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Wearable Devices for Continuous Monitoring of Bladder Function: A Review of Current Approaches and Future Perspectives

Mesane Fonksiyonunun Sürekli İzlenmesi İçin Giyilebilir Cihazlar: Mevcut Yaklaşımların ve Gelecek Perspektiflerinin Derlemesi

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ÖZET

Giyilebilir teknolojiler ve yapay zeka (YZ) ürolojide yeni bir dönemi başlatarak mesane fonksiyonlarının sürekli, non-invaziv ve hasta konforunu bozmadan izlenmesini mümkün kılmıştır. Geleneksel yöntemler üriner inkontinans, nörojen mesane, benign prostat hiperplazisi ve mesane çıkım obstrüksiyonu gibi sık görülen hastalıklarda kesintisiz takip olanağı sunmamaktadır. Bu derlemede giyilebilir sistemler; teknik altyapı, klinik uygulamalar, doğruluk, avantaj ve sınırlılıklar açısından değerlendirilmiştir. Ultrason, mikrodalga, biyoimpedans, kapasitif sensörler, yakın kızılötesi spektroskopi, elektromiyografi ve optik sensörler temelini oluşturan cihazlar geliştirilmiştir. YZ algoritmaları, mesane dolumu, boşaltım zamanı ve kapasite gibi parametrelerin gerçek zamanlı ve yüksek doğrulukla elde edilmesini sağlamaktadır. Ultrason temelli cihazlar klinik uygulamaya en yakın adaylardır; mikrodalga ve biyoimpedans yöntemleri ise daha fazla validasyona ihtiyaç duymaktadır. Bununla birlikte, çocuk, yaşlı ve özel gruplarda prospektif randomize çalışmalara gereksinim vardır.

Anahtar Kelimeler: Yapay zeka, mesane takibi, giyilebilir cihazlar, non-invaziv teknoloji, mesane fonksiyonu

ABSTRACT

Wearable technologies and artificial intelligence (AI) have initiated a new era in urology by enabling continuous, non-invasive monitoring of bladder functions without compromising patient comfort. Traditional methods do not provide uninterrupted follow-up in common conditions such as urinary incontinence, neurogenic bladder, benign prostatic hyperplasia, and bladder outlet obstruction. This review evaluates wearable systems in terms of technical infrastructure, clinical applications, accuracy, advantages, and limitations. Devices have been developed based on ultrasound, microwave, bioimpedance, capacitive sensors, near-infrared spectroscopy, electromyography, and optical sensors. AI algorithms allow real-time and highly accurate assessment of parameters such as bladder filling, voiding time, and capacity. Ultrasound-based devices appear to be the closest candidates for clinical application, while microwave and bioimpedance methods require further validation. However, prospective randomized trials in pediatric, elderly, and special patient populations are still needed.

Key words: Artificial intelligence, bladder monitoring, wearable devices, non-invasive technology, bladder function

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INTRODUCTION

Artificial intelligence (AI) and wearable device technologies make great contributions to healthcare services. These two technologies increase the quality of healthcare services by making patient monitoring, diagnosis and treatment processes more efficient, accurate and uninterrupted. AI analyzes large data sets and accelerates the decision-making process in healthcare thanks to its ability to detect patterns. Wearable devices can continuously collect data and continuously monitor patients with non-invasive methods. These innovations make significant contributions to the monitoring of bladder functions in the field of urology, as in all other fields (1, 2).

Monitoring bladder function is crucial in the treatment of urinary incontinence, neurogenic bladder, benign prostatic hyperplasia, and other urinary disorders (3). Traditional methods are invasive, can negatively affect patient comfort, and cannot provide continuous monitoring. In contrast, AI-based wearable devices provide more effective patient monitoring by providing uninterrupted monitoring of bladder functions (4).

This review evaluates wearable and implantable devices used for monitoring bladder function. It compares different technologies in terms of clinical applicability, accuracy, and patient comfort, aiming to guide future research and clinical use.

Ultrasound

Ultrasound is one of the most widely used non-invasive imaging methods. AI-powered ultrasound devices can accurately measure the bladder's fullness level, providing results close to manual measurements (Figure 1) (5). These devices automatically calculate bladder volume using two-dimensional ultrasound images, providing clinical information swiftly. With AI algorithms, ultrasound results are analyzed much faster and more accurately, thus enhancing clinical decision-making processes (6).

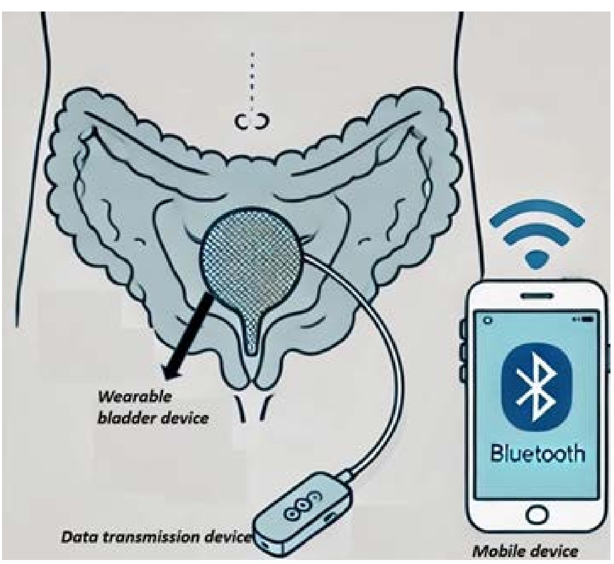

Figure 1. Schematic representation of the ultrasonic device placed on the bladder.

Near-Infrared Spectroscopy (NIRS) and Optical Sensors:

Near-infrared spectroscopy (NIRS) and optical sensors are used to monitor oxygenation and blood flow in the bladder wall. NIRS measures changes in these parameters according to bladder filling status, providing information about bladder activity. Optical sensors can precisely assess bladder filling levels by monitoring tissue changes (7).

Electrical Bioimpedance:

Electrical bioimpedance measures bladder fullness and urine flow using the electrical conductivity properties of body tissues. This technology is ideal for non-invasively monitoring bladder fullness levels. When integrated with AI, these sensors can provide continuous monitoring of bladder function, allowing for early detection of conditions such as urinary tract obstructions (8).

Microwave Technology:

Microwave sensors use electromagnetic waves to detect bladder fullness. These AI powered devices have been shown to measure bladder volume quickly and reliably in animal studies. It stands out as a suitable option for continuous monitoring in the clinical environment because it produces rapid results in human clinical studies (5).

Electromyography (EMG):

EMG is a technology that measures the electrical activity of muscles and allows the assessment of bladder function by monitoring the activity of the pelvic floor muscles. EMG has been found effective in monitoring functional disorders such as urinary incontinence and neurogenic bladder in animal and human studies (9). EMG devices integrated with AI have made patient management and treatment processes more efficient (10).

Capacitive Sensors:

Capacitive sensors detect bladder expansion and contraction to determine fullness levels. In both human and animal studies, these sensors have been found to track bladder volume with high accuracy and provide more precise results when integrated with AI. These sensors provide an ideal solution for continuous monitoring (11). These technologies, when combined with artificial intelligence, allow for non-invasive, continuous monitoring of bladder functions. This allows patients to be monitored at home or in non-clinical settings, improving the quality of patient care and improving clinical outcomes.

MATERIAL METODS

In this study, a literature review was conducted to examine

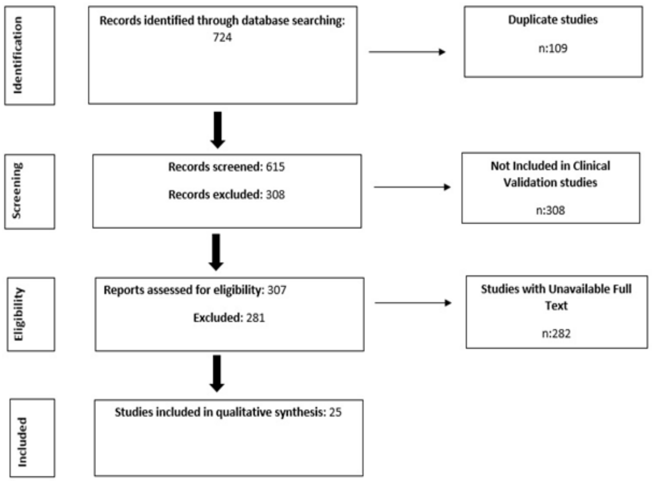

Figure 2. Flow diagram of study selection based on PRISMA guidelines.

the current status of wearable devices used for monitoring bladder functions.

Data Collection:

A systematic search was conducted using PubMed, Scopus, and Web of Science databases using the keywords. The keywords used were 'wearable bladder monitoring devices,' 'urology devices,' 'non-invasive bladder device,' and 'bladder wearable devices.' The search focused on studies published in the last 10 years (Figure 2). Duplicate records, non-clinical validation studies, and articles without full-text access were excluded from the review.

Analysis Method:

Selected articles were examined in detail and compared in terms of parameters such as bladder monitoring methods, measurement accuracy, suitability for clinical use, advantages and limitations. In order to evaluate the clinical validity and accuracy of the devices, the findings obtained from the studies were compiled and tabulated. The table includes the advantages, limitations, clinical application areas and market availability of the devices.

The obtained data examined the ability of each device to monitor bladder functions in terms of non-invasive data collection. In addition, the transition processes and limitations of the devices to clinical applications were emphasized, and different methods were evaluated in terms of patient comfort, accuracy and reliability.

Literature Review and Discussion

During the data collection phase, the articles obtained as a result of the scans made with the determined keywords were first eliminated by examining the titles and abstracts, then the full texts were read and the appropriate ones were included in the compilation. Clinical and experimental results in the literature for each technology were analyzed in detail. The studies compiled below are classified in terms of advantage, limitation, application, method and accessibility (Table 1).

Wearable bladder devices (portable, skin-attached imaging tools) are quite advantageous because they offer non-invasive options in continuous bladder monitoring and treatment processes. The study by Germini et al. emphasizes the continuous data monitoring of ultrasound-based devices,

Table 1. Summary of key studies evaluating wearable bladder monitoring technologies, highlighting their advantages, limitations, clinical applications, measurement methods, and current market availability.

No	Studies	Advantages	Limitations	Applications	Method/ Sample size/ Tested Group	Availability (On the market)
1	Germini F et al. (2022) (1)	Not aplicable	May require personal adjustments, short battery life.	Bladder fullness and urine tracking	All/65 articles/ General population	Not aplicable
2	Patel S et al. (2012) (5)	Comprehensive review with broad scope.	Lack of studies focusing on specific patient groups.	General health tracking	All/18 patients/ Healthy and LUTS group	Not aplicable
3	Zhang L et al. (2023) (12)	Easy home use Flexible design	Clinical validation of phased-array ultrasound still lacking.	Bladder volume monitoring	Phased-array Ultrasound Patch/ 20 subjects/ Healthy group	Not on the market
4	S Hofstetter et al. (2023) (13)	FDA-approved, patients found it convenient.	Did not yield statistically significant results.	Bladder fullness monitoring	Ultrasound/18 patients/Bladder disfunction	On the market

5	Kim J et al. (2024) (14)	Wireless data transmission. Post-surgery bladder function monitoring.	Long-term implantation studies are still lacking.	Bladder function monitoring	Wireless Implant/5 rodent, 2 babun/	Not on the market animalmodel
6	Toymus A et al. (2024) (15)	Flexible, integrated ultrasound device for continuous bladder volume monitoring.	Extensive clinical adaptation studies required.	Bladder volume monitoring	Ultrasound/-/Healthy group	On the market
7	Nasrabadi MZ et al. (2021) (7)	Not aplicable	Further studies needed on the accuracy of sensors.	Bladder volume monitoring	Various Non-invasive Methods/-/-	Not aplicable
8	Jo HG et al. (2021) (16)	Forward-looking ultrasonic scanner provides continuous bladder volume monitoring.	Accuracy of improved ultrasound system requires clinical validation.	Bladder volume monitoring	Ultrasound/ ex vivo/ one porcin bladder	Not on the market
9	Tu KJ et al. (2024) (17)	Not aplicable	Limited studies on NIRS accuracy and application challenges.	Bladder volume monitoring	NIRS/-/-	Not aplicable
10	Lee S et al. (2024) (18)	Monitors and analyzes nocturnal enuresis, easy home use.	More clinical studies needed for long-term use.	Nocturnal enuresis monitoring	Wearable Integrated System/ 34 pediatric patients	On the market
11	Kuru K et al. (2024) (19)	AI-powered miniature mechatronic systems for nocturnal enuresis treatment.	Requires broader clinical validation.	Nocturnal enuresis treatment	AI-Powered Mechatronics/2 Healthy volunteer	Not on the market
12	Song Z et al. (2024) (20)	Memory-efficient algorithms for low-compute ultrasound devices.	Clinical validation of algorithms is ongoing.	Bladder monitoring and volume measurement	Ultrasound/ 434 patients/ Urinary retention patients	Not on the market
13	Baran B et al. (2024) (21)	Solves discretization issues in bladder tracking via machine learning algorithms for electrical tomography.	Requires clinical adaptation of developed methods.	Bladder monitoring and volume measurement	Electrical Tomography & ML/A healthy male	Not on the market

14	Amina M et al. (2024) (22)	Fuzzy-based approach for determining liquid level in the bladder.	Extensive validation studies required.	Nocturnal enuresis monitoring	Ultrasoun-based Approach/ 1 cadaver, 3 male healthy volunteer	Not on the market
15	Kuru K et al. (2024) (23)	Feasibility of autonomous systems for detecting bladder voiding needs using AI and ultrasound.	Requires broad clinical validation.	Bedwetting treatment and bladder monitoring	Ultrasound & AI-based System/ No patient	Not on the market
16	van Leuteren et al. (2017) (24)	Continuous bladder fullness monitoring, non-invasive methods for pediatric use.	Lacks widespread clinical validation and application.	Bladder monitoring in children	Ultrasound/ 14 children/ Dysfunctional Voiding	Not on the market
17	Palla A et al. (2015) (25)	Continuous monitoring for patients with neurogenic bladder dysfunction via bioimpedance.	Limited clinical validation and widespread usage.	Neurogenic bladder monitoring	Bioimpedance/ A healthy subject	Not on the market
18	van Leuteren et al. (2024) (26)	Continuous ultrasound -based monitoring, early notification for bladder fullness.	Pilot study, requires further clinical validation.	Bladder fullness notification	Ultrasound/ 15 children/ urinary incontinence	On the market
19	van Leuteren et al. (2024) (27)	Validated in children, allows non-invasive bladder monitoring during urodynamic studies.	Requires larger clinical trials for widespread application.	Pediatric bladder monitoring	Ultrasound/ 30 children/ urinary incontinence	On the market
20	Shin S et al. (2024) (28)	Real-time bladder volume monitoring in wearable form, non-invasive.	Requires further validation for clinical use.	Continuous bladder volume monitoring	Ultrasound/ 3 male volunteer/ Healthy subject	Not on the market
21	Wang Q et al. (2016) (29)	Non-invasive urination -desire detection using bioimpedance.	Requires further validation in different populations.	Urination desire	Bioimpedance / 3 volunteer/ Healthy subject	Not on the market

22	Li R et al. (2016) (30)	Non-invasive method to assess bladder volume using electrical impedance tomography.	Preliminary study, further validation required for clinical application.	Bladder volume monitoring	Electrical Impedance Tomography/ 6 healthy volunteer, 4 porcin bladder	Not on the market
23	Leonhäuser D et al. (2018) (31)	Comparison of electrical impedance tomography with standard ultrasound methods in healthy volunteers.	Study limited to healthy volunteers, broader validation needed.	Bladder volume monitoring	Electrical Impedance Tomography/ 10 volunteer/ Healthy subject	Not on the market
24	Noyori SS et al. (2021) (32)	Small device for urine volume estimation, non-invasive.	Needs further validation in clinical settings.	Urine volume estimation in the bladder	Electrical Impedance Measurement/ A young volunteer/ Healthy subject	Not on the market
25	Soebadi MA et al. (2019) (33)	Real-time bladder pressure monitoring, non-invasive.	Study conducted on animals, further validation required in humans.	Bladder pressure monitoring	Wireless Intravesical Device/ 5 minipig/ Animal model	Not on the market

stating that the devices have limitations such as the need for personal adjustment and battery life (1). In contrast, although AI-based mini devices produce effective results with AI integration, the need for validation through extensive clinical studies remains a significant limitation (19).

Similarly, in the study by Patel et al., bioimpedance based devices were studied. Although they allow noninvasive bladder monitoring, they show that they may not be accurate enough in certain patient groups (5). The inability to generalize to all patient groups presents a significant limitation.

Ultrasound-Based Methods: When we examine the studies in the table, it is seen that ultrasound-based devices are much more common than other technologies, as expected. The ultrasound patch developed by Zhang et al. provides ease of use and flexibility, but as with other devices, the lack of clinical validation is a limitation of this technology (12). The ability of these devices to provide fast and reliable data provides a significant advantage in clinical applications that require results in a short time (1, 28). The ability of these devices to provide fast and reliable data provides a significant advantage in clinical applications that require results in a short time (24). It can be quite advantageous in terms of reducing potential trauma that invasive procedures may cause on child psychology.

Bioimpedance and Electrical Tomography Methods:

Bioimpedance technology may be advantageous for detecting urge to urinate (29). However, due to technical reasons, the accuracy of bioimpedance methods cannot be widely adopted without sufficient validation, especially in different patient groups. Electrical impedance tomography, proposed by Li et al., offers potential for non-invasive bladder volume monitoring, yet the lack of clinical validation limits the large-scale use of these Technologies (30). These methods are currently not suitable for large-scale applications without further testing on a wider range of patient groups.

Microwave and Other Optical Methods:

The study by Germini et al. demonstrates that microwave technologies offer advantages in terms of speed and accuracy, yet there are concerns about the long-term effects of electromagnetic waves. Optical sensors, on the other hand, are a method commonly used in daily life, even in our smartwatches. However, the accuracy of optical sensors is sensitive to environmental factors, which can reduce their efficiency in certain settings (1). Similarly, NIRS based methods offer advantages for oxygenation and hemodynamic monitoring; however, further studies are needed to enhance their accuracy (17). Additionally, these methods are expected to improve in accuracy as the technology advances.

Artificial Intelligence and Data Analysis Methods:

The integration of AI (Artificial Intelligence) has shown great potential in improving the efficiency of monitoring devices. In particular, Kuru et al.'s AI powered mini mechatronic device and Lee et al.'s home-based AI-based systems demonstrate how the integration of AI with non-invasive monitoring systems can improve patient care (18, 19). These devices may provide significant advantages in the future, especially in the continuous monitoring of urinary incontinence in neurogenic bladder patients. However, further clinical validation is needed for these devices to find a place in the commercial market.

In tomography devices, continuous electrical signals coming from body tissues are sampled at certain intervals. During this sampling process, while the signal is being transferred, the detail between the signals may be lost or misinterpreted. This is called discretization. In the study conducted by Baran et al, they demonstrated the ability of machine learning algorithms to solve discretization problems in electrical tomography devices (21).

However, further validation and verification are necessary for the integration of such advanced technologies into clinical applications.

Future insights: While the development of wearable devices for non-invasive bladder function monitoring is promising, there are challenges to clinical transition and adoption. Most devices have not yet gained widespread clinical acceptance and require further study before they can be commercially marketed. Although some FDA-approved devices are available, further research is needed to determine safety and efficacy, particularly in children and elderly populations.

In the near future, integration of wearable devices with smartphone applications and cloud based AI systems will likely enable real time remote bladder monitoring, particularly valuable in home care settings. Additionally, multimodal devices combining ultrasound, bioimpedance, and EMG data may improve diagnostic precision. Personalized bladder management systems tailored to individual voiding patterns are expected to emerge, especially for neurogenic bladder and elderly patients.

CONCLUSION

The devices and methods discussed in this review offer significant potential for continuous bladder function monitoring. However, further validation and development studies are required for these technologies to be transferred to clinical applications. Integration of AI-based devices can improve patient care and provide valuable contributions to clinical decision support systems. Future studies will increase the reliability of these devices, enabling them to find a place in the commercial market and be used in larger patient groups.

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