Non-invasive Portable Technologies for Monitoring Breast Cancer Related Lymphedema to Facilitate Telehealth: A Scoping Review

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***Abstract*—Breast cancer related lymphedema (BCRL) is a common, debilitating condition that can affect up to one in five breast cancer surviving patients (BCSP). BCRL can significantly reduce the quality of life (QOL) of patients and poses a significant challenge to healthcare providers. Early detection and continuous monitoring of lymphedema is crucial for the development of client-centered treatment plans for post-cancer surgery patients. Therefore, this comprehensive scoping review aimed to investigate the current technology methods used for the remote monitoring of BCRL and their potential to facilitate telehealth in the treatment of lymphedema. Initially, five electronic databases were systematically searched and analyzed following the PRISMA flow diagram. Studies were included, specifically if they provided data on the effectiveness of the intervention and were designed for the remote monitoring of BCRL. A total of 25 included studies reported 18 technological solutions to remotely monitor BCRL with significant methodological variation. Additionally, the technologies were categorized by method of detection and wearability. The findings of this comprehensive scoping review indicate that state-of-the-art commercial technologies were found to be more appropriate for clinical use than home monitoring, with portable 3D imaging tools being popular (SD 53.40) and accurate (correlation > 0.9, $p < 0.05$) for evaluating lymphedema in both clinic and home settings with expert practitioners and therapists. However, wearable technologies showed the most future potential for accessible and clinical long-term lymphedema management with positive telehealth outcomes. In conclusion, the absence of a viable telehealth device highlights the need for urgent research to develop a wearable device that can effectively track BCRL and facilitate remote monitoring, ultimately improving the quality of life for patients following post-cancer treatment.**

***Index Terms*—Scoping Review, PRISMA, Lymphedema, Diagnostics, Portable Devices, Wearable Devices, Remote Monitoring, Telehealth, Quality of Life.**

I. Introduction

LYMPHEDEMA is a chronic condition that occurs when the lymphatic system is disrupted, causing lymph to accumulate in the limbs, groin or other regions [1]–[4]. BCSPs undergo medical procedures, such as radiation therapy or surgery, which may damage or remove lymph nodes in the axillary region (i.e., armpit) or other areas of the upper body [5]–[7]. These interventions frequently cause iatrogenic abnormalities to the lymphatic system that can result in the onset of BCRL [5]–[8]. This condition usually manifests in the arm or hand, but can also affect other regions, such as the breast, chest, underarm, trunk, or back [9], [10]. Around 20% (1 out of 5) of BCSPs may develop BCRL, which causes painful swelling of the affected limb, resulting in discomfort, distress, and reduced QOL [11]–[14]. Lymphedema is a condition that cannot be completely cured once it manifests itself [15]–[17]. Early detection, however, could be crucial in halting the disease's progression [8]. Without early detection, it can escalate into a chronic, agonizing disorder that affects patients' QOL and leads to several functional and physical disabilities [18]. Individuals have nearly 10% risk of acquiring lymphangiosarcoma (i.e., an incredibly destructive tumor that requires removal of the afflicted limb and has a terrible medical prognosis) [19], following ten years of persistent lymphedema [20]. The survival rate is under 10% after five years of the chronic condition. Therefore, to avoid any severe consequences, BCSPs must be routinely monitored in the clinic by a well-trained clinician [18], [21]–[23]. Practitioners exercise traditional lymphedema detection methods like Lymphangiogram, Lymphoscintigram, Ultrasound, Computed Tomography (CT), Duplex Ultrasound Technology and Magnetic Resonance Imaging (MRI) that are clinically regarded as standards [24]–[28]. Most of the methods make use of heavy machines with high maintenance, rarely available on the market and extremely costly. Also some of them employ invasive techniques that are not suitable for home applications or remote monitoring of the edema (lymphedema) [29]. Besides, risks are present throughout all processes, which cannot be overlooked. As a consequence, patients need to travel to specialized clinics almost every two weeks for physical examinations [30], [31]. This might pose a problem for village-living patients, as the clinicians are fewer in number and also far away from the areas. The patient's need to travel back and forth between centers can be expensive, tiresome, and time-consuming for patients, degrading their QOL [32], [33]. Ahmadi et al. [34] implemented a mobile application for self-management of patients with BCRL, demonstrating the effectiveness of remote management in reducing self-care costs and improving health outcomes of BCSPs. Despite the promising results of remote management of BCRL, a proper remote monitoring system has yet to be developed. Therefore, the motivation of this scoping review is to improve health outcomes by reducing the burden of frequent clinic visits and potentially improving the QOL of BCSPs. This can be achieved by contributing to the creation of a convenient

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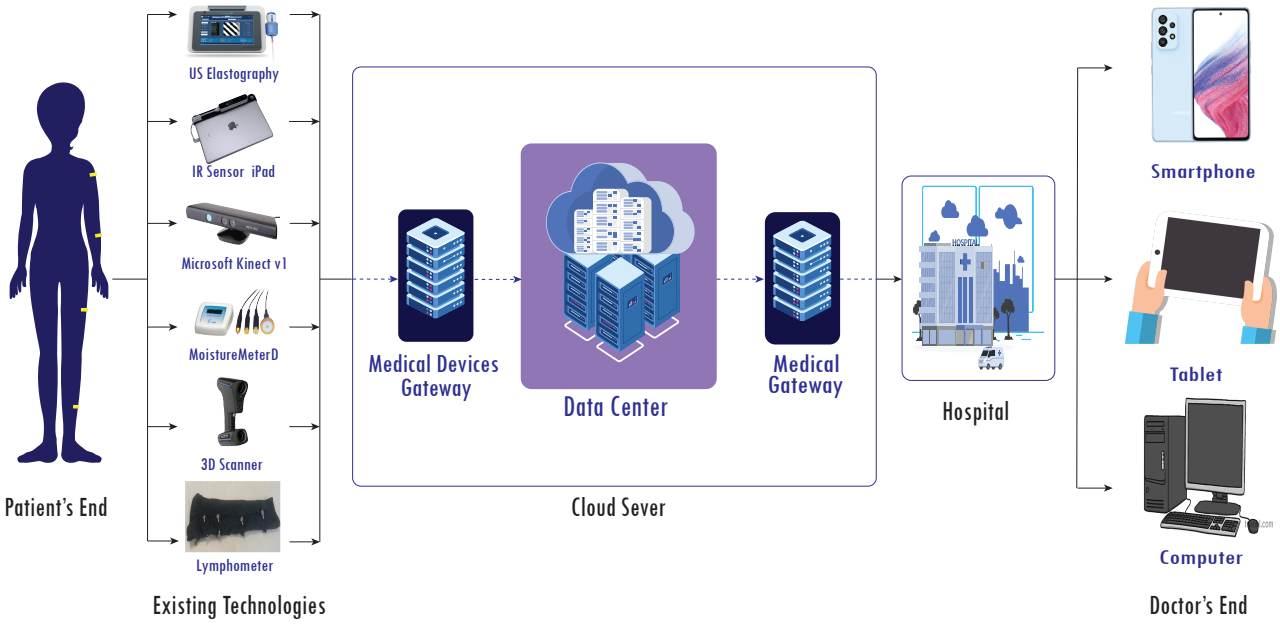

Fig. 1. A conceptual diagram of a telehealth system for remote monitoring of BCRL.

remote monitoring system that will enhance the effectiveness of remote management of BCRL.

The advent of technological advancements has revolutionized the healthcare industry, providing greater accessibility to healthcare services and information [35], [36]. Telehealth, which refers to the use of telecommunication technologies to deliver healthcare services remotely, has emerged as a valuable tool in the field of healthcare [37], [38]. This includes the use of various hardware technologies such as laptops, cellphones, tablets, or monitoring devices, as well as software technologies such as Skype, Messenger, or any other built-in application for secure communication [39], [40]. Telehealth has been used as a crucial tool to provide services such as virtual consultations, remote patient monitoring, and remote chemotherapy administration in post-cancer care, especially during and beyond the COVID-19 pandemic [41], [42]. Studies have shown that telehealth can effectively deliver cancer care services while reducing the burden on patients, particularly those living in remote areas [42]–[44]. Fig.1 illustrates a conceptual diagram of a telehealth system for remote monitoring of lymphedema in a BCSP. It encompasses various monitoring devices that continuously acquire patient data related to their lymphedema status. This data is then transmitted via a medical device gateway to a cloud server, where it is stored securely and can be accessed by medical professionals at any time. The cloud server plays a critical role in enabling real-time monitoring by receiving and analyzing the data from the medical device gateway. Finally, the medical gateway allows doctors to access the patient's data remotely, either through a smartphone, tablet, or computer, providing a convenient and efficient way to monitor the patient's health status.

In contrast to clinical setup, the strategies discussed in this paper may be applied outside of a therapeutic setting, are reliable and long-lasting, and support telehealth. This research gathered all currently available technology methods that can be used in remote monitoring of BCSP, together with information on their effectiveness and outcome results. The study gained its novelty by categorizing those technologies along with their method of detection. The appropriateness of the telehealth implementation technologies revealed in this study was also reviewed, along with potential future prospects. The goal of this comprehensive scoping literature is to highlight current non-invasive transportable technologies which are safe and cannot disrupt the user, can be easily utilized by numerous patients, and will serve patients who live distant from healthcare facilities by bringing telehealth into their hands.

II. Method

A. Overview

A scoping review is a suitable methodology for thoroughly examining the most recent writing on a particular research issue [45]. According to Arksey et al. [46], a scoping review is a bibliometric formulation architecture for mappings all the literature currently accessible on a chosen topic. The scoping review emphasizes all the literature on a specific topic exploring critical aspects when the research area is complex and has not been investigated yet. Therefore, a scoping review was conducted following Arksey et. [46] to determine the technologies that are used to identify lymphedema with non-invasive portable devices to promote telehealth or virtual health assessments [45], [46].

B. Research Questions

The specific research questions of this literature review are:

1) What are portable technologies available to people susceptible to lymphedema to track lymph node blockage in the upper arm?
2) What are the approaches used by the technologies for detecting lymphedema, and how are the technology methods classified?
3) What are the performance appraisals of the reported technologies mentioned in the literature?
4) Which types of methods are suitable to facilitate telehealth?

C. Objectives of Scoping Review

The aim of this scoping review includes: i) to assess the state of the art and compile a list of all the technologies currently in practice for diagnosing and tracking lymphatic sickness, ii) to identify viable devices that are both portable and capable of detecting lymphedema in consumer applications, iii) to know the outcome (performance) appraisals of existing methods mentioned in included studies, and iv) to allude suitable methods for frequent monitoring of lymphedema to promote telehealth.

D. Reviewed Literature

Throughout the course of the exploration, the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) had been followed entirely, especially in terms of the Scoping Reviews' extension (PRISMA-ScR) protocol [46]. Total five distinct electronic databases were chosen to find published articles on the topic that could be specifically identified and methodically recognized. Scopus, PubMed, IEEE Xplore, Cochrane Library, and Google Scholar were the electronic databases. The literature search was conducted by the researchers (ARA, KH, MMI & MMH) between December 2021 and September 2022..

E. Search Parameters

Papers for this review were pulled out from the online databases using the combinations of "AND" and "OR," logical operators with the help of following search parameters.
First Search Query:(lymphedema OR dropsy OR oedema OR hydrops OR "Lymph Node Blockage" OR "lymph node blockage" OR "Blockage of Lymph Node" OR "Lymph Node Disruption" OR "Lymphatic system disruption" OR "Lymphatic system blockage" OR "build up fluid") AND (detect* OR monitor* OR sens* OR diagnosis OR identificat* OR measur* OR spot* OR find*) AND ("Wearable" OR "Wireless Wearable" OR "Portable" OR "Convenient" OR "Handy") AND (tech* OR device OR gadget OR tool OR "Sensor").
Second Search Query:(Oedema* OR Lymph* OR edema* OR (upper extrem*) OR (lower extrem*) OR Swell*) AND (detect* OR monitor* OR diagn* OR measur*) AND (wear* OR wireless OR portable OR mobile) AND (tech* OR device* OR Sensor).

F. Study Selection Process

The study selection procedures of Arksey et al. [46] were used to select the specific studies: firstly, the research questions were created, and then the search string was formulated based on the research question. Three researchers (MMI, ARA & KH) performed the database search and the initial duplicate elimination. After that, two independent researchers (ARA & KH) read all the extracted abstracts for evaluating with the Inclusion and Exclusion criteria. In case of any dissatisfaction, the paper was reviewed by the senior researchers (MMI, MMH, & MFA). When the senior researchers agreed to include the paper, the article was accepted for the data extraction step.

G. Inclusion Criteria:

1) Studies that included at least one method which is used for detecting or monitoring lymph node blockage on both upper and lower limb or related activities in real-time.
2) Studies that included portable technologies based on Inclusion criteria (1).
3) Studies that were released in conference or peer-reviewed journals and made fully accessible via electronic abstract database systems.
4) Research articles published in the English language.
5) Published between January 2005 to September 2022.

H. Exclusion Criteria:

1) Studies that didn't employ portable technology to monitor lymph nodes in an individual's limb.
2) Studies that involve the use of chemicals, medicines, or injection of tracer elements (Fluorescent Tracer).
3) Studies that included only treatment of lymphedema.
4) Studies included monitoring of stroke related swelling of wrist.
5) Studies that have no data to extract or did not reported any method.
6) Studies that include heavy, non-portable device.
7) Studies that include use of X-ray or radiation.
8) Abstracts of journal articles and papers that were not available to access in full.
9) A research article published in a language other than English
10) Studies that did not implemented technology on human or human tissue like substance.
11) Duplicate articles and studies published in review articles and journals, book chapters, published books, news reports, magazines, newspapers and discussion articles, and Master's, or Ph.D. dissertations.
12) Abstracts of journal articles and papers that were published before 2005.

I. Study Selection & Bias Control

In this scoping review, it was anticipated that selection utilizing a combination of engineering and health science online databases would increase dependability and lessen source

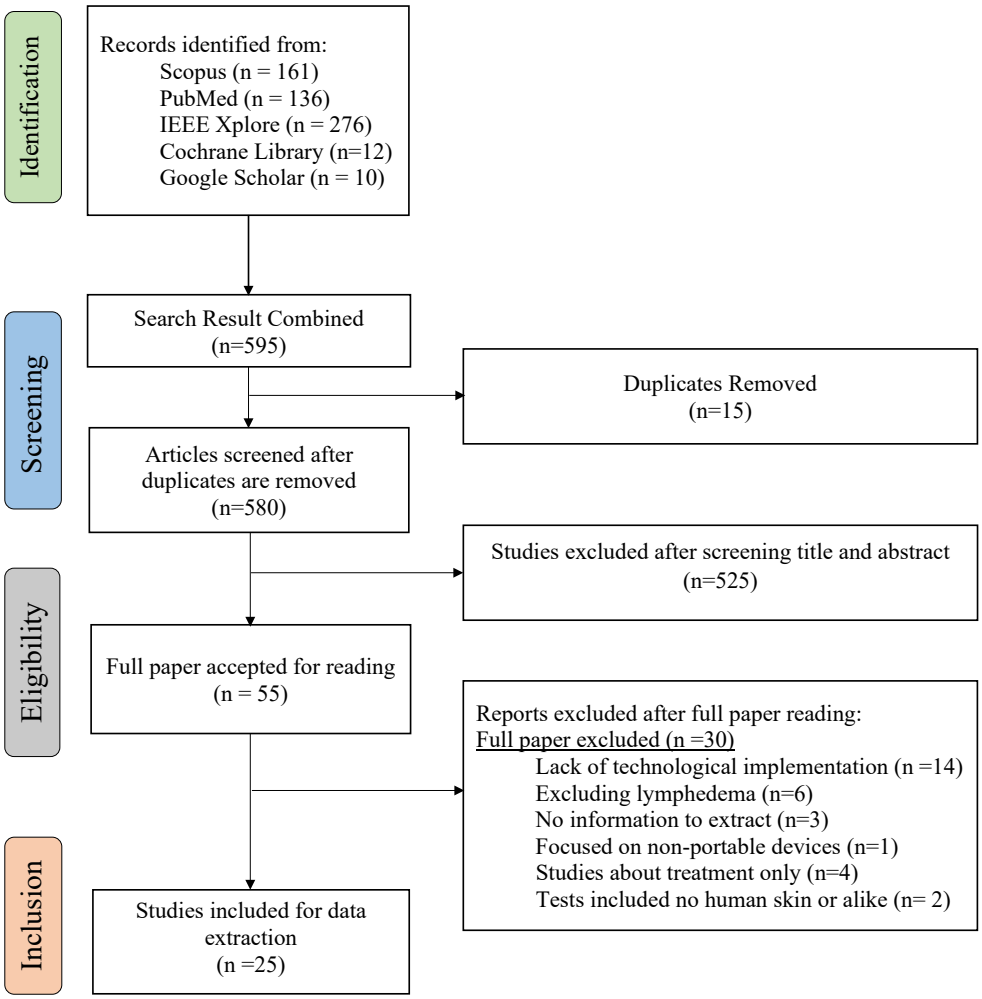

Fig. 2. PRISMA - Study selection process.

publication bias. Papers on digital systems at the scientific level were included in the first consistency filter to assure a particular level of rigour. Two researchers were included in the evaluation of the title and abstract to eliminate bias. A couple of senior researchers looked over and examined the full report to determine any contradictions, minimizing bias.

J. Data Extraction and Bibliometric Indicators

At the outset of data extraction, the senior researchers (MMI, & SKD) notified the other researchers (ARA & KH) how to retrieve data from the paper in a scoping review. The senior researchers (MMI, MMH, & MFA) resolved any disagreement concerning data extraction and advised as to which information should be stored in the Excel file. The independent researchers (ARA & KH) extracted the data of total included studies in an excle master file. Furthermore, the data extraction master file was thoroughly checked by the other researchers (MMH, & MFA) independently. The extracted data from each included studies contained: Informations regarding publication and authors; Simplified Objective of the study; Method of Detection; Observation Criteria; Observable Indicators; Type of Technology (both software and hardware); Digital Platform; Participants Gender, Age, Medical History, Settings; Any outcome of the study; and lastly, a Study Comment.

III. Result

A. Data Overview

The search method generated a total of 595 abstract articles. Only 15 duplicates were discovered and eliminated afterwards. A total of 580 studies were chosen for screening based on title and abstract after duplicates were eliminated, as shown in Fig 2. After reading the title and abstract of 580 included studies 525 abstracts were failed to reach the inclusion criteria. Subsequently, a total of 55 abstracts were selected for full paper reading. Furthermore, a list of 30 studies were found to have fallen short of the required inclusion criteria after reading full papers. Finally, 25 articles were selected for data extraction (see Fig. 2).

B. Bibliometric Characteristic of the Journals and Papers Included

A total of 25 studies were included for data extraction in this scoping review, 92% (23/25) of the research was journal publications, and 8% (2/25) were conference papers. A clear

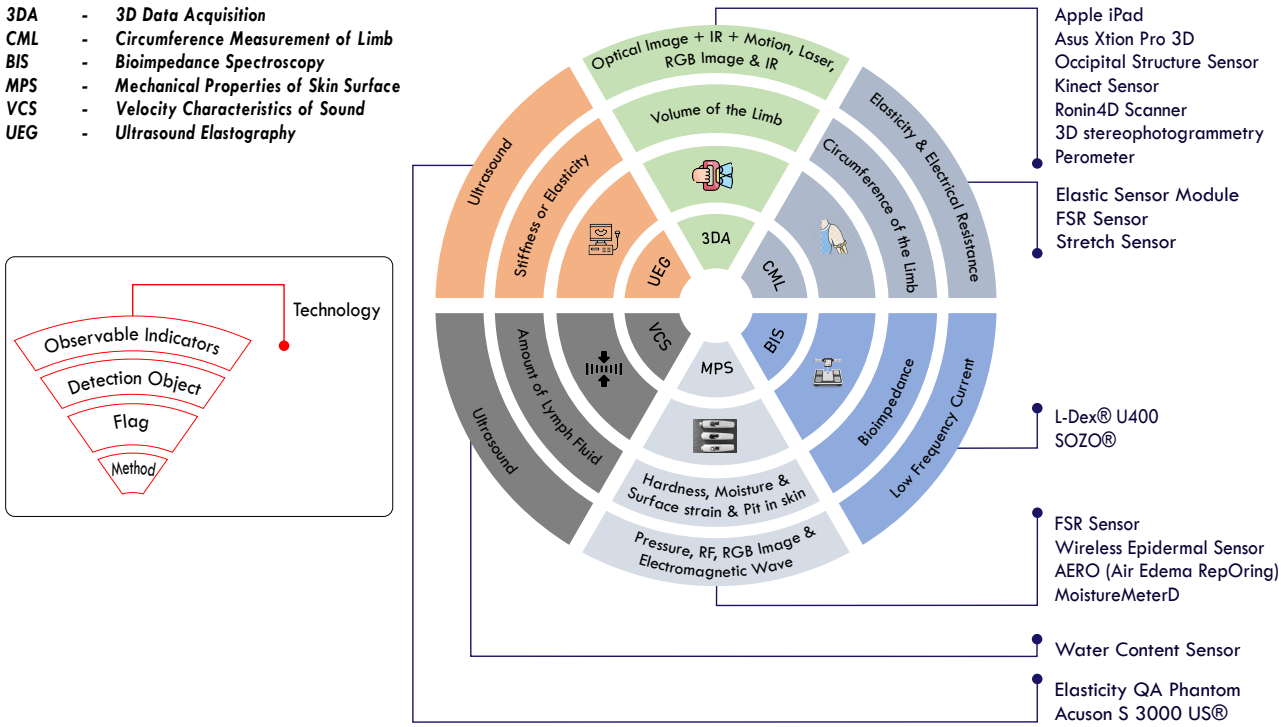

Fig. 3. Categorization of the methods of lymphedema detection addressing detection object, observable indicators, and technology.

upward trend in the number of papers published over time was found and around 72% (18/25) of the studies were in the past five years (i.e., from 2017 to 2021). The studies published in journals were characterized by a high normalized impact factor, and were located mostly in Q1 (i.e., 64% (16/25)) followed by 16% (4/25) are Q2, 12% (3/25) are Q3, and 4% (1/25) are Q4 according to the SJR journal classification [47]. The studies took place across eleven (11) countries. More than half (60%) of the research was conducted in USA (36%), Netherlands (12%), and Italy (12%).

C. Participants

There were 783 participants across all included studies. The mean participant was about 31 with approximately 42 standard deviation (SD). Cau et al. [48] included the maximum number of participants (n = 200) in his study, all of whom had upper limb lymphedema. Overall, there was a distribution of 94.5% (740/783) female and 4.73% (37/783) male across the included studies 88% (22/25) that provided participants with any demographic information (i.e., gender, age, and medical history). Females at risk of UAL comprise the majority of the study participants. Studies involving women who have had breast cancer-related treatment (i.e., mastectomy, axillary lymph node dissection, and radiation therapy) included more participants 81.6% (639/783), than studies including healthy participants 12% (94/783). A total of 8% of the interventions (2/25) for lower limb lymphedema and lymphedema filariasis are also included. Among included studies, 8% (2/25) didn't include any participants but skin samples that were able to distinguish different lymphedema stages.

D. Environment of Experiment

The majority of the trials especially 60% (15/25) are carried out in medical settings (i.e., hospitals, rehabilitation centers, and clinics). Only one piece of research 4% (1/25) was carried out in a home context to support telehealth. Besides, 4 out of the 25 studies were completed in university labs. In 20% (5/25) of the occurrences, the settings were not reported.

E. Methods of Lymphedema Detection

As lymphatic fluid begins to accumulate in the limb, various physical attributes undergo changes, including moisture, hardness, stiffness of the skin of the affected limb [73], volume or circumference of the affected limb [14], and water content inside the limb [73]. Portable technologies that can measure lymphedema have the potential to detect these changes by utilizing image data, infrared rays (IR), motion, low-frequency current, ultrasound, and other innovative methods. This study identified six methods of detection by which portable technologies can screen lymphedema, including 3D data acquisition (3DA), circumference measurement of limb (CML), bioimpedance spectroscopy (BIS), measuring mechanical properties of skin (MPS), ultrasound elastography (UEG), and utilizing the velocity characteristics of sound (VCS). Fig. 3 broadly categorizes the methods of detection according to detection object, observable indicators, and technology. Among the studies reviewed, 52% (13/25) utilized 3DA, making it the most popular method. These studies utilized image data, infrared rays, motion, or laser to construct a digital 3D model of the affected limb and measure its volume. In comparison, 12% (3/25) of the studies utilized wearable force sensing resistor

TABLE I
SUMMARY OF THE STUDY CHARACTERISTICS

Author (publication date), Location	Aim of the Study	Detection Object (Unit)	Method of Detection	Observable Indicators	Technology Used	Participants (n); Gender; Age; Medical History/Conditions)	Outcome/Result
White et al. (2020), USA [49]	To determine the feasibility of a portable scanning device in screening of UAL & finding associations between relative volume change and other demographics.	Volume of the limb (ml)	3D scanning	Optical Image + IR + Motion	iPad @ Apple Inc.	n=21; Female; not mentioned; BCRL patients	Patients who received chemotherapy and a relative volume change of ($< 5\%$) were correlated, according to multi-variable logistic regression (p = 0.0272). No correlation found with other demographics.
Binkley et al. (2020), USA [50]	To validated the clinical usage of the LymphaTech in screening of upper arm lymphedema.	Volume of the limb (ml)	3D scanning	Optical Image + IR + Motion	iPad @ Apple Inc.	n=66; Female; Age: 55 year (mean); BCSPs	The Inter-class correlation, ICC 0.99 with Perometer with identical standard error in length measurement. The bias of measurement was between 38.0–40.7 ml.
Karakashian et al. (2017), UK [51]	To check the suitability of a 3D depth sensing camera for clinical screening lymphedematous arms.	Volume of the limb (ml)	3D imaging from 360 degree	Optical Image + IR + Motion	ASUS Xtion Pro 3D with a rotating Tripod	n=24; Female; Age: 29-76 years; Mild unilateral lymphedema	Statistically significant difference ($p < 0.05$) was found in measurement of affected and healthy arm with CM. ICC: 0.957 (Lower bound 0.898, upper bound 0.985) in single measurement.
Vitali et al. (2020), Italy [52]	To create a virtual framework that is simple for medical staff to use so they may receive more unbiased assessments while treating lymphedema.	Volume of the limb (ml)	3D scanning	Optical Image + IR + Motion	Occipital Structure Sensor @ Occipital Inc.	n=8; males:6 & females:2; Age: 24 year (mean); Healthy	With an average difference of 2 mm, results are extremely accurate. Medical professionals who evaluated the procedure have ignored the errors.
Zhou et al. (2019), USA [53]	To determine the validity of 3DIS in detecting filarial lymphedema	Volume of the limb (ml)	3D imaging	Optical Image + IR + Motion	iPad @ Apple Inc.	n=41; Female:33 Male:8; Age: 56 years median (range 35–73); Lower lymphedema (stages 1–6)	Screening of lower lymphedema was done outside laboratory environment successfully. Variation was found 1.7% & 2.2% for left and right legs respectively.
Lu et al. (2019), USA [54]	To demonstrate the Kinect IR system's capability to assess UAL compare to Perometer cost effectively.	Volume of the limb (ml)	3D scanning from single point	Optical Image + IR + Motion	Kinect @ Microsoft Corporation	n=73; Female; Age: 18+ years; BCSPs	The system showed k=0.2663 (fair agreement) in 10% difference of arm volume & k=0.5475 (moderate agreement), in 200 ml difference. The system was found to be clinically valid tool to detect and monitor severe lymphedema patients.
Buffa et al. (2015), Italy [55]	To validate a novel 3D acquisition system with SkanLab software to estimate the volume of total arm.	Volume of the limb (ml)	3D imaging from 360 degree	Optical Image + IR + Motion	Kinect @ Microsoft Corporation with a stand and a rotating detection frame	n=30; Female:15 Male:15; Age: 19-60 years; Not mentioned	The bias of arm volumes was 0.6% (9.9 ml) where limit of agreement (found by Bland–Altman method) was 2.6% to 1.4%. Inter-rater reliabilities > 0.99.
Ohberg et al. (2014), Sweden [56]	Analyzing the performance of a novel 3D acquisition method with traditional screening techniques.	Volume of the limb (ml)	3D scanning	Optical Image + IR + Motion	3D acquisition platform with 3 Kinect v1	n=25; Female; Age: 60.5 years (28–86); Lymphedema patient	The system overestimates the volume measurement by 45.25 ml (Confidence interval, CI: 95%, p = 0.270) comparing to water displacement method.
Cau et al. (2017), Italy [48]	To find the validity of the usage of a laser scanning system in screening of upper arm lymphedema.	Volume of the limb (ml)	3D scanning	Laser	Rodin4D Scanner @ Rodin4D	n=200; Female; Age: 64.69 years mean; UAL patients	A good correlation (0.738, P $< .05$) was found with manual circumference measurement with a bias of -0.09 dm^3.

Author (publication date), Location	Aim of the Study	Detection Object (Unit)	Method of Detection	Observable Indicators	Technology Used	Participants (n); Gender; Age; Medical History/Conditions)	Outcome/Result
Hameeteman et al. (2016), Netherlands [57]	To justify the reliability of measuring lymphedema in the upper arm using 3D stereophotogrammetry.	Volume of the limb (ml)	3D stereophotogrammetry	RGB Image	Overall 15 cameras using a total of 5-pod arrangement.	n=11; Female; Age: 54 (42-74); All patients received breast cancer related treatment.	Pearson's correlation with WD, r = 0.99 when critical value $p < 0.01$. The difference between variance computed by the 3D acquisition system (205 ml) and water displacement method (1540 ml) was very significant with probability of ($p < 0.001$).
Hoevenaren et al. (2016), Netherlands [58]	To varify the usage of 3D volumetric scanning as a clinical tool in assessment of upper arm lymphedema	Volume of the limb (ml)	3D stereophotogrammetry	RGB Image	15 cameras with 5 pod setup	n=18; Female; Age: 56.5 years mean; Unilateral lymphedema of the hand	With Chi-Square = 18.9, Patients with hand edema and the control group had significantly different hand volumes, according to post-hoc analysis ($p < 0.001$).
Verhulst et al. (2017), Netherlands [59]	To validate the reliability of 3D stereophotogrammetry for measuring upper arm volume.	Volume of the limb (ml)	3D stereophotogrammetry	RGB Image	Overall 15 cameras using a complete 5-pod arrangement	n=10; males:5 and females:5; Age: 28.6 years mean (SD:3.8); Healthy	Intrarater variability for hand and forearm was 0.96 and 0.99, and for latter, interrater variability for hand and forearm was 0.98 and 0.99 respectively. Both have a high degree of repeatability.
Lee et al (2011) Australia, Turkey [60]	To find the validity of Perometer for clinical assessment of lymphedema.	Volume of the limb (ml)	3D scanning (infrared optoelectronic volumetry)	IR (Infrared Ray)	Perometer @ Pero-System GmbH	n=40; Female; Age: 56±12 years; Lymphedema: 20 Healthy: 20	Inter-class correlation was found 0.989 (CI: 95%), Inter-rater reliability was 0.993 (CI: 95%) with bias of 7.5%
Yanmin et al. (2021), China [61]	To design and optimize a portable wearable device that can remotely monitor lymphedema and also provide compression treatment.	Circumference of the limb (mm)	Change in arm circumference changes elasticity	Elasticity	Elastic sensor module in the wearable device	n=1; Female; Age: 20-30 years; Grade 0 lymphedema	The intervention was found less expensive and more accurate comparing to manual tape measurement as it ensures measurement of the same point. No clinical validation was shown.
Fallahzadeh et al. (2016), USA [62]	To propose a real time low-powered wearable device to track edema in remotely	Circumference of the limb (mm)	Change in length of the stretch sensor causes change in electrical resistance	Electrical Resistance	A wearable cuff with a longitudinal force sensitive resistor (FSR)	n=10; not mentioned; Age: 22-31 years; Healthy	With an R2 of 0:87 for our regression model and ICC of 0:971; More than 96% accuracy was found in measurement.
Bethencourt et al. (2021), France [63]	To design client centric lymphedema monitoring system along with patient to doctor communication protocol	Circumference of the limb (mm)	Change in length of the stretch sensor causes change in electrical resistance	Electrical Resistance	Stretch sensor in a wearable device	n=1; Female; Age: not mentioned; BCRL patients	A custom application was developed for the facilitation of remote monitoring of the patient. No mention of accuracy of their intervention
Donahue et al. (2020), USA [64]	To investigate the claim that Breast cancer related lymphedema (BCRL) damage typically affects both hemispheres and goes beyond the areas that are frequently assessed using portable external instruments.	Bioimpedance (Ω)	Bioimpedance spectroscopy	Low Frequency Current	L-Dex® U400 @ ImpediMed inc.	n=66; Female; BCRL (n=33, stage = 1.5 ± 0.8), Mean age = 54.1 years Total healthy subjects: n=33, Average age = 49.4 years	Relaxation times elevated in for superficial tissue: ranging from 49.8 ± 13.2 ms to 56.0 ± 14.8 ms and in deep muscle: 37.6 ± 3.5 ms to 40.5 ± 4.9 ms and . Results shows statistically significant(p=0.04)
Koelmeyer et al. (2021), Australia [65]	To test the feasibility and usefulness of the Bioimpedance System (BIS) home monitoring of patients who have high risk of Lymphedema.	Bioimpedance (Ω)	Bioimpedance spectroscopy	Low Frequency Current	SOZO® @ ImpediMed inc.	n=20; Female; Age: 18-85 years; All undergone breast cancer related treatment	Patients adhire the bioimpedance system (BIS) 74% of the time. Mean L-Dex rose up to 8.4 (Standard deviation, SD = 11.1); after six months, successfully screened five (5) patients with lymphedema (L-Dex > +6.5).

Author (publication date), Location	Aim of the Study	Detection Object (Unit)	Method of Detection	Observable Indicators	Technology Used	Participants (n); Gender; Age; Medical History/Conditions)	Outcome/Result
Kato et al. (2019), Japan [66]	To develop a wearable device which can estimate fluid content utilizing pressure.	Hardness of inner layer of skin (N/A)	Measuring reaction force of skin using pressure	Pressure	FSR sensor	n=11; Female; Age: 20-30 years; Healthy	Statistically, the difference between regression coefficient and interception was significant ($P < 0.003$). Moisture D meter shows strong correlation = 0.998.
Huang et al. (2014), USA [67]	To design and create a very thin, flexible device that can be laminated to the skin's surface for wireless measurement of surface strain and dielectric characteristics.	Moisture & surface strain of the skin (N/A)	Changing of RF (1MHz - 1GHz) w.r. to skin moisture & surface strain	Moisture + Surface Strain	Wireless epidermal sensor and a impedance analyzer	Human skin like substance (ballon); N/A Age: N/A; N/A	Precision = 1.1 (arbitary unit of the commercial device used) for moisture measurement; strain was detected up to 1.3%.
Williams et al. (2018), USA [68]	To propose a device that to differentiate between lymphedema stages.	Pit in the skin (N/A)	Pitting edema assessment	RGB Image	A high speed camera with macro lens and compressed air flow	Human tissue like substances; N/A; Age: N/A; N/A	Data (area vs. time) were collected for several test samples, and it was discovered that there were distinct differences across the four stages of lymphedema.
Bakar et al. (2017), Turkey [69]	To ascertain the specificity (%)and sensitivity of LTW in differentiating stages of lymphedema.	Moisture of skin (%)	Measuring tissue dielectric constant (TDC)	300 megahertz (MHz) electromagnetic wave	MoistureMeterD @ Delfin Technologies inc.	n=63; Female; Mean Age: 53.34 (for latent) for latent and 54.54 years (for lymphedema)	Difference of absolute local tissue water (LTW) and LTW ratio between forearm and biceps was statistically significant (for absolute LTW, $p < 0.001$; LTW ratio, $p < 0.001$). Sensitivity = 65% and specificity = 94%.
Zhang et al. (2018), USA [70]	To propose a novel wearable sensor device that is convenient for home-base monitoring of fluid accumulation.	Amount of accumulated fluid (N/A)	Changing of ultrasound velocity	Ultrasound	Wearable water content sensor	n=1; Male; Age: Not mentioned; Not mentioned	The ultrasound velocity was found smaller (1521–1629 m/s) in the upper portion of leg.
Hashemi et al. (2019), Canada [71]	To ensure reliability & making the system cost effective	Stiffness or elasticity of the tissue (N/A)	Ultrasound elastography	Ultrasound	Elasticity QA Phantom @ CIRS inc.	n=7; Female; Age: 54-81 years; Stage 2 lymphedema	Wilcoxon sign-rank test was performed to find p-values, High level of p-value was obtained in this process (p for skin = 1.24×10^{-5}, p for subcutaneous fat = 1.77×10^{-8} and p for skeletal muscle = 8.11×10^{-7}).
Erdogan et al. (2018), Turkey [72]	To diagnose and determine different stages of lymphedema with the application of sonoelastography	Stiffness or elasticity of the tissue (N/A)	Ultrasound elastography	Ultrasound	Acuson S 3000 US® @ Siemens Healthineers	n=36; Female; Age; 50.8 year median (30–69); stage 1 = 47.2%, stage 2 =52.8%, 33.3% with treatment previously.	Arm circumference measures, L-DEX scores, and lymphedema duration were significant (p 0.002). Readings between the healthy and damaged forearms was observed (p = 0.012). Forearm circumference measures and elastography values were found to be correlated (p = 0.004, r = 0.471) and a correlation was found (p = 0.041, r = 0.352) with L-DEX scores.

(FSR) sensors, elastic sensor modules, or stretch sensors to measure the increasing circumference of the affected limb (CML). Furthermore, 16% of the studies (4/25) employed technologies to assess the mechanical properties (e.g. moisture, hardness, stiffness etc.) of the skin, utilizing electromagnetic waves, pressure, radio frequency (RF), or image data. Two studies (8%) implemented the BIS method, which uses low-frequency current flow to measure extracellular and bodily fluids. Another two studies (8%) used the UEG method to screen for edema, which utilizes high-frequency waves to examine tissue characteristics. Finally, only one study (4%) was found to implement a novel method (VCS) for the measurement of fluid content.

F. Types of Technologies Used

Based on the clinical validity of the technologies used in the studies, all technologies can be categorized into two divisions: conventional devices were reported 24% (6/25) and non-conventional were actually mentioned 76% (19/25) of included devices (See TABLE 2). This study selected conventional technologies based on their availability and their satisfactory performance for the practitioner to use in clinical settings. All conventional gadgets are non-wearable, but there are two categories for non-conventional devices: wearable technologies and non-wearable technologies (See TABLE 2). Wearable interventions are novel approaches to monitor the disease's progression. Wearable technologies are electronic devices that can be attached to the skin or incorporated into clothing [74]. Studies that used non-wearable technologies made up to 72% (18/25) of total studies whereas wearable technologies made only 28% (7/25) in overall. All conventional technologies consist of bioimpedance spectroscopy a number of 33.33% (2/6), elastography 33.33% (2/6), skin mechanical properties measuring 16.67% (1/6), and 3D volumetric scanning 16.67% (1/6). Contrarily, non-conventional methods include arm circumference measuring was normally 15.8% (3/19) among included studies, skin mechanical properties measuring reported to 10.52% (2/19), ultrasound velocity emphasized to 10.52% (2/19), and 3D scanning was equal to 63.2% (12/19) of included studies.

G. Conventional Technologies (Outcome Appraisal)

Two studies [64], [65] utilized BIS, one study, Donahue et al. [64] employed ImpediMed L-Dex® U400 for assessment and validated its practice in clinical evaluation with magnetic resonance imaging (significantly correlated, p=0.041); another study, Koelmeyer et al. [65] implemented SOZO® device in-home monitoring of lymphedema patients (n=20) and successfully screened 5 patients with lymphedema (L-Dex $>$ +6.5) after 6 months of observation. Hashemi et al. [71] found a high level of statistical significant contrast between the normal and affected arms applying CIRS elastography phantom. Erdogan et al. [72] also deployed an elastography machine (Acuson S 3000 US®) in screening lymphedema patients (n = 36) and found elastography outperformed circumference measurement (CM) technique by distinguishing stage-1 and stage-2 lymphedema, where CM could not (for stage-1 lymphedema, p = 0.85, for stage-2 lymphedema, p = 0.003). Bakar et al. [69] found a significant difference in interarm local tissue water ratio ($P < 0.001$) using a moisture meter (i.e., moisture D meter) and declared it to be a preferred technique of early edema identification. In a study [60], Lee at el. [60] validated the reliability of perometer in screening patients with or without lymphedema [Inter-class correlation was found 0.989 (Clearance Interval, CI: 95%), Inter-rater reliability was 0.993 (CI: 95%) with bias of 7.5%].

H. Non-conventional Non-wearable Technologies (Outcome Appraisal)

1) 3D Stereophotogrammetry: The 3D scanning technique, known as 3D Stereophotogrammetry, was validated as a reliable tool by Hameeteman et al. [57] and Hoevenaren et al. [58] (ICC: 0.997; CI:95%; $P < 0.001$) in UAL screening, employs configuration of 15 cameras to assess RGB data of the complete arm, recording the bottom and upper-arm individually.

TABLE II
CATEGORIZATION OF TECHNOLOGIES BASED ON WEARABILITY

Type of Technology	Wearability	Sub-category	Technology	References
Conventional	Non-wearable	BIS	SOZO® @ ImpediMed inc.	[65]
			L-Dex® U400 @ ImpediMed inc.	[64]
		UEG	Elasticity QA Phantom @ CIRS inc.	[71]
			Acuson S 3000 US® @ Siemens Healthineers	[72]
		MPS	MoistureMeterD @ Delfin Technologies inc.	[69]
		3DA	Perometer @ Pero-System GmbH	[60]
Non-conventional	Wearable	CML	Elastic Module	[61]
			Stretch Sensor	[62], [63]
		MPS	Wireless Epidermal Sensor	[67]
			FSR Sensor	[66]
		VCS	Water Content Sensor	[70]
	Non-wearable	3DA	iPad @ Apple Inc.	[50], [49], [53]
			Occipital Structure Sensor @ Occipital Inc.	[52]
			Kinect @ Microsoft Corporation	[56], [55], [54]
			3D stereophotogrammetry	[57], [58], [59]
			ASUS Xtion Pro 3D @ ASUSTeK Computer Inc.	[51]
			Rodin4D Scanner @ Rodin4D	[48]
		MPS	AERO (Air Edema RepOring)	[68]

2) Stationary Infrared Depth Sensors: Three studies used Microsoft Kinect sensors as an essential component, with notable variations in research designs. In 2014, Ohberg et al. [56] placed 3 Microsoft Kinect v1 sensors in each corner of a triangle-shaped construction that reveals an overestimation (45.25 ml) compared with water displacement (WD), confidence interval was 95% (p=0.270). Later in 2015, Buffa et al. [55] utilized Microsoft Kinect in a rotational arrangement that captured the circumference of the arm by rotating around it, capturing images from every angle. The free software Skanect, in conjunction with MeshLab, creates a 3D rendition of the arm with a bias of -0.6% (volume: -9.9 ml; limit of agreement: from 2.6% to 1.4%).

Karakashian et al. [51] implemented ASUS Xiong Pro 3D camera instead of Microsoft Kinect on a rotating tripod, similar to the setup of SkanLab (Buffa et al., 2015) [55] and found the difference between normal and affected arms was statistically significant ($p < 0.05$; CI 95% ICC:0.957). In 2019, Lu et al. [54] used a single Microsoft Kinect v2 and a custom acquisition software program to capture a good correlation (R-squared = 0.8799 in the arm volume; R^2 value was 0.6277 to 0.7098 in percent difference; bias 6.016 ml) with perometer.

3) Mobile Infrared Depth Sensors: The infrared depth sensor of a mobile device and the external occipital structure sensor have become popular 3D acquisition tools for screening UAL due to their great mobility and accessibility [49], [50], [52], [53], [75]. Some proprietary software companies (i.e., LymphaTech and Lym 3DLab) have developed an optical three-dimensional imaging system with an infrared depth sensor incorporated or externally coupled to a tablet, along with custom accelerometer software to assess lymphedema. In 2017, Yahathugoda et al. [75] developed the method to identify lymphatic filariasis (LF) of the lower limbs. White et al. [49] and Binkley et al. [50] validated the use of the Lymphatech system as a feasible tool for screening UAL in clinics. White et al. [49] showed a statistically significant difference (p = 0.0272, OR 46.203) between patients with more relative volume change (5%) and neoadjuvant chemotherapy using multivariable logistic regression. Binkley et al. [50] found a strong intraclass correlation (0.99) between the Lymphatech system and the perometer. Zhou et al. [53] found the technique feasible for home monitoring of patients. Vitali et al. [52] mounted an Occipital Structure Sensor instead of an in-built infrared depth sensor on the iPad and found it precise (average difference of 2 mm) with a negligible measurement error.

4) Appraisal of Other Non-wearable Methods : Williams et al. [68] used camera to assess the mechanical properties of the skin rather than 3D volumetric measurement. The proposed device utilized compressed air to make a pit on the skin and capture the area with a high-speed camera. A graph (area vs. time) was plotted for a number of test samples, and it was shown that the four phases of lymphedema differed noticeably from one another. The study failed to show any result on patients with lymphedema, also lacked clinic clinical validation. Cau et al. [48] made use of a highly precised (up to 0.75 mm) three-dimensional laser scanner, Rodin4D, for 3D modeling the upper limb of 200 subjects (Mean total volumes = 2.00 ± 0.59 dm^3). The study found difference statistically significant ($p < 0.05$) and a fair correlation (R-square = 0.738) with a traditional approach (Mean total volumes = 2.00 ± 0.59 dm^3; bias = -0.09 dm^3).

I. Non-conventional Wearable Technologies (Outcome Appraisal)

1) Circumference Measuring Approach: Six studies proposed wearable devices that would be able to constantly monitor the progression of swelling. The scoping review outlines that two studies created a sleeve spanning the length from the shoulder to the wrist [61], [63], with an elastic sensor measuring the circumference of the arm. Yanmin et al. [61] employed low-ductility massage belts along with an elastic sensor module and a signal processing module to both monitor and provide compression treatment for lymphedema. This wearable device's key benefit over traditional screening methods (such as the tap measurement method and water displacement) is that the latter requires an expert physician to obtain an accurate measurement whilst the former does not.

Fallahzadeh et al. [62] and Bethencourt et al. [63] used force sensitive resistor sensor (FSR) that linearly converted its longitudinal stretch into electrical resistance, evaluates the difference in sleeve stretches caused by variations in arm circumference. The stretch value was then calculated by converting the resistance into an electrical voltage using a conditioner circuitry that monitored the capacitor's loading time through the electrical resistance of the sensor. Fallahzadeh et al. [62] found the sensor 96% accurate (ICC: 0.97, R2 = 0.87) in monitoring while remotely monitoring 15 subjects. Bethencourt et al. [63] affixed the stretch sensor to a sleeve extending from armpit to wrist. The device was connected to a smartphone using a Bluetooth module and the data was transferred to the server. A custom smartphone application was used to connect the device, alert and show measured values to the patient, along with sending data to the clinician.

2) Appraisal of Other Novel Approaches: Several wearable devices were proposed to assess edema based on mechanical properties of the skin. Huang et al. [67] designed a wireless epidermal sensor, a small patch consisting of dielectric and strain sensors sits on the bare skin of the limb to measure swelling due to lymphedema. The strain sensor showed a drop in frequency of 22.7 MHz with a precision of 1.3% when extended by up to 29.1%, and the capacitance decreased with a precision of 1.1 typical units on the scale of the commercially available moisture meter. Kato et al. [66] proposed a wearable device utilizing a pressure sensor to measure the reaction force of subcutaneous tissues. The regression coefficient and intercept showed a statistically significant difference ($p < 0.003$) with a high correlation of 0.998 with the moisture meter. Zhang et al. [70] proposed a wearable water content sensor for monitoring fluid accumulation. The wearable sensor consisted of ultrasonic transducers and a magnetic sensor that measured the distance. The ultrasound velocity was found to be smaller in the upper portion of the leg where muscle builds up mostly water (1521-1629 m/s).

IV. Discussion

This scoping review clearly maps all available technologies for remote assessment of lymphedema, along with their challenges, and prospects to facilitate telehealth. Following that, to answer the initial research question, 25 studies were found with significant methodological variation and generally, small sample sizes reported 18 technological solutions that could track lymphedema in the limb. In answer to the second research question, si different methods (e.g., 3DA, CML, BIS, MPS, UEG, and VCS) were found with their clinical evidence of the outcomes. Considering the accuracy appraisals, each method mentioned a different measurement scale, and there was no common scale of measurement for monitoring the progression of lymphedema. Therefore, it is also a well-known challenge to introduce a common scale of measurement for everyday applications. Especially, this research gained novelty by categorizing all the technologies into divisions and sub-divisions. The reported interventions were categorized into two divisions based on their clinical application and availability: conventional technologies and non-conventional technologies. Further categorization of all conventional and non-conventional technologies were found to be in two categories: wearable technologies and non-wearable technologies. In answer to the final research question, the reported outcome was analyzed and the challenges of the studies were discussed to facilitate telehealth. The literature review discovered 6 studies that used technologies that are commercially available and clinically verified in the diagnosis of lymphedema. Most of the commercial technologies (i.e., Elasticity QA Phantom, Acuson S 3000 US®, ImpediMed L-Dex® U400, and MoistureMeterD) featured are more appropriate for clinical use than home monitoring as they require a skilled operator to function. Besides, Koelmeyer et al. [65] used BIS (e.g., SOZO®, ImpediMed) for remote assessment of edema and found participants (n=20) extremely confident in using the device. The study reported 85% of participants faced technical problems in the first 3 months of usage due to a lack of operational training, which reduced to 35% after 6 months of use. Commercially available edema assessment systems are highly accurate but are also fairly expensive and not affordable for rural patients. Wearable interventions are affordable, easy to use and less space-consuming. Very little research has been conducted on this innovative strategy [61]–[63], [66], [67], [70]. The key benefit of these wearable devices over traditional screening methods, such as the tape measurement method and water displacement, is that the latter require an expert physician to obtain an accurate measurement, whereas the former do not. The current body of studies that included wearable technologies remain in its early stages, as evidenced by the participation of the least number of subjects (mean participant 4, SD 5.32), which lacked information about how the described intervention affects real-time monitoring and developmental outcomes in patients with BCRL. None of them have received any clinical validity in regards to commercial availability and screening for lymphedema surplus for developmental stage especially under laboratory conditions. Besides, further research and clinical trial is mandatory for wireless epidermal sensors to track skin edema and expected to be a reliable method of lymphedema assessment in the future. However, the technology readiness level and clinical standards does not mention in the included studies. In addition, its adaptability to facilitate telehealth is still unclear. On the other hand, this scoping review found of non-wearable methods, 3D volumetric screening of edema enrolls the maximum number of participants (mean participant 43.92, SD 53.40). 3D scanning of limbs is proven to be a cutting-edge technique for screening lymphedema [48]–[59]. In the past, infrared optoelectronic perometry was the only method of 3D scanning volumetry that was accurate, dependable, and valid [60]. But the device is expensive, requires high maintenance, and occupies a large space. From 2014 to 2020, a series of research and development has been conducted to develop a reliable, small, and convenient device for 3D scanning of arm edema. The 3D scanning methods proved most reliable based on correlation (> 0.9) and the statistically significant ($p < 0.05$) measurement difference with traditional volumetric measurement methods (i.e., Perometer, WD, and CM). The 3D scanning methods have also proven to be a reliable method for screening lymphedema but are inappropriate for people with functional impairment and who cannot raise their arms to 90 degrees. Although the modern mobile portable depth sensor appears to be state of the art for screening purposes, more convenient alternatives, especially wearable devices are essential to overcome complications for facilitating telehealth.

V. Implication for telehealth and future aspects

Facilitating telehealth of BCSPs' is a key emphasis, and this scoping assessment is consistent in pointing out the necessity in order to create a novel portable device. A portable monitoring device is evident in the early detection of lymphedema as well as reducing the frequent visits of patients to clinics. In particular, clinicians have expressed receptiveness to using a portable 3DS system [49], [50], [52], and currently, it would be the best option for patients who already own a 3DS. Despite the cost burdening for rural people and facilitating telehealth using 3DS approach is still unclear. In contrast, a recent study demonstrated that people are becoming more likely to utilize wearable devices to keep tabs on their health as it is convenient to use and has a tiny form factor [76]. For fundamental biomedical and health science research, the need for a wearable device to monitor lymphedema is therefore of utmost importance. A wearable assessment device would be most convenient for patients as they are affordable and the demand for such a device is rising daily [76]. Despite the possibility of a wearable device in patients with lymphedema, the scant amount of data currently accessible necessitates higher validity investigations. More importantly, a wearable monitoring device that can provide compression therapy is the crucial intervention for long-term lymphedema conditions, minimizing the need for frequent clinic visits by lymphedema patients [77]. Additional advancements required creating a user-friendly interface for reported interventions, connecting patient to doctor, sending real-time data of patients to a server where a comparison is made with previous data, and finally,

the doctor prescribing patients based on the comparison. In addition to storing data in the cloud, datasets can be used to train an advanced machine learning algorithm to predict a patient's status and automate compression treatment in the future. In conclusion, this scoping review highlights the importance of developing low-cost wireless wearable technology that can detect lymphedema early and improve the overall quality of life for BCSP. However, the cost of the device is only one aspect of ensuring long-term monitoring and treatment for lymphedema patients. Access to health or care insurance is essential for patients to receive the necessary care without financial burden [78]. To address this issue, collaboration between healthcare providers, policymakers, and insurance companies is required to develop comprehensive coverage plans that include early detection, monitoring, and treatment of lymphedema. To make lymphedema treatment more accessible and affordable for patients, it is crucial to address the issue of insurance coverage in addition to developing affordable wearable devices. Therefore, this literature review advocates for a multi-pronged approach that includes both the development of affordable wearable devices and the exploration of ways to make lymphedema treatment more accessible and affordable for patients.

VI. Study limitations

The studies compiled for this scoping review were studies that only track swelling brought on by lymphatic fluid accumulation. The publications were pulled based on the five databases, which might introduce bias. The databases were chosen using the researcher's empirical knowledge rather than any systematic process. Due to limited access, some databases (e.g., "Web of Science", "CINAHL", and "PsycINFO") were not included. The inclusion and exclusion criteria were rigorously developed to get a fair search result. Only English-language publications of the studies considered in this evaluation. The studies were included that have been published between January 1, 2005, to September 30, 2022. The earliest papers, on the other hand, are probably no longer relevant given technical improvement over the literature search period.

VII. Conclusion

Researchers have paid a little attention to telehealth facilitation for people with UAL over the years. To improve the quality of life after cancer treatment, it is advised to urgently conduct further research in order to devise wireless technologies to remotely monitor the progression of lymphedema, promoting telehealth. Moreover, machine learning and deep learning can be employed on patients' data to accurately forecast the state of a patient, and deliver optimal medical care for people with lymphedema. Portable 3D imaging devices are presently the most practical and reliable way to screen for lymphedema at home, owing to the advancement of proprietary software, but further development in the algorithm of the software is required to overcome its blind spot and limitations for embedding into the wearable devices. Significantly, wearable technologies have the potential to intervene for remote management of lymphedema to promote telehealth. In addition, wearable devices are getting its popularity among clinician and practitioners. Yet, current wearable interventions are still in their early stages of development, and further research is indispensable for developing a clinical acceptable gadget. Therefore, it is important to develop a more sophisticated wearable method that can be used to precisely determine the water content of the limb in real-time and deliver compression treatment. Therefore, the findings of this scoping review could be pertinent to the establishment of a wearable device that enhances physician accessibility and facilitates telehealth. Remotely monitoring the progression of lymphedema using a wearable device, the clinicians and therapists will provide client-centered treatment plan for people with lymphedema; resulting improve their quality of life.

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