and significant advantages, challenge lies in the need for refinement of sensor sensitivity and specificity. While sensors can detect a wide range of skin hydration lev other biomarkers by utilizing various frequencies, ac consistent accuracy across different skin types, conditio environmental set- tings remains a significant hurdl variability in individual skin properties and external factors lighting conditions can affect the reliability of hy measurements, necessitating on- going advancements in technology and data analysis algorithms.

Moreover, Current optical-based methods mainly assess or near-surface hydration levels, limiting their ability to capture deeper skin layers or the body's overall hydration status. Developing techniques with deeper penetration capabilities, while ensuring safety and simplicity, could enhance optical hydration tracking effectiveness (98).

Leveraging artificial intelligence and machine learning algorithms to analyze the vast amounts of data collected by these sensors could improve their accuracy, sensitivity, and ability to adapt to individual variations and environmental changes.

C. Thermal and Microwave-based sensors

Other methods have been identified including thermal and microwave-based sensors, comprising 11 publications. While these methods represent a smaller portion of the research landscape, they cater to specific applications and niches. Thermal sensors offer a unique perspective on skin hydration, probing the skin's thermal properties for insights. They have seen notable advancements, particularly in the development of sensors capable of measuring thermal properties beneath the skin's surface. Additionally, some sensors measure skin temperature and thermal transport for evaluating skin hydration and blood flow dynamics. While promising, thermal sensors face challenges in terms of precision and sensitivity. Calibration is crucial, and factors like ambient temperature can influence results.

Microwave-based systems leverage electromagnetic waves' interaction with water molecules to assess skin moisture. These sensors are non-invasive and can penetrate deeper layers of the skin. However, such systems face several challenges that could limit their practical application. One of the main drawbacks is the difficulty in miniaturizing these systems to fit comfortably and unobtrusively into wearable devices. The complexity and size of the components required for microwave sensing can make it challenging to develop compact, wearable devices that are convenient for everyday use. Another significant limitation is the power consumption of microwave sensors. High power requirements can lead to shorter battery life in wearable devices, reducing their practicality for continuous, long-term monitoring.

Additionally, microwave sensors can be susceptible to interference from external electro- magnetic sources, which can affect the accuracy and reliability of hydration measurements. Future improvement opportunities in this field should look to achieve greater miniaturization and integration into wearable devices. Addressing power consumption issues, making continuous hydration monitoring more feasible. Furthermore, developing advanced algorithms for signal processing and interference rejection could enhance the accuracy and reliability of microwave-based hydration tracking, even in environments with significant electromagnetic noise.

D. Multimodal sensors

8 publications explore the use of multimodal sens hydration monitoring. This emerging trend sugges researchers are recognizing the potential benefits of co multiple sensor types to enhance accuracy and rel Multimodal sensors could address limitations as- sociat single-mode sensors, providing a more compre understanding of hydration dynamics by addressing the lim of individual sensors. As technology continues to advance, expect to see further exploration of this approach.

However, integrating multiple sensor technologies into wearable device introduces a set of challenges and limitatio primary drawback is the complexity involved in sensor inte and the management of data from diverse sources. Ensur sensors operate harmoniously without interfering with each signals requires careful design and calibration. Additionally, the increased complexity might lead to higher power consumption, larger device size, and potentially higher costs, which could limit the practicality and accessibility of multimodal hydration monitors for everyday use.

Another significant challenge is optimizing data fusion algorithms to combine data from multiple sensors meaningfully. This is crucial for interpreting complex data streams but requires algorithms that can accurately process relevant data from each sensor, considering context and potential errors or noise.

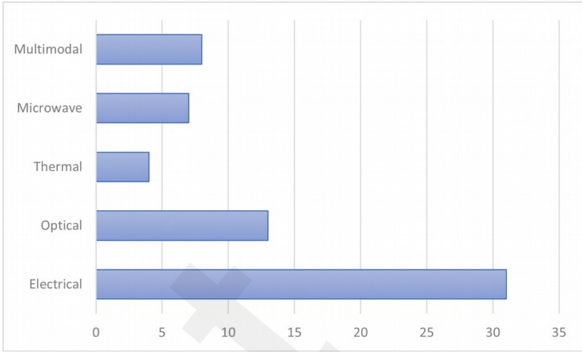

Fig. 3: Number of publications of Hydration monitoring system categorized based on the type of sensors used.

E. Commercial Products and Practical Implementations

Our analysis of commercial hydration monitoring products shows a growing market with diverse offerings. Companies are effectively translating academic research into practical products catering to various consumers. These products bridge the gap between theoretical research and real-world applications, providing accessible hydration monitoring for individuals, athletes, and health practitioners. The commercial availability and validation of products like Gx Patch and Nix demonstrate their potential to offer actionable insights into hydration management. Optical-based techniques, which are cost-effective and practical for real-time monitoring, are gaining traction in the market due to their versatility and convenience, making hydration tracking more accessible to a broader audience.

VI. Conclusion

This scoping review provides a comprehensive analysis of recent advancements in wearable hydration monitoring technologies, offering insights into their capabilities, limitations, and research trends. The review covers various sensor types and technologies, highlighting the growing interest in non-invasive, portable hydration monitoring systems utilizing physiological biomarkers. The findings reveal a predominant focus on electrical-based sensors, particularly BIA, due to their ease of use, and accuracy.

Optical-based sensors, while fewer in number, offer molecular-level insights and are gaining traction, especially with recent advancements in LED-based and semiconductor photonic sensors,which address cost and size limitations. Thermal and microwave-based sensors cater to specific applications, providing unique insights into skin hydration. Challenges remain in terms of precision, sensitivity, and miniaturization. The emergence of multimodal sensors suggests a growing trend towards combining technologies for enhanced accuracy and reliability. Commercially available hydration monitoring products demonstrate a growing market with diverse offerings, primarily dominated by optical-based solutions due to their cost-effectiveness and diverse number of biomarkers they give access to.

Future research should focus on enhancing sensor accuracy, miniaturization, and wearability, standardizing measurement protocols, and re-fining data interpretation algorithms. Multimodal systems and AI-driven analysis show promise for personalized hydration management, with broad applications in healthcare and beyond. Overall, wearable hydration monitoring devices offer significant potential for real-time hydration assessment. Overcoming challenges such as reliability, accuracy, and applicability across diverse populations will be crucial for their widespread adoption and impact in healthcare and performance optimization.

VII. Conflicts of Interest

The authors declare that no conflict of interest exists in the preparation and execution of this re- search. The authors also declare no competing financial interest that could influence the work reported in this document.

SUPPLEMENTARY DOCUMENTS

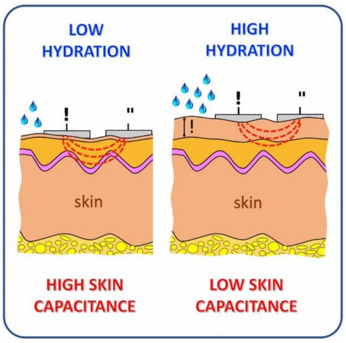

Fig. 4: (supplement) The correlation between skin capacitance and hydration (99).

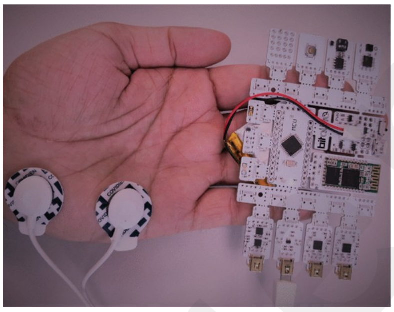

Fig. 5: (supplement) GSR data collection using BITalino EDA sensor by placing two electrodes (15).

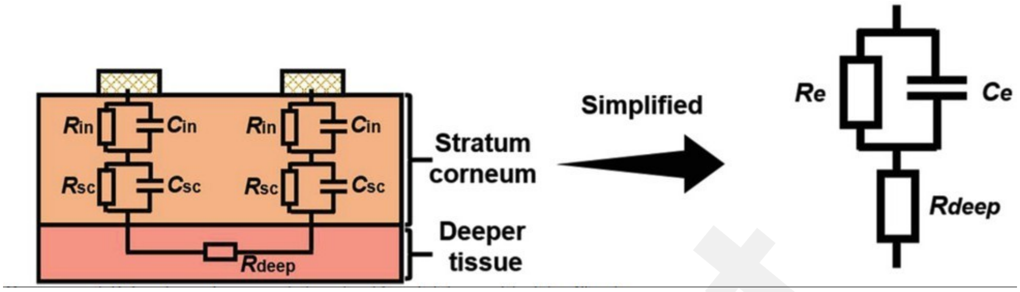

Fig. 6: (supplement) Skin impedance analysis simplified model (40).

(60).

Fig. 9: (supplement) Microfluidic patch with embedded operation during sweat(76)

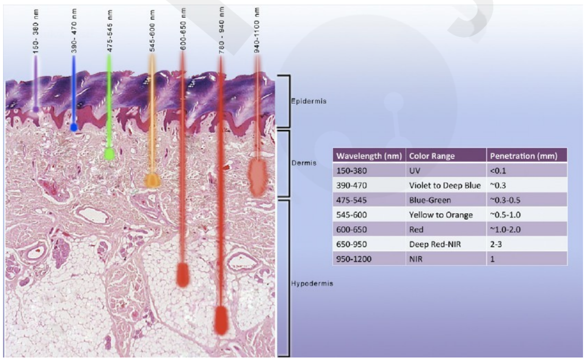

Fig. 7: (supplement) Tissue penetration depths of various wavelengths. (Figure courtesy of Well- man Center for Photomedicine.)

Fig. 8: (supplement) Wearable Compact CMOS spectrometer for skin hydration monitoring

Fig. 10: (supplement) Bioptx™ Biosensing Band

Fig. 11: (supplement) Sixty App-Enabled Hydration Monitor

Fig. 12: (supplement) LVL wearable hydration monitor

Fig. 13: (supplement) hDrop Gen 2 - wearable hydration sensor

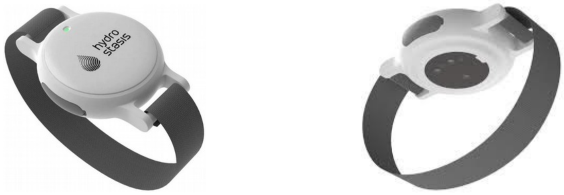

Fig. 14: (supplement) GECA™ Hydration Watch

Fig. 15: (supplement) AURA Strap 2

Fig. 16: (supplement) Gx Sweat Patch.

Fig. 17: (supplement) Nix Hydration Biosensor Patch.

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