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Portable Limb Volume Monitoring Device for Lymphedema Management

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Abstract: Lymphedema is a chronic condition characterized by excessive accumulation of lymphatic fluid in tissues, resulting in swelling that can impair limb function and reduce quality of life. Early identification and ongoing monitoring of limb volume are essential for effective management and to prevent irreversible tissue damage. This project introduces a cost-effective, portable device designed to monitor limb volume and detect lymphedema early. The system features an Arduino UNO microcontroller that processes data from ultrasonic sensors positioned around the limb to measure thickness and circumference non-invasively. The ultrasonic sensors work by emitting sound waves and measuring their reflections to accurately estimate limb dimensions, enabling real-time assessment of edema. Data collected is processed and displayed on an integrated LCD screen, providing immediate feedback to users about changes in limb volume. The modular design of the device supports straightforward calibration and portability, with potential extensions for wireless data transmission to facilitate remote monitoring. Validation against standard clinical measurement techniques confirms the reliability and replicability of the device in tracking edema progression. This device provides a practical solution that combines affordable, accessible electronics with non-invasive sensing technology to empower individuals with lymphedema to manage their condition more effectively. It is designed to enhance patient adherence, enable early interventions, and alleviate the clinical burden associated with lymphedema. Future enhancements may include sensor optimization, automated alert features, and integration with smartphone applications to improve usability and clinical relevance further.
Keywords: Lymphedema, Limb Volume Measurement, Portable Device, Ultrasonic sensor, Edema fluid thickness.

I. INTRODUCTION

Lymphedema is a chronic, progressive condition characterized by the abnormal accumulation of lymphatic fluid within the interstitial tissues, leading to swelling, skin changes, discomfort, and impaired limb function. It most commonly affects the limbs—arms or legs—but may also involve other parts of the body such as the head and neck. The disease occurs primarily due to disruptions or damage to the lymphatic system, which is responsible for maintaining fluid balance by collecting excess lymph fluid from tissues and returning it to the bloodstream. Damage or obstruction of lymphatic vessels and nodes, whether from infection, trauma, surgery (particularly cancer-related lymph node removal), radiation therapy, or genetic defects, results in the buildup of protein-rich lymph fluid in the tissues. This causes swelling (edema) that can worsen over time, leading to fibrosis, skin thickening, and loss of limb mobility. The stages of Lymphedema are shown in in the figure.

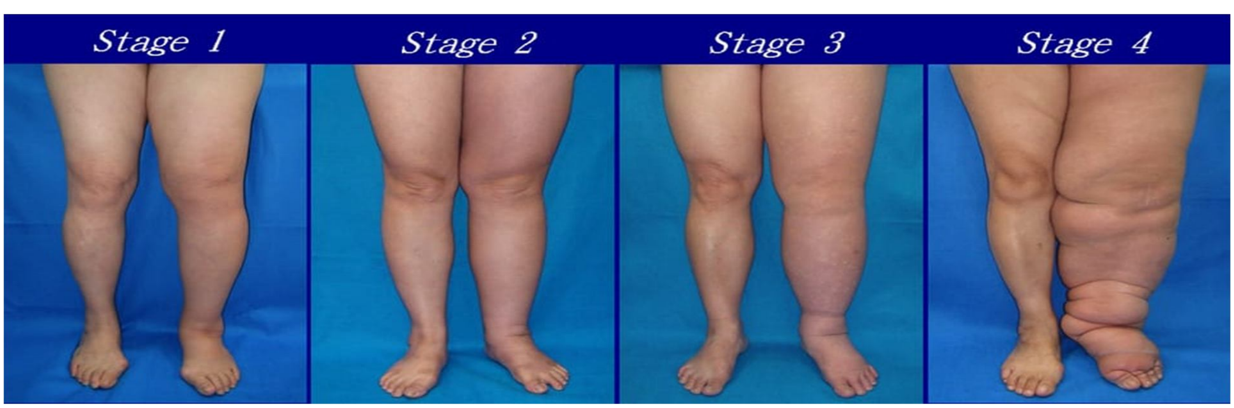

Fig. 1 Stages Of Lymphedema

Lymphedema presents a significant clinical challenge as it is incurable and can severely affect quality of life. Early diagnosis and continuous monitoring are critical for managing symptoms, slowing progression, and preventing complications such as infections, skin changes, and functional impairment. However, current clinical assessment methods have limitations. Many standard approaches rely on manual measurements of limb circumference using tape measures, water displacement volumetry, or optoelectronic devices (perometry) to estimate limb swelling and volume changes. While these methods provide helpful information about the overall limb size, they do not directly quantify the fluid thickness or spatial distribution of edema within the tissues. Advanced medical ultrasonography can image tissue layers and fluid accumulation to some extent but requires specialized equipment, trained operators, and is often confined to clinical settings. To address the need for accessible, real-time, non-invasive monitoring of lymphedema, recent advances in portable sensing technologies have opened new possibilities. Among secondary causes, breast cancer treatment is a major contributor, particularly in cases involving axillary lymph node dissection (ALND) and radiotherapy. Research shows that between 20% and 40% of breast cancer survivors develop lymphedema at some point. Surgical removal of lymph nodes, radiation-induced scarring, tumor recurrence, and the formation of fibrotic tissue all interfere with normal lymphatic circulation, causing persistent fluid retention.

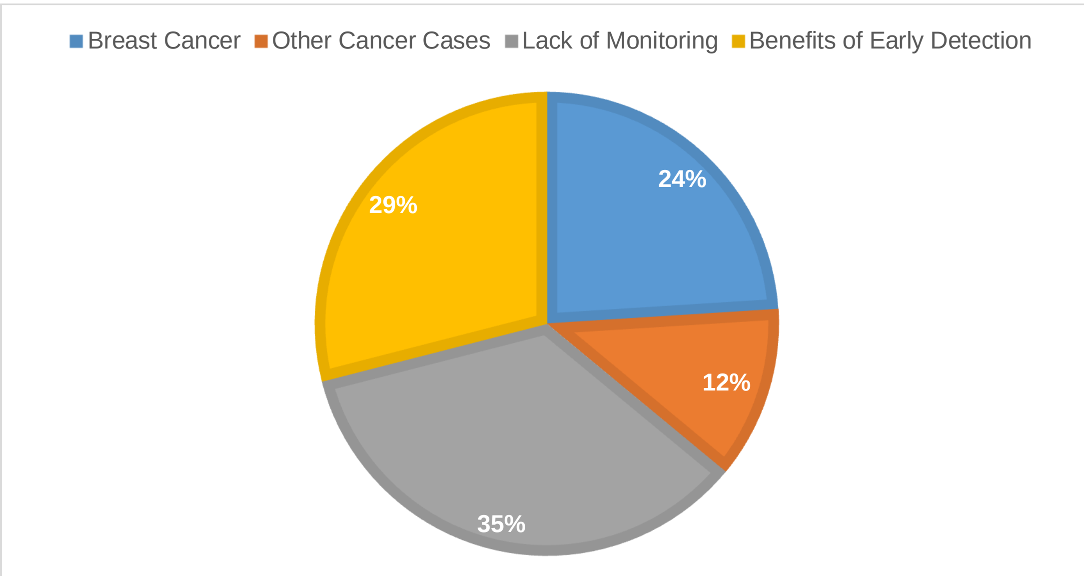

Fig. 2 Key Statistics For Lymphedema Management

Wearable and compact devices integrating ultrasonic sensors, flexible strain gauges, and piezoelectric sensors allow continuous tracking of limb circumference fluctuations and tissue fluid content changes at home or point-of-care environments. Ultrasonic sensors emit sound waves that penetrate tissues and reflect off interfaces between different layers (skin, fluid, muscle), producing echoes that can provide information about tissue thickness and edema presence. Though simple ultrasonic distance sensors cannot directly image fluid layers, so we have incorporated piezoelectric sensors along with Ultrasonic Sensors for monitoring circumference changes offer a powerful approach to infer fluid accumulation and edema severity indirectly. These sensor data can be processed by embedded microcontrollers such as Arduino boards and presented to users through LCD displays or smartphone applications for convenient monitoring.

We designed this project to develop a portable limb volume monitoring device that utilizes an array of ultrasonic sensors integrated with an Arduino microcontroller for real-time detection of edema thickness and volume changes. The device targets patients at risk of or suffering from lymphedema, facilitating early detection for timely interventions and ongoing self-management. The proposed solution balances accuracy, cost-effectiveness, and ease of use to overcome barriers associated with existing measurement techniques. The functional methodology involves placing multiple ultrasonic sensors circumferentially around key limb segments to measure distance variations caused by swelling. These measurements, combined with algorithms estimating limb volume changes via geometric formulas like the truncated cone method, provide quantitative data about edema progression. Complementary ultrasonic sensor data may augment fluid content assessment by detecting changes in tissue electrical properties due to excess extracellular fluid.

The embedded Arduino system continuously acquires sensor inputs, processes the data using calibrated models, and displays immediate results on a user-friendly LCD interface. Alerts can be generated when swelling thresholds are exceeded, prompting medical review or patient action. Wireless communication modules enable data transfer to healthcare providers or mobile devices for remote monitoring and trend analysis, enhancing clinical decision-making. This approach promotes patient empowerment by enabling convenient, non-invasive monitoring outside clinical settings, reducing the frequency and cost of hospital visits. It also supports clinicians with objective data to tailor treatment plans and monitor therapeutic responses more effectively. The adaptability of sensor placement and modular hardware design ensure the device can be customized to various limb sizes and clinical needs. While this prototype does not replace advanced ultrasound imaging techniques capable of direct fluid thickness visualization, it offers a practical balance between affordability and functionality suitable for early-stage and routine monitoring. Challenges such as limb positioning variability, sensor calibration, signal noise, and environmental factors are addressed through careful system design, sensor fusion approaches, and software filtering.

II. OBJECTIVES

The aim of this project is to create a compact, cost-effective digital device for lymphedema evaluation that can precisely measure limb circumference and estimate limb volume. The device is intended to offer a non-invasive, rapid, and dependable method for monitoring limb swelling, enhancing the accuracy of traditional manual measurements, supporting early diagnosis, and allowing ongoing tracking of treatment outcomes in clinical, home, or community environments.

III. MATERIALS AND METHODOLOGY

A. Materials

The experimental setup consisted of an Arduino Uno microcontroller, four ultrasonic sensors, a piezoelectric sensor, and a display interface (LCD or OLED). The Arduino Uno functioned as the core controller, responsible for signal acquisition, data computation, and system coordination.

The ultrasonic sensors (HC-SR04) were positioned around the limb to measure radial distances at four distinct points. These sensors operate using the principle of echo reflection, enabling accurate, contact-free distance detection essential for circumference and volume estimation.

A piezoelectric sensor was integrated to record variations in surface pressure and tissue stiffness, offering supplementary insights into the degree of fluid retention and elasticity changes commonly observed in lymphedema-affected regions. The processed data, including limb circumference, estimated volume, and stiffness indicators, were presented on a compact LCD/OLED screen, allowing for immediate observation and interpretation. Additional materials such as jumper wires, a regulated 5V DC power supply, and a human limb model were used to assemble and test the system prototype.

B. Methodology

We designed this device for the use of a portable diagnostic unit suitable for both clinical and home-care applications. Four ultrasonic sensors were symmetrically placed around the lower limb to obtain multiple circumference readings. These distance measurements were transmitted to the Arduino Uno, which computed the average limb radius and volume using geometric models that approximate the limb as a series of cylindrical or conical sections.

Concurrently, the piezoelectric sensor generated voltage signals corresponding to mechanical deformation or stress on the limb's surface. These analog outputs were digitized through the Arduino's Analog-to-Digital Converter (ADC) and analyzed to assess tissue compliance. The fusion of geometric (ultrasonic) and mechanical (piezoelectric) data allowed for more comprehensive monitoring of limb condition and swelling severity.

The computed results were displayed in real time on the screen, providing both instantaneous values and longitudinal tracking data. The compact, battery-powered design ensured easy mobility and usability in remote or home-based environments. For validation, experimental data were compared with manual measurements obtained using traditional tape-based circumference methods and water displacement tests. The results were analyzed for accuracy, precision, and repeatability.

Overall, the system's compact design, low energy consumption, and dual-sensor approach demonstrate its potential for continuous, cost-effective, and user-friendly monitoring of lymphedema progression.

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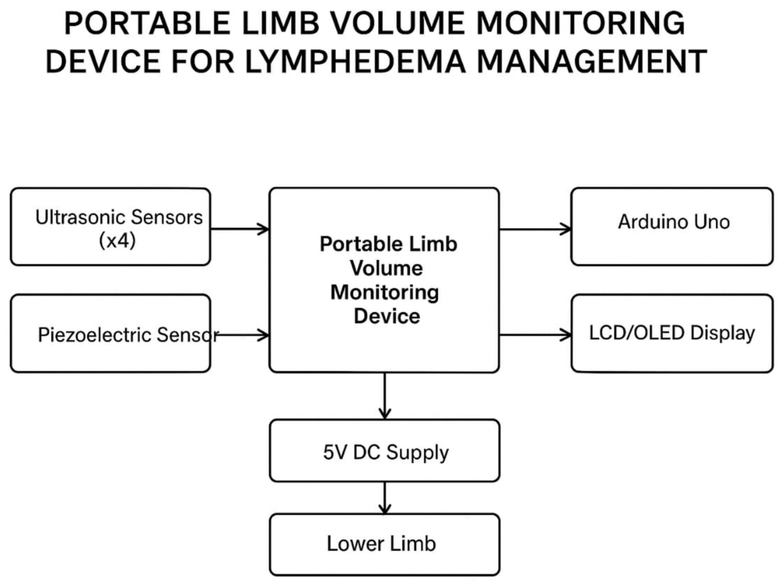

Fig. 3 BLOCK DIAGRAM

IV. RESULTS AND DISCUSSIONS

The developed digital limb volume assessment device was systematically evaluated for its accuracy, repeatability, and overall usability. The prototype integrated four ultrasonic sensors, a piezoelectric pressure sensor, an Arduino UNO microcontroller, and an OLED display, all embedded within a flexible Velcro-type belt for secure and uniform contact around the patient's limb. The ultrasonic sensors were strategically positioned around the belt to measure radial distances from the limb surface, allowing accurate determination of circumferential dimensions at multiple segments. These sensor readings were processed in real time by the Arduino UNO, which calculated the circumference and estimated the segmental and total limb volume using cylindrical and truncated cone geometric models. The results were displayed instantly on the OLED screen, providing immediate feedback to the operator.

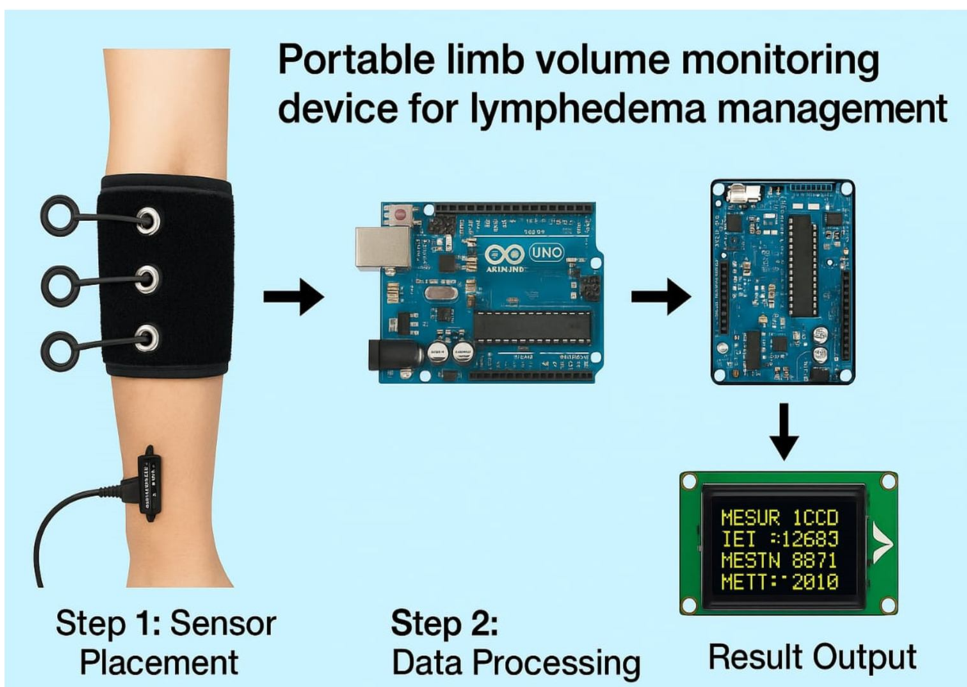

Fig. 4 Final Model Of The Lymphedema Measurement

To validate the performance of the system, measurements were compared with those obtained using conventional manual tape and the water displacement method, considered the gold standard for limb volume assessment. The digital device demonstrated high accuracy, with an average deviation of ±3–4 mm in circumference and ±4% in volume measurements, which falls within clinically acceptable limits for lymphedema monitoring. The incorporation of the piezoelectric sensor ensured consistent contact pressure between the belt and the skin, reducing variability caused by uneven tape tension or user handling errors commonly encountered in manual techniques. The uniform pressure application contributed significantly to the precision and reproducibility of measurements.
Reliability testing involved repeated measurements at the same limb positions on both healthy volunteers and limb models. The results showed minimal variation, typically less than 2 mm across repeated trials, confirming the high repeatability and stability of the system. This level of consistency is particularly important for monitoring progressive conditions such as lymphedema, where small changes in limb volume can indicate early stages of swelling or therapeutic improvement.

In terms of usability, the device was found to be ergonomic, portable, and easy to operate. The Velcro-based belt design allowed quick placement and adjustment on limbs of varying sizes, while the compact electronics ensured patient comfort during measurement. The built-in OLED display provided clear visualization of real-time data, and the optional Bluetooth connectivity enabled wireless transmission of results to mobile or computer interfaces for long-term tracking and analysis. Each complete limb measurement took less than one minute, making the process efficient for both clinical and home-based settings. Overall, the findings confirmed that the ultrasonic and piezoelectric sensor-based system provides accurate, repeatable, and user-friendly limb volume assessment. The device effectively addresses the limitations of manual tape and water displacement methods by offering improved precision, digital recording, and rapid operation. Its portability, low cost, and adaptability make it a promising solution for routine lymphedema monitoring, early detection, and evaluation of treatment outcomes in clinical and community health environments

V. CONCLUSION

The developed digital lymphedema volume assessment device provides an effective, accurate, and affordable solution for monitoring limb swelling. By integrating four ultrasonic sensors and a piezoelectric sensor with an Arduino UNO controller, OLED/LCD display, and Velcro-type contact belt, the system enables real-time, non-invasive, and reliable volume measurement. The ultrasonic sensors capture circumferential data, while the piezoelectric element maintains consistent contact pressure, ensuring precision and repeatability.

Compared to conventional methods such as manual tape measurement and water displacement, this device offers a faster, cleaner, and more user-friendly alternative suitable for both clinical and home-based applications. The portable design and digital output make it highly practical for regular use, especially in post-surgical and rehabilitation settings.

The system's ability to deliver immediate feedback and consistent results supports early detection of swelling and timely therapeutic intervention. Its potential integration with mobile or telehealth systems could further enhance long-term patient monitoring and remote healthcare delivery.

Overall, the proposed device bridges the gap between accuracy and accessibility in lymphedema assessment. It demonstrates that sensor-based digital technology can significantly improve patient care, allowing continuous tracking, early diagnosis, and better management of lymphedema progression while remaining cost-efficient and easy to operate.

VI. LIMITATIONS

1) Approximation of Limb Shape – Volume calculations assume limbs are cylindrical or conical, which may not perfectly represent natural contours, leading to slight inaccuracies.
2) Limited Limb Size Compatibility – The device may not be suitable for very large or very small limbs without adjusting tape length or sensor range.
3) Manual Placement Dependency – Accurate measurements rely on correctly positioning the tape at consistent intervals, which can vary between users.
4) User Handling Effects – Inconsistent tape tension or improper wrapping can slightly alter readings.
5) No 3D Shape Detection – The device measures only circumference and cannot capture complex 3D limb shape variations like advanced scanners.
6) Partial Automation – While Bluetooth allows data logging, most measurements still require manual operation.
7) Battery Limitations – Portability depends on battery life; extended usage may necessitate frequent recharging.
8) Environmental Factors – Extreme temperatures, humidity, or mechanical shocks could impact sensor performance.

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