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RESEARCH ARTICLE

UBICU: A Gamified Respiratory Incentive System for Pulmonary Re-Expansion

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ABSTRACT Pulmonary complications can arise due to trauma, postoperative conditions, or as sequelae of diseases such as COVID-19. To help patients restore lung functionality, most undergo lung re-expansion physiotherapy using a Respiratory Incentive Spirometer. However, currently available Respiratory Incentive Spirometers do not allow for quantitative tracking of performance during inspiration exercises, require physiotherapist supervision to ensure exercise quality, and show low treatment adherence. To address these limitations, we developed UBICU, an assistive product for lung re-expansion physiotherapy. UBICU includes a flow measurement device, an app with a video game interface to motivate exercise performance, and cloud-based software for the remote prescription and evaluation of physiotherapy. We conducted a quasi-experimental study with a sample of 30 healthy individuals, aged 18 to 65 years and balanced by age and sex. We assessed pulmonary ventilation distribution before, during, and after using two flow respiratory incentive spirometers, UBICU and TriFlo, with electrical impedance tomography. Our findings indicate that UBICU provides accurate and reliable measurements of pulmonary ventilation distribution, showing statistically significant improvements after use ($p < 0.01$), validating its effectiveness as a respiratory incentive spirometer. To evaluate the usability of the video game component, we conducted a perception survey, achieving an acceptance rating above 5 on a scale of 0 to 6. Notably, UBICU was shown to favor lung re-expansion more effectively than the traditional TriFlo mechanical system.

INDEX TERMS Biomedical measurement, spirometry, telemedicine, user-centered design, videogames.

I. INTRODUCTION

Pulmonary complications can arise because of polytrauma, side effects of a critical illness (e.g. COVID-19), as a postoperative complication, referral of other pathologies in intensive care units, or diseases of the lung itself. To recover their lung functionality, most of the patients undergo lung re-expansion physiotherapy using a device called Respiratory Incentive Spirometer (RIS). Currently, the most commonly used RISs do not allow a quantitative follow-up of the performance of the inspiration exercises. They also require physiotherapist supervision to ensure exercise quality and adherence to

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treatment is low. These characteristics show a lack of attention to the needs of patients and physiotherapists to control the pulmonary recovery process [1], [2]. User-centered product design allows us to offer products with features that meet the needs of the users. In medical product design, the concept of the user encompasses two key individuals: the patient, who experiences the disease, and the healthcare professional, who possesses knowledge about the disease and its treatment [3]. In this way, designing a product in healthcare must account for the needs of both users, ensuring the product meets the clinical, technical, and ergonomic requirements of healthcare professionals, along with the usability and comfort needs of patients. The objective of this work is to propose a new assistive product that supports respiratory physiotherapy for pulmonary re-expansion, enables remote quantitative monitoring of patient performance, and promotes treatment adherence. Our contributions are as follows:

- UBICU enables the guided performance of lung re-expansion exercises together with remote prescription and analysis of its results.
- UBICU's design involved an interdisciplinary team focused on both the patient and the physiotherapist.
- UBICU supports lung re-expansion, encourages regular physiotherapy for lung health, and provides physiotherapists with a tool for remote prescription and monitoring.
- Finally, UBICU motivates patients to engage in respiratory exercises through interactive features with visual and auditory feedback.

II. BACKGROUND

A. PULMONARY COMPLICATIONS

Pulmonary complications impair lung function, leading to a loss of volume and capacity, which can extend hospital stays, increase healthcare costs, and potentially result in death [4], [5], [6], [7]. Postoperative pulmonary complications occur in 2% to 5.6% of average surgical interventions; however, this rate rises to between 30% and 40% for thoracic or abdominal surgeries [8]. These complications are characterized by impairments in both physical and respiratory functions. The physiotherapist prescribes and oversees the use of the RIS as a complement that helps maintain the therapeutic objective of improving and/or maintaining lung expansion. The American Association of Respiratory Therapists has reported little evidence to support routine use and does not recommend it as a preventive measure against complications. However, it continues to be suggested in some patients, such as those with atelectasis with retention of secretions in the airways [9].

Respiratory physiotherapy plays an essential role in patient recovery through manual or instrumental techniques. Among the instrumental techniques, the RIS stands out and is available in flow- and volume-based models. The main objective of its use is to facilitate pulmonary re-expansion. The patient during the exercise takes a deep inspiration through the mouthpiece, where the flow is laminar, followed by an inspiratory pause at the end of the inhalation. Throughout the exercise, the patient receives feedback in real time. The exercise prescription is tailored to the individual's needs, considering frequency, series, repetitions, pauses, and rest intervals.

B. TELEHEALTH IN PHYSIOTHERAPY

The purpose of assistive products is to provide technology to individuals with disabilities to improve their capabilities and therefore reduce their dependence on others [10]. Internet of Things (IoT) in rehabilitation comprises medical devices with "medical software in the cloud to meet healthcare needs by monitoring patients, sharing information, analyzing data, and transmitting it to doctors or physiotherapists, thereby improving the quality of health care" [10]. In telehealth, IoT serves as an alternative for expanding service coverage, reducing both travel costs and waiting times for care. The COVID-19 pandemic promoted telehealth technologies driven by the need to minimize physical contact and prevent disease transmission. In respiratory physiotherapy, remote care has been done through direct patient-physiotherapist communication to support cystic fibrosis treatment [11]. However, scientific literature on support products for remote physiotherapy is still scarce. In the instrumentation field, for monitoring inspiratory flow, there are several methods using different principles, some of them using ultrasound [12], other images/videos [2], and others differential pressure [13], [14], [15], [16], [17]. This project integrates instrumentation and IoT elements into a new assistive product for monitoring respiratory physiotherapy aimed at pulmonary re-expansion. The design of this telehealth device carefully considers the security and confidentiality of patient information.

C. SERIOUS GAMES IN HEALTHCARE

Gamification incorporates elements of game design into new contexts outside of traditional games [18]. Serious games represent a form of gamification, engaging users in activities beyond entertainment, and are widely used in fields like education and rehabilitation [19]. Examples include virtual reality games for stroke rehabilitation and low-technology applications, such as SMS-based systems for monitoring cystic fibrosis. Additionally, software has been developed for local Positive Expiratory Pressure (PEP) physiotherapy assistance, where patients control a game by exhaling into a mouthpiece [20]. In addition, virtual reality [21] can offer cystic fibrosis patients an immersive diving experience, where breathing exercises guide their movement through an underwater environment. Evidence suggests that virtual reality and video games may benefit pulmonary and cardiopulmonary therapies [22], [23]. However, we found no evidence of video games dedicated exclusively to the recovery or prevention of lung capacity loss across various diseases, while also enabling physiotherapists to manage multiple patients remotely.

III. METHOD

We employed an interdisciplinary approach in the product design process, utilizing three synergistic, user-centered

strategies: the Theory of Inventive Problem Solving (TRIZ) [24], Axiomatic Design (AD), and Design Thinking (DT). To validate the product as a lung re-expansion device, we conducted a clinical study with healthy participants, comparing our proposed system—UBICU—against the conventional TriFlo system [25]. To assess the motivational qualities of video game engagement, we used a specific evaluation instrument. The interdisciplinary team included engineers, physiotherapists, an industrial designer, a visual designer, a biologist, and a psychologist.

The design process had the following steps: Problem analysis for identifying product requirements; Selection, modeling, and testing of the system; Materialization of the product and Validation.

Validation for pulmonary re-expansion was conducted through a clinical trial using Electrical Impedance Tomography (EIT) with the Draeger PulmoVista 500 [26], which provides a transverse view of the thorax approximately 10 cm in width, allowing for observation of air distribution and behavior at a regional or sectional level. The electrode belt was positioned between the 4th and 6th intercostal spaces along the midclavicular line for measurement. Additionally, the app's usability was validated through a usability test.

IV. RESULTS

A. REQUIREMENTS OF THE DESIGN

We applied the nine-windows technique, grounded in technological evolution, to analyze the problem with input from both users and physiotherapists. This technique enables the design team to perform a systemic analysis by first defining the problem and main function of the product, then using an existing product that partially addresses the issue as a basis for evolution. The nine-windows technique is a spatiotemporal analysis (Fig. 1): on the horizontal axis, the analysis progresses from past to future, whereas on the vertical axis, it spans from the product's components to its social context of use.

1) PROBLEM DEFINITION

Current spirometers used in physiotherapy do not ensure treatment adherence, provide limited quantitative data for the physiotherapist to assess patient performance, and pose a risk of contagion when the physiotherapist must accompany the patient in person.

2) MAIN FUNCTION

Encourage the patient to perform respiratory physiotherapy of pulmonary re-expansion.

3) CURRENT PRODUCT FOR EVOLVING

TriFlo.

Systemic analysis involves progressing through each window in the specified order, from 1 to 9 (Fig. 1). The present and past are either known or can be researched, whereas the future is projected by examining emerging realities in the

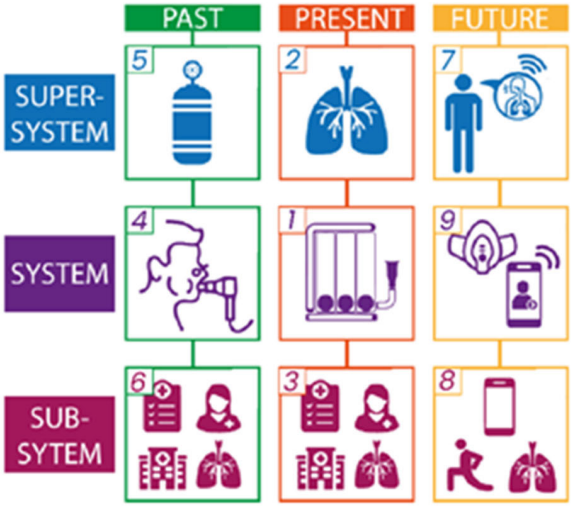

FIGURE 1. Nine-windows analysis for a new assistive product for physiotherapy.

context and advancements in technology. The ninth window outlines the attributes of a new assistive product designed to address the problem: it possesses qualities that are either distinct from or complementary to existing devices and holds potential for future innovation. From the list of attributes expressed in natural language, we propose three functional requirements, FR1 to FR3, for a new product:

FR1: Measure the inspired airflow [0 to 1200 cm^3/s]

FR2: Transmit wireless data [200 samples/s]

FR3: Motivate the patient to do the exercises [Interaction by image and sound]

Meeting these requirements would enable us to measure airflow, transmit information wirelessly, and engage the patient in physiotherapy. The third requirement should be supported by software that allows for remote prescription and analysis of exercise quality performed by patients.

B. SELECTION, MODELING, AND TESTING OF THE SYSTEM

For the first requirement, measure the inspired airflow [0-1200 cm^3/s], we considered different alternatives for flow measurements: a turbine, an orifice plate, a Venturi tube, and a hot wire, among others. We selected a Venturi tube due to its precision in medical applications [27], [28] and designed it according to BS 1042 standards from the British Standards Institution. Following recommendations for a Classical Venturi tube with a machined convergent section (Fig. 2), we determined that the diameter of the entrance cylinder (D) is 14 mm, and the diameter of the cylindrical throat (d) is 8 mm [29]. The tube was manufactured using a 3D printer with Polyethylene Terephthalate Glycol-modified (PET-G), a biocompatible, easy-to-print material with the required hardness. We then performed a finite element simulation to ensure measurement accuracy.

Fig. 3 shows flow plotted against differential pressure using the theoretical expressions [29] [30] and the tabulated experimental values for some terms in the equations from

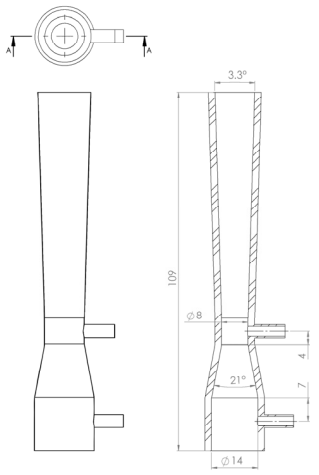

FIGURE 2. Parameters of venturi tube designed for UBICU.

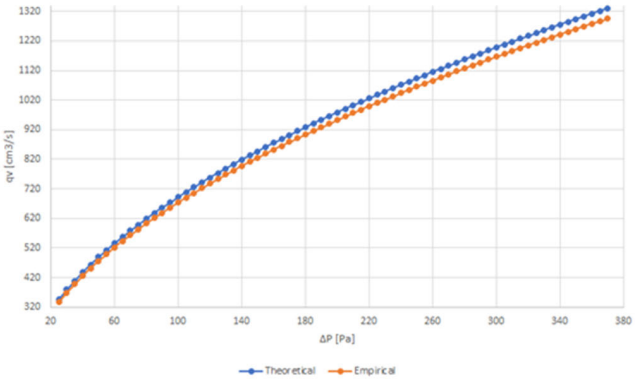

FIGURE 3. Sensor calibration data according to the BS 1042 standard.

BS 1402. The resulting plots are third-grade polynomials and the error between them is around 2.63%. The primary sensor's high- and low-pressure nozzles were connected via two flexible hoses to a Micro Electro Mechanical System MEMS; we chose the XGZP6897A001KPDPN (−1 to 1 kPa) differential pressure sensor to measure the inspired airflow (Fig. 4); it incorporates a silicon piezoresistive pressure transducer and signal-conditioning circuitry in a SOP8 package with two air vents. The module is fully calibrated, and temperature compensated for offset, sensitivity, temperature, and non-linearity, thus satisfying repeatability, linearity, stability, and sensibility.

The transducer is connected to a microcontroller system for data interpretation and transmission. An Arduino Nano Every board was selected due to its compact size (45 × 18 mm) and lightweight design (under 5 g), making it ideal for wearable applications. This board features an ATMega4809 microcontroller operating at 20 MHz, with 48 KB of Flash memory, 6 KB of SRAM, and a 256-byte EEPROM. Its internal 10-bit ADC enables connection with the differential pressure transducer.

TriFlo has three markers for inspired airflow: 600, 900, and 1200 cm^3/s, intended for reaching the prescribed reference point during use. In contrast, UBICU can display intermediate values, offering an added benefit by allowing the physiotherapist to assess the patient's progress in pulmonary re-expansion more precisely between therapy sessions.

We connected a calibration syringe, which generates different inspiration flow values, to a Citrex H3 flow validator in series with UBICU. Fig. 4 shows the correlation between the Citrex H3 measurements and the UBICU outputs.

As shown, the coefficient of determination (R^2) is 0.9822, indicating that UBICU closely follows the trend of the Citrex H3 measurements. This provides physiotherapists with reliable information to assess improvements in pulmonary re-expansion.

For the second requirement—transmitting wireless data [200 samples/s]—we used an HC06 Bluetooth 2.0 module. This class-2 follower module (2.5 mW, 10-meter range) provides two-wire serial communication (UART) to connect with the microcontroller. Operating on the 2.4 GHz ISM band, it supports transmission rates up to 2.1 Mbps and includes an integrated antenna. The module measures 36.5 × 16 mm and weighs approximately 4 g. The circuits are powered by a 3.7 V, 1000 mAh Li-Ion battery, with an LM2596S-ADJ DC-DC adjustable voltage converter. A TP4056-42-SOP8-PP constant-current/constant-voltage linear charger with thermal regulation is used to recharge the battery.

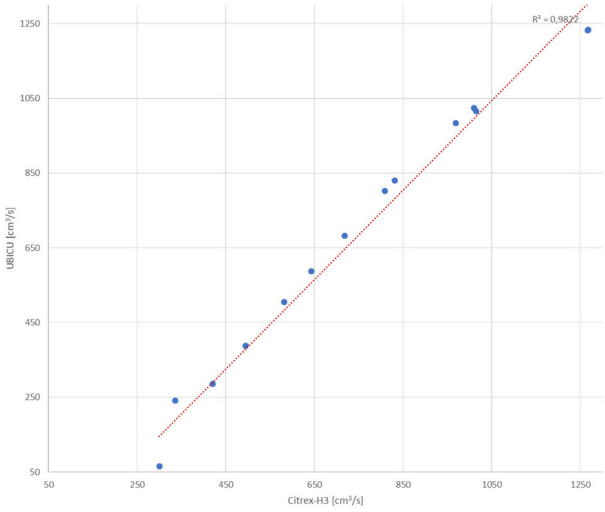

FIGURE 4. Correlation between Citrex H3 validator and UBICU data.

For the third requirement—motivating the patient to perform the exercises through interactive visuals and sound—a video game was developed using the Unity platform. In the game, an otter is challenged to overcome some barriers represented by seaweed. The otter's movement is controlled by the patient's inspiration, with the height of the barriers corresponding to the target inspiratory flow levels (Fig. 5).

The mobile device reads the prescription and transmits the exercise execution data to the cloud, allowing the

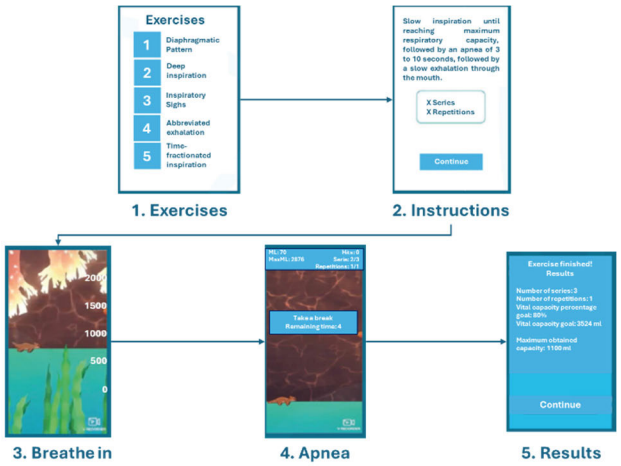

FIGURE 5. UBICU video game sequence: 1: Activity selection; 2: Give instructions to the patient; 3: upward movement when breathing in; 4: Apnea or no breathing; and 5: Results of exercises for the patient.

physiotherapist to review it later. The exercises prescribed by the physiotherapist are a set of sequences of inspirations according to the patient's needs.

In the video game, the patient takes on the role of the otter, performs the exercises, and receives feedback on the results. The UBICU's interface is presented to the patient through the Presentation Layer. The patient signs in and their information is verified against the data stored in the database. Data from the physiotherapy session is then retrieved from the database (Data Layer), organized according to the patient's progress (Control Layer), and displayed in a menu (Presentation Layer). The patient selects an exercise and starts the game. While the patient performs the exercises using the video game interface (Presentation Layer), the mechanics and algorithms of the video game are controlled by the Control Layer. Once the video game session is completed, the Control Layer plots the results, which are displayed to the patient in the Presentation Layer. Additionally, the results are sent to the Data Layer for future analysis by the physiotherapist. The physiotherapist retrieves the patient's data, visualizes the results, analyzes them, and stores a new session of exercises for the patient based on their progress as is shown in Fig. 6.

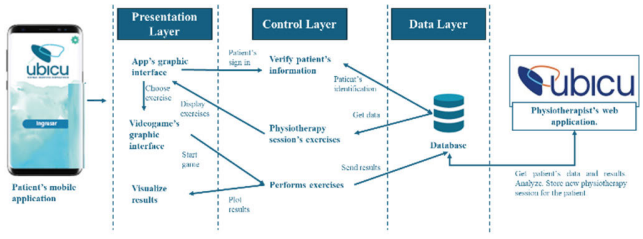

FIGURE 6. Logical architecture of video game for physiotherapy.

The web software, designed for physiotherapists, addresses four key requirements: (i) Register physiotherapists, (ii) Sign in as a physiotherapist, (iii) Enable or disable patient exercises, and (iv) Retrieve data from a selected exercise. We utilized MongoDB [31], a document-oriented, non-relational database that stores data in JSON format. This database is highly scalable, capable of managing large data volumes, and supporting high user concurrency—an essential feature for a product intended to serve a large population requiring home-based physiotherapy. The database is cloud-based and shared with the video game app. Fig. 7 shows the flow diagram of the web software, and Fig. 8 presents the complete system architecture.

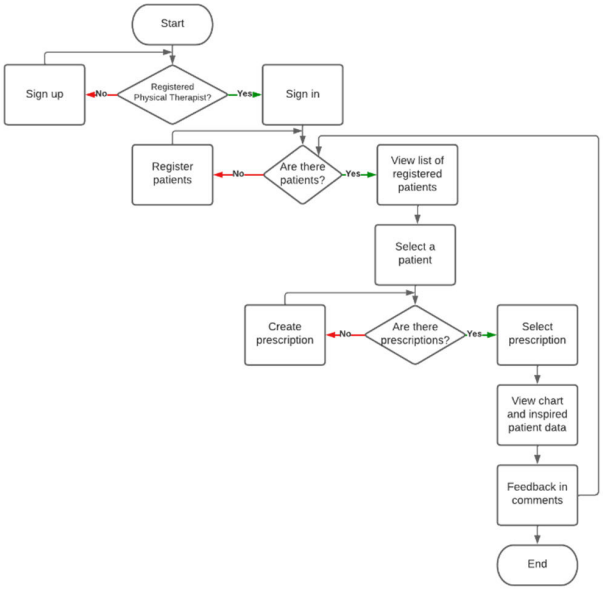

FIGURE 7. Flow diagram of UBICU's cloud component.

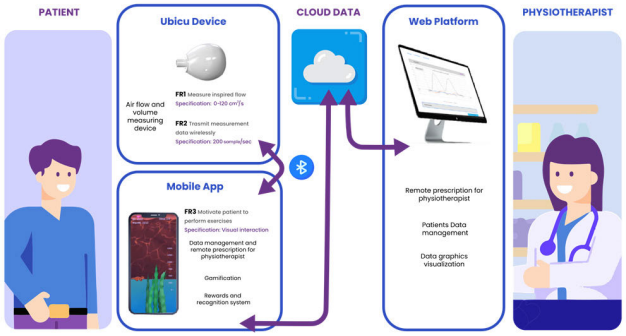

FIGURE 8. UBICU general architecture for assisting physiotherapy with a flow respiratory incentive spirometer using telehealth.

C. MATERIALIZATION OF THE PRODUCT

UBICU is an assistive product for re-expansion physiotherapy, incorporating a hardware system for flow measurement, data acquisition, reception, and transmission, along with gamified software to support physiotherapy. The system enables remote prescription and management of physiotherapy sessions (Fig. 9).

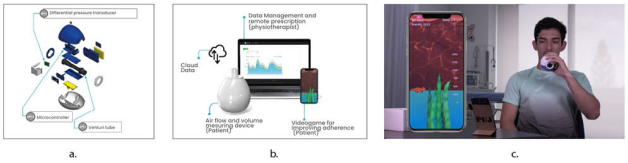

FIGURE 9. UBICU is an assistive product for re-expansion pulmonary physiotherapy: (a) Industrial design of the product; (b) Complete system for assisting pulmonary re-expansion; and (c) Use of UBICU.

D. VALIDATION THROUGH CLINICAL TRIALS USING PULMONARY TOMOGRAPHY AND USABILITY TESTING

We conducted a cross-sectional study to evaluate pulmonary ventilation distribution using Electrical Impedance Tomography (EIT) by comparing UBICU with TriFlo, a commercial flow RIS, in a sample of 30 healthy adults. The participants included 5 individuals aged 18 to 24, 7 aged 25 to 34, 5 aged 35 to 44, 6 aged 45 to 54, and 7 over 54 years old, with equal representation of males and females. All participants used both RISs, with the order of device assignment randomized. The study was approved by the Ethics Committee of Pontificia Universidad Javeriana Cali (Code 012-2021). Each participant provided informed consent, and to ensure anonymity and confidentiality, an alphanumeric code was assigned to each participant.

Each participant was instructed to breathe slowly at their tidal volume—the volume of air inhaled during a relaxed breath—for two minutes, with continuous monitoring via Electrical Impedance Tomography (EIT). As shown in Fig. 10, the first event, labeled 'T1,' was marked at the end of these two minutes. Re-expansion exercises were then initiated using the assigned RIS, with three series of 10 breaths each, separated by a one-minute break between series. At the end of the final series, the second event, 'T2,' was marked. Participants then resumed slow breathing for two minutes, and the third event, 'T3,' was marked during the final resting ventilation.

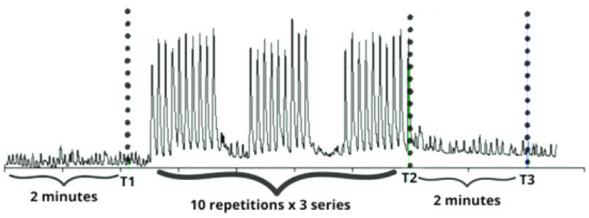

FIGURE 10. Measurement protocol: T1: initial resting ventilation; T2: re-expansion; and T3: final resting ventilation.

Each participant used both devices, and an increase in intrapulmonary volume (VT) was observed following their use. The study found that UBICU led to a significant volume gain, with the median impedance increasing from 2458 AU to 4950 AU (Fig. 11-a), indicating a statistically significant difference ($p = 0.01$). In contrast, TriFlo did not produce a significant volume gain, with a median impedance change

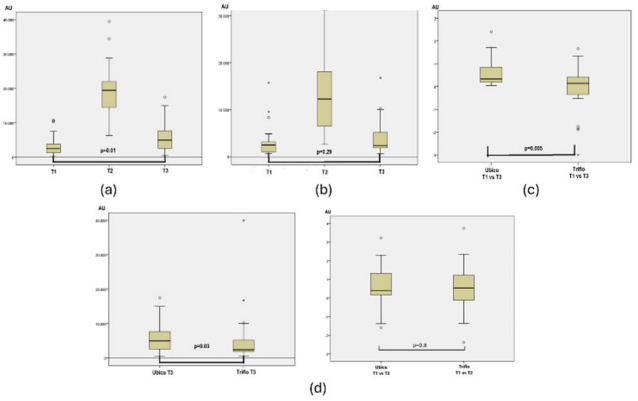

FIGURE 11. (a) Difference in VT, in the use of UBICU between T1: initial resting ventilation and T3: final resting ventilation; (b) Difference in VT, in TriFlo between T1: initial resting ventilation and T3: final resting ventilation; (c) Difference in ΔEELI between UBICU vs TRIFLO in T3: final resting ventilation; and (d) ΔEELI UBICU vs TRIFLO at times T1 vs T2 and T1 vs T3. T1: initial resting ventilation, T2: re-expansion, and T3: final resting ventilation. AU: arbitrary units of impedance.

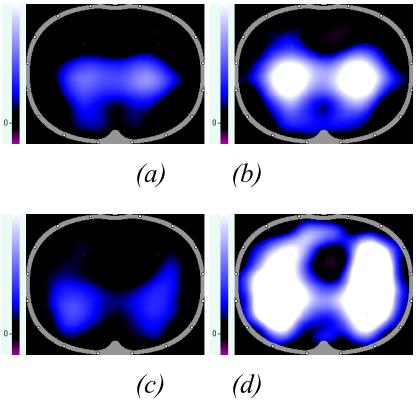

FIGURE 12. Pulmonary impedance tomography images of the same patient before and after the intervention with TriFlo and UBICU respiratory incentive spirometers. Upper image TriFlo: (a) before the intervention and (b) after the intervention. Lower image UBICU: (c) before the intervention and (d) after the intervention.

from 2511 AU to 2592 AU ($p = 0.29$) (Fig. 11-b). Additionally, when comparing VT values during and after the use of each RIS, a statistically significant difference was found between UBICU and TriFlo ($p = 0.03$) (Fig. 11-c).

When analyzing the change in End-Expiratory Lung Impedance (ΔEELI) between T1 and T2 with both RISs, results showed positive values for functional residual capacity, though without statistical significance ($p = 0.80$). However, a significant increase in functional residual capacity was observed when comparing T1 and T3, with a statistically significant difference ($p = 0.005$) (Fig. 11-d and Fig. 12). Functional residual capacity, the volume of air remaining in the lungs after a normal, passive exhalation, is a critical measure closely associated with pulmonary health [32].

We administered a questionnaire with ten questions to the 30 participants to measure the level of mastery, acceptance, adherence potential, and enjoyment of the game as a factor that contributes to the understanding of the physiotherapist's

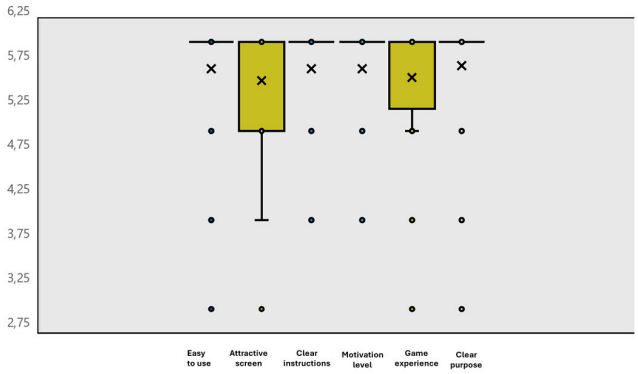

FIGURE 13. Results of patients' perception of software evaluation.

prescription and the exercise performed by the patient. These were the relevant questions: Q1. Ease of use of the application, from the moment you log in until the exercise ends. Q2. Game display or screens. Q3. Understanding the instructions and/or descriptions of the exercises. Q4. The level of motivation that the game gives me to perform physiotherapy. Q5. In-game experience. Q6. Understanding the purpose of the game. All questions were ranked from 1 (I did not like it at all) to 6 (I liked it a lot). There was one binary question: Was the information you saw in the game enough for you to understand how to use it during a session?

Finally, there were two open questions: What would you change to the application? What would you change to the device? Results show that the level of acceptance in aspects such as usability, screen design, instructions, experience, and understandability was greater than 5 on a scale of 1-6 (Fig. 13). Regarding the binary question, 29 participants believed the information provided was clear enough to play the game.

V. DISCUSSION

In this work, we developed UBICU, a respiratory incentive system designed to guide lung re-expansion exercises while enabling remote prescription and result analysis. This system offers significant benefits to patients by reducing the costs and time associated with visits to rehabilitation facilities, thereby supporting at-home recovery. For physiotherapists, UBICU expands service coverage through continuous follow-up and monitoring, facilitating decision-making with quantitative data. Additionally, it enables research based on previously acquired and stored patient data. Unlike current commercial devices [33], which function as real-time systems for patient feedback only, UBICU incorporates storage and communication capabilities for patient registration and interaction.

UBICU was developed through collaboration with professionals from the health, design, and engineering fields. This interdisciplinary approach leverages the unique processes, techniques, and tools of each discipline to better address patient needs. In this project, electronic technology measures and transmits inspiratory flow, design enhances patient-product interaction, and computing encourages patient adherence to treatment through gamified elements, promoting at-home recovery supported by telehealth software. Additionally, the involvement of health professionals enabled the creation of a tool for remotely prescribing physiotherapy, paired with a respiratory incentive spirometer (RIS) and a quantitative system to assess patient performance. Whereas current systems may address some of these aspects individually, no existing solution offers the level of integration proposed by UBICU.

UBICU provides physiotherapists with a technological tool for remotely prescribing and monitoring physiotherapy. The quantification of respiratory exercises enables physiotherapists to maintain a traceable digital record of the patient's exercises, assessing lung re-expansion with an RIS as part of the recovery process. This level of integration is not feasible with current mechanical systems that lack electronic support.

TriFlo, a flow-RIS, provides feedback to patients on their inspiratory activity with three reference marks at 600, 900, and 1200 cm^3/s, which physiotherapists prescribe as targets during exercise sessions. However, neither patients nor physiotherapists can accurately measure or track the flow levels achieved with TriFlo, as it lacks graduated markings and the capability to store flow data. In contrast, UBICU offers measurement accuracy exceeding 85% for flow rates above 500 cm^3/s (see Fig. 4), as the dynamic performance of the primary transducer is reduced at lower flow levels.

Additionally, UBICU allows for intermediate reference levels beyond the three markings provided by TriFlo. To support pulmonary rehabilitation therapy, UBICU enables a structured exercise regimen tailored to the physiotherapist's prescription, controlling the number of inspiratory repetitions, the interval between repetitions, the number of series, and the time lapse between series—all essential elements of pulmonary re-expansion physiotherapy. Furthermore, UBICU stores the patient's exercise history, allowing physiotherapists to monitor and assess progress over time.

The clinical study used methods from previous research in the scientific literature, incorporating EIT and re-expansion techniques [34], [35], [36]. The aim was to compare the performance of TriFlo and UBICU to determine whether UBICU functions similarly to TriFlo during re-expansion exercises, thereby validating its effectiveness as a flow respiratory incentive spirometer.

The study's findings indicate that UBICU achieves superior distribution and increases in intrapulmonary volume compared to TriFlo. This suggests that UBICU delivers appropriate and reliable outcomes for pulmonary re-expansion, making it a viable alternative to TriFlo. Moreover, UBICU offers enhanced features benefiting both patients and physiotherapists.

VI. CONCLUSION

The clinical study demonstrated that UBICU, with its low resistance to inspired airflow and visual feedback via the video game, enhances lung re-expansion compared to the

traditional TriFlo mechanical system, as evidenced through impedance tomography.

By integrating information and communication technologies, UBICU extends the reach of care services and reduces patients' travel time to medical centers. This enables physiotherapists to prescribe exercises and monitor patient progress remotely through cloud storage and communication technology.

UBICU improves user engagement during lung re-expansion exercises compared to current mechanical systems. The video game provides clear visual feedback on achieved flow levels, which is easy to interpret, thereby enhancing patient adherence to treatment.

VII. CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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