



The Effect of Thermocouple and Flex Sensors in Real-Time Biofeedback System for Voice Training or Therapy

Seong Hee Choi¹, Jong In Youn², Chul-Hee Choi^{1,3}

¹Department of Audiology & Speech Language Pathology, Catholic Hearing Voice Speech Center, and Research Institute of Biomimetic Sensory Control, Daegu Catholic University, Gyeongsan;

²Department of Biomedical Rehabilitation, Daegu Catholic University, Gyeongsan;

³CEO, Health TechPia Inc., Daegu, Republic of Korea

Purpose: This study investigated the feasibility and clinical relevance of a low-cost, wearable biofeedback system designed to monitor physiological signals related to respiration and phonation in real time.

Methods: In this study, a wearable biofeedback system consisting of a thermocouple sensor and a flex sensor was designed and developed, along with a real-time feedback interface. To evaluate the system's effectiveness, sensor data were collected from ten healthy adult participants during the performance of semi-occluded vocal tract exercises (SOVTE). The synchrony and consistency between phonation onset and abdominal motion were measured, along with the exhaled air volume and abdominal wall movement in response to variations in straw width and depth. Additionally, the effect of the water level and straw shape on the system's performance was analyzed, with temperature changes detected by the thermocouple sensor used to predict variations in exhaled air volume. The analysis also included an evaluation of user satisfaction.

Results: During phonatory tasks, the thermocouple consistently detected temperature increases ranging from 1.8°C to 5.2°C, validating its sensitivity to expiratory airflow. Larger-diameter straws (10 mm) were associated with greater temperature elevations than narrower ones (8 mm), suggesting a direct correlation with airflow resistance in water. Simultaneously, the flexible pressure sensors demonstrated stable, repeatable waveform patterns aligned with inhalation and exhalation cycles, allowing precise tracking of thoracoabdominal expansion. Real-time data visualization enabled intuitive feedback for users to self-monitor respiratory and phonatory dynamics during vocal exercises.

Conclusions: These findings support the potential utility of thermocouple and flex sensors as accessible, real-time monitoring tools for individualized voice training and therapeutic intervention.

Keywords: Biofeedback, Thermocouple sensor, Flexible pressure sensor, Respiration monitoring, Voice therapy, Real-time feedback, Wearable system



Received: February 18, 2025

Revision: March 10, 2025

Accepted: March 10, 2025

Correspondence:

Chul-Hee Choi

Department of Audiology & Speech Language Pathology, Catholic Hearing Voice Speech Center, and Research Institute of Biomimetic Sensory Control, Daegu Catholic University, 13 Hayang-ro, Hayang-eup, Gyeongsan 38430, Republic of Korea

Tel: +82-53-850-2541

Fax: +82-53-359-6780

E-mail: cchoi@cu.ac.kr

INTRODUCTION

Voice production is a multifaceted motor process that requires precise coordination between respiratory and phonatory subsystems. Adequate respiratory control provides the subglottal pressure necessary for initiating and sustaining phonation and directly

© 2025 The Korean Association of Speech-Language Pathologists

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

influencing vocal intensity, quality, and endurance [1]. Disruptions in respiratory-phonatory coordination—commonly observed in individuals with functional or organic voice disorders—can result in inefficient voice use, excessive vocal effort, and increased risk of vocal fatigue or strain. Therefore, optimizing this coordination is a foundational objective in voice therapy [2,3].

Conventional voice therapy approaches typically rely on auditory modeling, verbal instruction, and clinician-guided tactile cues to modify respiratory and phonatory behaviors. However, these methods often lack precision and depend heavily on the patient's ability to interpret internal kinesthetic signals, which are often diminished or distorted in voice-disordered individuals [4]. Consequently, many patients struggle to perceive or voluntarily regulate their breathing and phonation patterns without immediate and objective feedback.

Biofeedback has emerged as a valuable adjunct in voice therapy, offering real-time, external representations of physiological processes that are otherwise imperceptible. By increasing a patient's awareness of vocal behavior, biofeedback has been shown to enhance motor learning, facilitate accurate performance, and promote behavioral retention [5-7]. While prior studies have demonstrated the efficacy of biofeedback in areas such as pitch modulation, vocal intensity, and laryngeal muscle tension [8-10], its application to respiratory-phonatory coordination remains underdeveloped.

Recent advances in wearable sensing technologies now offer the potential to fill this gap. Thermocouple sensors can detect fluctuations in exhaled air temperature [11], providing indirect but reliable markers of airflow and phonatory timing. Flex sensors placed on the chest or abdomen can track thoracoabdominal expansion and contraction, allowing for real-time monitoring of respiratory movements [12,13]. The integration of these sensors into a biofeedback system enables real-time, multimodal visualization of both respiratory and phonatory behaviors during voice production, thereby offering a more comprehensive and actionable tool for voice therapy. One well-established therapeutic approach that benefits from biofeedback is semi-occluded vocal tract exercises (SOVTE). These techniques aim to optimize vocal tract impedance and glottal efficiency by partially closing the vocal tract at either the anterior or posterior end. Historically, lip trills and tongue trills have been employed, especially among singers and voice professionals [14]. More recently, straw phonation and tube exercises, including air- and water-based phonation methods such as LaxVox, have gained widespread

clinical use. These exercises manipulate oral pressure by generating resistance, which facilitates improved glottal closure, vocal fold vibration, and vocal tract tuning [7,15]. Particularly, water resistance tube phonation—which involves phonating through a straw or tube submerged in water—produces bubbling and pressure fluctuations that can enhance proprioceptive feedback. The effectiveness of this method is closely linked to two physical parameters: the depth of the tube below the water surface and the internal diameter of the tube [15]. These variables influence intraoral pressure and airflow resistance, thereby modulating the therapeutic load applied to the vocal mechanism. Accordingly, water resistance phonation has shown efficacy for both hyperfunctional and hypo-functional dysphonia, making it a versatile intervention across a wide range of clinical populations [16]. Despite these advances, a persistent challenge in voice therapy remains: how to monitor and quantify the physiological effects of exercises like SOVTE in real time. While acoustic or aerodynamic instrumentation exists in laboratory settings, their clinical accessibility is limited. There is growing demand for portable, low-cost biofeedback devices that can support both clinician-guided therapy and patient-driven self-training, including in home environments [7,13,17]. An ideal system would provide feedback not only on acoustic outcomes but also on respiratory behavior, oral airflow, and vocal tract engagement, all of which are critical during SOVTE and other direct voice training tasks. To address this need, previous work has introduced a water cup device equipped with pressure sensors to measure the effects of tube depth and diameter during water resistance phonation, offering visual biofeedback of bubbling dynamics [7]. Building upon this line of research, the present study aims to develop and evaluate a novel biofeedback system that integrates two wearable sensors: a thermocouple, used to detect exhaled air temperature changes within a straw during phonation, and a flex sensor, used to measure abdominal wall movement associated with diaphragmatic breathing. These sensor signals provide real-time feedback on two critical dimensions of voice production—respiration and phonation timing—and are designed to support self-monitoring, self-correction, and clinician-patient communication during therapeutic voice tasks. This study therefore contributes to the growing field of technology-enhanced voice rehabilitation by introducing a holistic, sensor-based biofeedback system that supports effective respiratory and phonatory control during voice therapy and training exercises, particularly those involving semi-occluded vocal tract techniques. With the aim of de-

veloping a holistic biofeedback model for voice therapy or training, this study investigated the effect of a thermocouple sensor measuring the temperature changes in the straw during exhalation and a flex sensor detecting the abdominal flexural changes induced by diaphragmatic breathing as an element of biofeedback system for voice training or therapy.

METHODS

Development of biofeedback system for voice therapy or training

This study aimed to evaluate the feasibility of a wearable, low-cost biofeedback system designed to monitor critical physiological subsystems involved in voice production—specifically, expiratory airflow, diaphragmatic respiratory movement, and vocal fold contact area—during phonation. The long-term goal of the system is to support voice therapy and training by providing real-time feedback for self-monitoring, self-evaluation, and self-correction (Figure 1). Due to limitations in project duration and funding, the present study focused on assessing the usability and signal fidelity of two components: a thermocouple sensor and a flexible pressure sensor. The electroglottography (EGG) subsystem was reserved for future development.

The biofeedback system comprises three integrated sensor modalities:

1. **Thermocouple Temperature Sensor:** A K-type thermocouple module (MAX6675, Maxim Integrated Inc., USA) was embedded in a phonation therapy straw to measure temperature changes in the exhaled air. Since exhalatory temperature fluctuations are proportional to pressure variations, this sensor functions as an indirect indicator of subglottal pressure and airflow dynamics during voice production. Its high sensitivity to thermal changes allows for real-time monitoring of phonatory effort without intrusive instrumentation.
2. **Flexible Thin-Film Pressure Sensor:** To assess diaphragmatic breathing, two flexible pressure sensors (SEN0293, Elec Solution Inc., Korea) were positioned bilaterally on the lateral abdominal wall. These regions expand and contract during respiration, enabling the detection of dynamic flexural changes associated with abdominal breathing. The sensors were mounted onto a semi-elastic belt (Model 09-657, Wondan Inc., Korea), which was selected based on its ability to maintain firm contact with the body while minimizing discomfort and movement artifacts. This configuration facilitated accurate measurement of respiratory patterns without restricting natural body motion during therapeutic exercises.
3. **EGG (Planned):** A third subsystem, not evaluated in the current phase due to temporal and financial constraints, consists of an EGG module designed to measure vocal fold

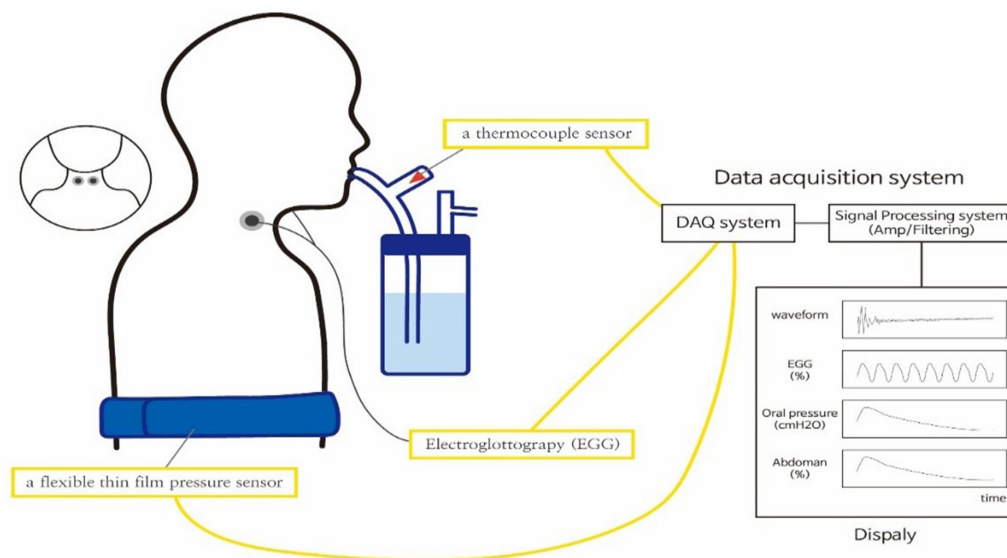


Figure 1. Schematic overview of the biofeedback system. The system integrates (1) a thermocouple sensor inserted into a phonation straw for detecting exhaled air temperature changes, (2) flexible thin-film pressure sensors for monitoring abdominal expansion during diaphragmatic breathing, and (3) an Arduino Uno microcontroller for real-time data acquisition and signal processing.

contact area by detecting impedance changes via electrodes placed on either side of the thyroid cartilage. This component will be integrated into future iterations to provide a complete, tri-modal biofeedback system covering phonatory initiation, respiratory support, and glottal closure.

The integrated design of the system enables a holistic view of voice production by linking biomechanical signals from the respiratory and phonatory subsystems. Real-time signal feedback is intended to assist both clinicians and patients in assessing and modifying performance during voice therapy sessions.

Data acquisition and processing

The thermocouple sensor was attached to the side of the straw through a small gap, allowing it to measure temperature variations. When flow phonation was applied at the straw's inlet, the flow rate was determined by the temperature difference. The principle underlying this method relies on the increase in exhaled volume and temperature generated during phonation within the straw. The flexible pressure sensor attached to the semi-elastic waist band was used to detect the abdominal changes associated with diaphragmatic breathing.

For real-time data acquisition, the thermocouple and flex pressure sensors were interfaced with an Arduino Uno microcontroller (ATmega328, Arduino Inc., Italy), which features a built-in 10-bit analog-to-digital converter (ADC) and is capable of efficient signal acquisition and processing (Figure 1). The Arduino board served as the central platform for sensor integration, enabling the collection, digitization, and transmission of physiological signals in a seamless manner (Figure. 2).

A custom program was developed to sample data from both sensors at 300 ms intervals, which was empirically determined to be sufficient for capturing the temporal dynamics of exhalatory airflow and abdominal motion during voice exercises. The flex sensor data reflected abdominal wall movement during diaphragmatic breathing, while the thermocouple readings corresponded to airflow-induced temperature fluctuations during phonation. These data streams were processed in real time by Arduino and transmitted to a personal computer via USB connection.

To facilitate immediate visualization and user-friendly monitoring, the PLX-DAQ (Parallax Data Acquisition) tool, integrated with Microsoft Excel (MS Office 365, Microsoft Corp., USA), was used as the primary data interface. This setup allowed for dynamic plotting of sensor outputs, enabling clinicians and participants to observe intraoral pressure changes and respiratory movement patterns during voice therapy tasks. The system thus provides a cost-effective and accessible platform for multimodal biofeedback in both clinical and home-based therapeutic contexts.

The figure illustrates the connectivity and signal flow between the biofeedback system components. The thermocouple sensor (K-type) embedded in the phonation straw and the flex pressure sensors attached to the semi-elastic waistband are interfaced with the Arduino Uno microcontroller (ATmega328), which performs analog-to-digital conversion and real-time data processing. Sensor data are transmitted via USB to a personal computer and visualized using the PLX-DAQ data acquisition platform integrated with Microsoft Excel, enabling real-time monitoring of temperature and respi-

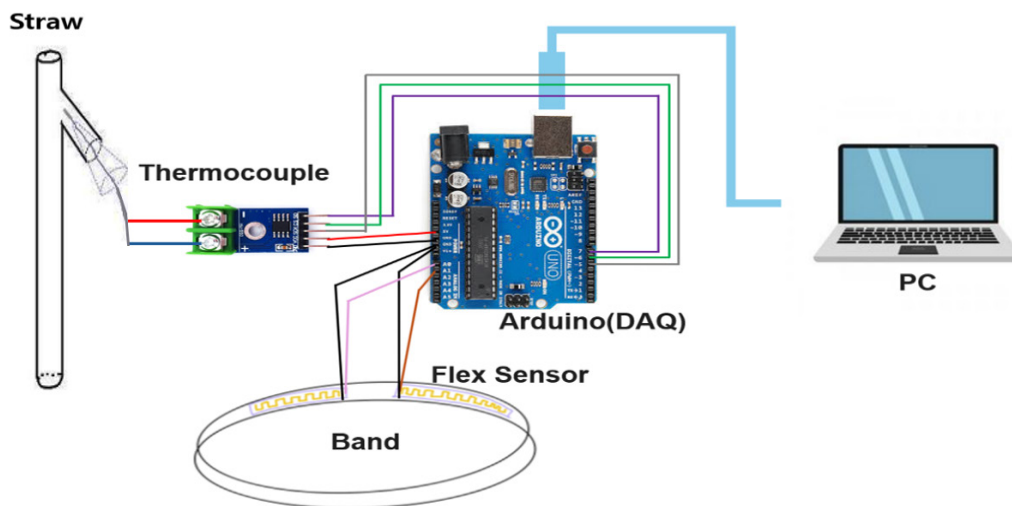


Figure 2. Diagram of the data acquisition system (Connection between sensors and PC).

ratory movement during voice tasks.

Procedures

The participants in this study were 10 healthy young adults (5 men and 5 women) aged between 21 and 27 years (mean age: 23.4 ± 1.8). Individuals with a history of voice complaints, laryngeal lesions, vocal disorders, recent upper airway infections, or any health issues that could affect phonation were excluded from the study [7].

Prior to the measurements, the examiner provided a detailed explanation of diaphragmatic breathing to the participants. The subjects were instructed to practice the diaphragmatic breathing technique as follows: "Breathe deeply through your nose and exhale slowly through your mouth. When inhaling through your nose, do so gently and slowly, and exhale slowly through your mouth, pushing the air from your stomach without raising your shoulders." Following this, the abdominal band with the attached flex sensor was worn by each participant. The examiner ensured that the flex sensor values changed appropriately during the breathing cycle, with the values increasing during inhalation and decreasing during exhalation.

With the abdominal band in place, the participants used straws of 8 mm and 10 mm diameters to measure Maximum Phonation Time (MPT) at two different straw depths (3 cm and 7 cm) submerged in a 500 mL plastic water bottle. The subjects were instructed to inhale fully through their nose after exhaling completely. During exhalation with sustained /u/ phonation, MPT measurements were taken using the 8 mm diameter straw at both 3 cm and 7 cm depths in the water. Subsequently, the same procedure was followed with the 10 mm diameter straw at the same two depths in the water bottle.

The effect of the thermocouple sensor on the amount of water in the water bottle and the width of the straw was measured twice. The amounts of water in the water bottle are 100, 200, and 300 mL and the widths of straw are 6, 8, 10 mm.

Statistics

The statistical package SPSS version 22.0 (Statistic Packages for Social Science; IBM Inc., Armonk, NY, USA) was used for data analysis. The maximum phonation time (MPT) of the straws of the different diameters (8 and 10 mm) inserted at two different depths (3 and 7 cm) in the plastic water bottle during phonation was analyzed by one-way repeated measure of ANOVA. The statistical significance was determined by *p* value of less than 0.5.

RESULTS

Sensor responsiveness and signal acquisition

The developed biofeedback system successfully captured synchronized physiological signals associated with respiration and phonation across all participants. The thermocouple sensor, integrated into the phonation therapy straw, consistently detected airflow-induced temperature changes during exhalation. On average, temperature increases of 1.8-5.2 °C were observed during sustained phonatory tasks, confirming the sensor's sensitivity to variations in expiratory airflow. Interestingly, straws with a larger internal diameter (10 mm) tended to produce greater temperature increases during phonation compared to narrower straws (8 mm), indicating higher expiratory airflow. Simultaneously, the flexible pressure sensors affixed to the lateral abdominal wall accurately tracked thoracoabdominal expansion and contraction during diaphragmatic breathing. The flex sensors exhibited stable and repeatable waveform patterns corresponding to inhalation and exhalation cycles, enabling real-time feedback on respiratory movement. A representative set of synchronized thermocouple and flex sensor signals during a sustained /u:/ phonation with bubbling task is shown in Figure 3, illustrating temporal coordination between the onset of airflow and abdominal expansion.

This figure demonstrates an example of real-time visualization of respiratory and phonatory data using the PLX-DAQ data acquisition tool. The user interface intuitively displays the real-time data flow, providing graphical representations of temperature variations and abdominal movements obtained from the sensors. The graphs show temperature fluctuations (indicative of expiratory pressure) and abdominal movements (associated with diaphragmatic breathing), recorded at 300 ms intervals. This setup allows the user to monitor and receive feedback on the physiological changes associated with respiration and phonation during voice exercises in real time.

Real-time visualization and usability

The data acquisition interface, developed using PLX-DAQ in Microsoft Excel, enabled real-time plotting of the temperature and flex sensor outputs. The visual feedback provided intuitive representations of intraoral pressure and respiratory movement, allowing users to monitor their performance during vocal exercises. The system operated without signal interruption or latency in all trials.

Informal feedback was obtained from 10 adult participants,

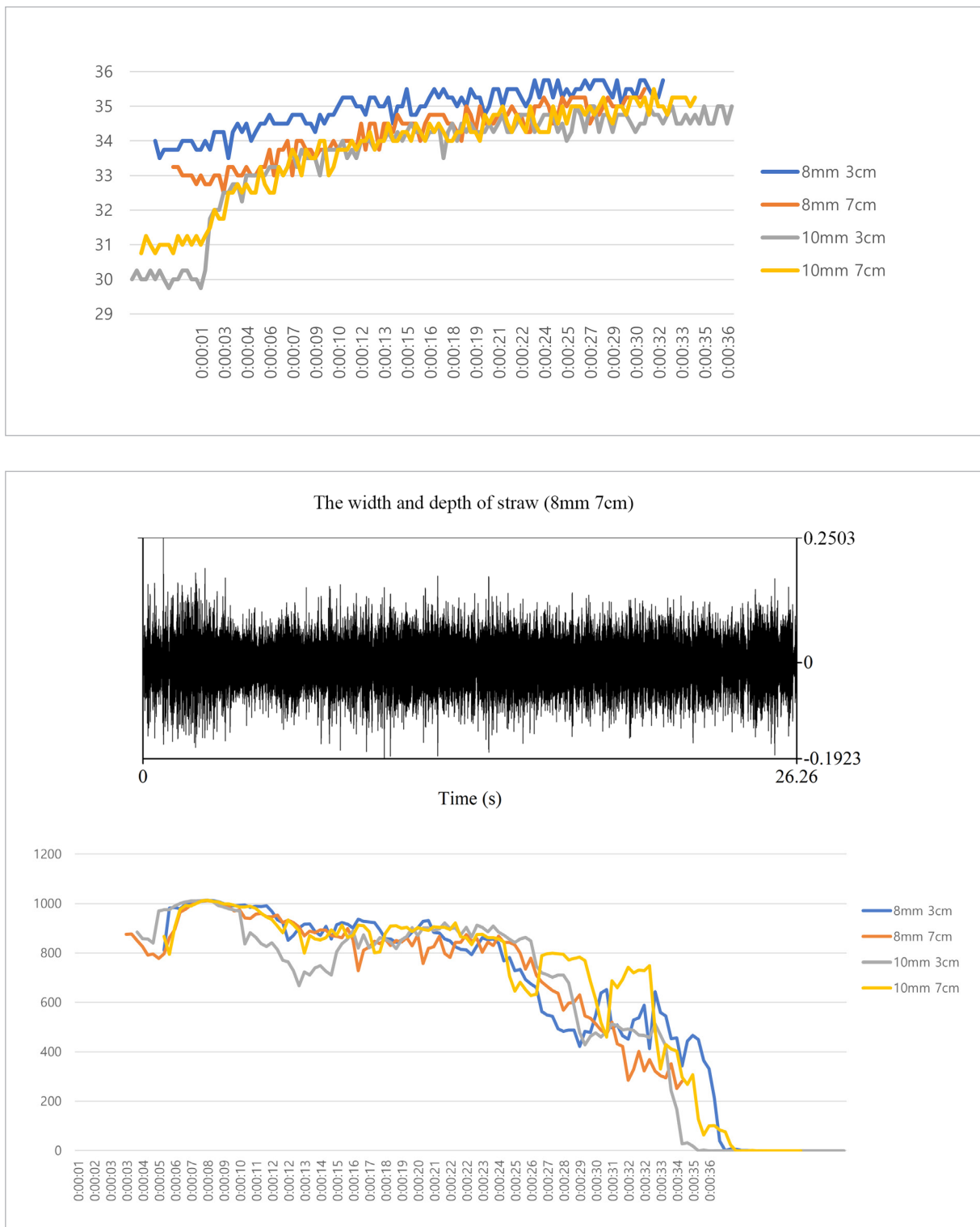


Figure 3. Onset of phonation and associated abdominal wall movement during sustained vowel /u/ production with bubbling. After full exhalation followed by deep inhalation, phonation was initiated with simultaneous activation of the abdominal musculature and temperature change.

all of whom reported that the biofeedback system was comfortable to wear, non-intrusive, and easy to interpret during exercises. The semi-elastic band provided sufficient stability for sensor placement while permitting natural movement, and no adverse effects or discomfort were reported.

Effect of straw dimensions and flex sensor on MPT

To investigate the impact of straw dimensions and the flex

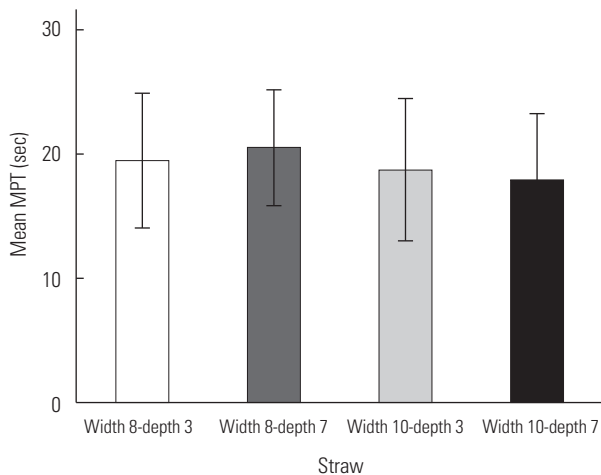


Figure 4. Mean Maximum Phonation Time (MPT) values measured using two different straw widths (8 and 10 mm) and insertion depths (3 and 7 cm) during water resistance phonation tasks.

sensor on MPT, different straw widths (8 mm and 10 mm) and depths (3 cm and 7 cm) were tested during phonation.

A one-way repeated measures ANOVA were conducted to examine the statistical significance of the variations in MPT based on straw dimensions. The analysis revealed no statistically significant differences in MPT across the different straw widths and depths ($F(3, 27) = 12.158, p = 0.338$).

Although no significant differences were found, some notable trends were observed. The shortest MPT occurred with the straw that had a width of 10 mm and a depth of 7 cm, while the longest MPT was observed with the straw that had a width of 8 mm and a depth of 7 cm (Figure 4). These results suggest that increasing the straw's width and depth may increase the water resistance, which, in turn, reduces the MPT during phonation.

Effect of water volume and straw shape on temperature response across different water volumes

As shown in Figure 5, when the water volume was 100 mL, the tree branch-shaped straw resulted in lower thermocouple temperatures and longer times to reach peak temperature across all straw diameters (6 mm, 8 mm, and 10 mm) compared to the inverted tree branch-shaped straw. Notably, in the inverted tree branch configuration, an increase in straw diameter led to a consistent rise in recorded temperature. In

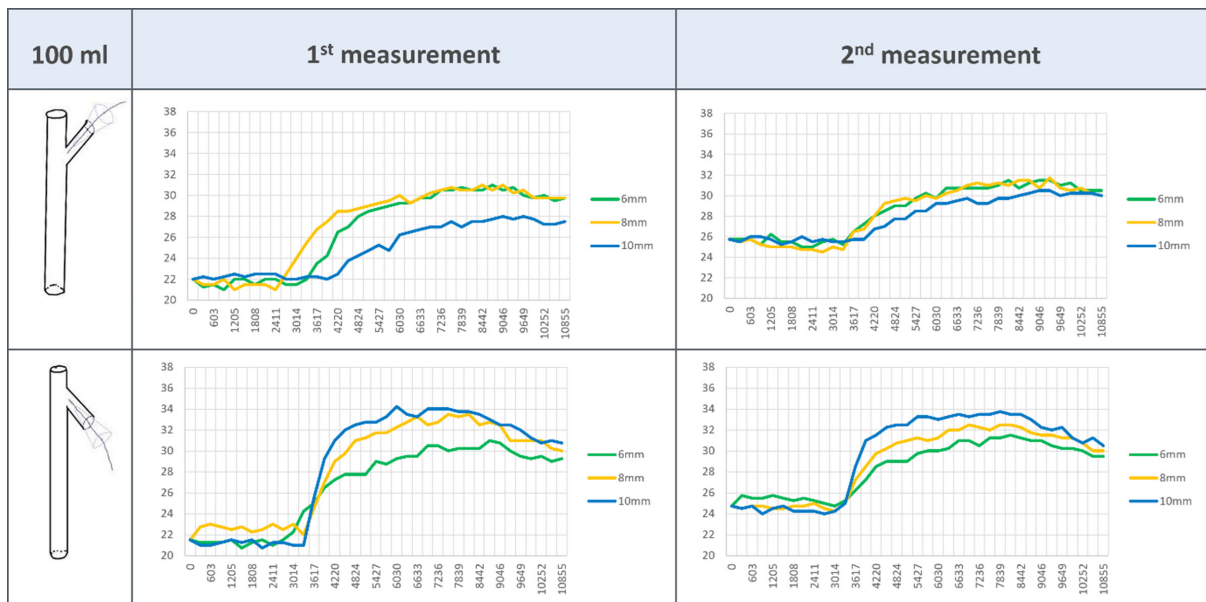


Figure 5. Two measurements of straws with tree branch and inverted tree branch shapes with different widths (6, 8, 10 mm) of the straw in the water bottle of 100 mL. In this figure, x and y axes indicates time (s) and temperature (°C), respectively. The shapes of straw in this study are tree branch (above) and inverted tree branch (below) shapes. The amounts of water in the water bottle are 100, 200, and 300 mL and the widths of straw are 6, 8, 10 mm.

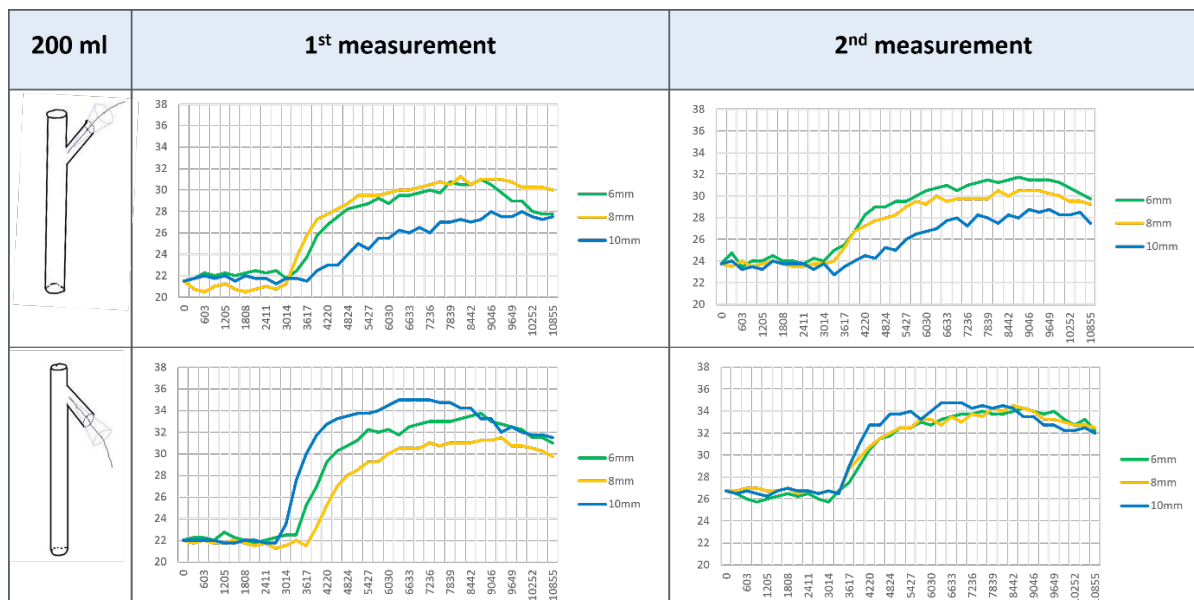


Figure 6. Two measurements of straws with tree branch and inverted tree branch shapes with different widths (6, 8, 10 mm) of the straw in the water bottle of 200 mL.

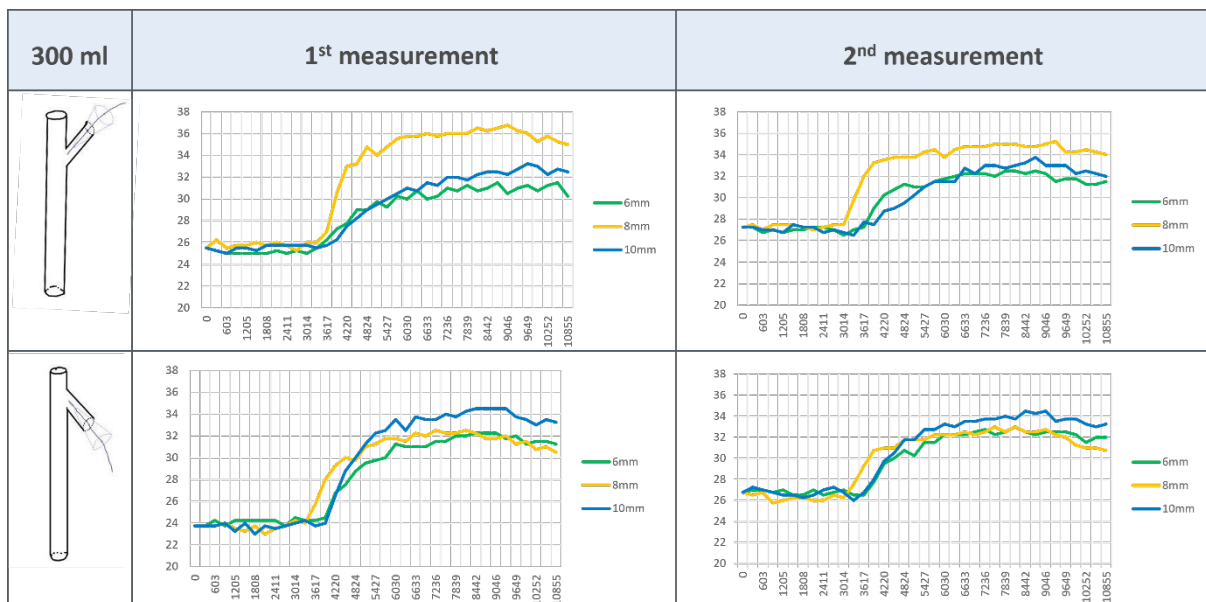


Figure 7. Two measurements of straws with tree branch and inverted tree branch shapes with different widths (6, 8, 10 mm) of the straw in the water bottle of 300 mL.

contrast, the tree branch configuration displayed no consistent relationship between straw width and temperature.

Figure 6 presents the results for a water volume of 200 mL. The trend was consistent with the 100 mL condition: the tree branch-shaped straw showed a lower peak temperature and longer time to reach peak compared to the inverted tree

branch shape for all straw widths. In the inverted tree branch shape, increasing straw width was again associated with a steady increase in temperature. However, in the tree branch shape, the temperature decreased or remained inconsistent with increasing straw diameter.

As illustrated in Figure 7, the results at 300 mL water volume

followed the same pattern. The tree branch-shaped straw consistently showed a delayed and lower temperature rise than that of the inverted tree branch-shaped straw for all tested diameters. The inverted tree branch shape maintained a stable positive relationship between increasing straw diameter and thermocouple temperature, whereas the tree branch shape showed irregular or even inverse responses.

Across all water volumes (100, 200, and 300 mL), the inverted tree branch-shaped straws demonstrated more stable and predictable thermal responses with increasing straw diameter. In contrast, the tree branch-shaped straws showed inconsistent or opposite trends. In addition to the thermal measurements, a practical advantage was observed: during phonation, users experienced no direct air flow to the face with the inverted tree branch shape, making it more comfortable and user-friendly for voice therapy.

DISCUSSIONS AND CONCLUSIONS

The findings of this study demonstrate the practical feasibility and potential clinical utility of a sensor-based biofeedback system designed to monitor and provide feedback on respiration and phonation coordination during voice therapy. By integrating a thermocouple sensor for airflow monitoring and a flex sensor for diaphragmatic movement, the system offers a non-invasive, real-time means of visualizing key subsystems involved in voice production.

Compared to conventional voice therapy approaches that rely primarily on verbal instruction or subjective clinician feedback, this system provides an objective, quantifiable means for patients to observe their own performance. This capability is particularly beneficial in SOVTE such as straw or tube phonation, where maintaining appropriate expiratory pressure and diaphragmatic control is critical. Real-time feedback can enhance proprioceptive awareness, support motor learning, and increase engagement in therapy, consistent with previous studies on the benefits of multimodal biofeedback in voice therapy or training [7-10,18].

Regarding the temperature change, the current study demonstrated larger-diameter straws (10 mm) were associated with greater temperature elevations than narrower ones (8 mm). These results suggest that in submerged phonation conditions, straws with larger internal diameters (e.g., 10 mm) produced greater temperature increases than narrower straws (8 mm). This is likely due to the higher volume of exhaled air passing through the straw, generating more pronounced ther-

mal variations detectable by the thermocouple sensor.

For measuring the effect of the thermocouple sensor, the widths of straw with either tree branch shape or inverted tree branch shape were changed from 6 to 10 mm in 2 mm step while the amounts of water in the water bottle with either tree branch shape or inverted tree branch shape were changed from 100 to 300 mL in 100 mL step. For measuring the effect of the flex sensor during phonation, the MPT was obtained with two different widths (8 and 10 mm) and different depths (3 and 7 cm) of straw.

In the water bottle of 100, 200, and 300 mL, the straw with inverted tree branch shape showed the higher temperature and shorter time to reach the highest temperature than the straw with tree branch shape at the different widths of straw (6, 8, 10 mm). When the widths of straw increased from 6 to 10 mm in the water bottle of 100, 200, and 300 mL, the temperature of thermocouple sensor in the straw with inverted tree branch shape increased consistently while the temperature in the straw with tree branch shape did not show similar results. In addition, the straws with the inverted tree branch shape showed ease of use because there was no air flow reaching on the face of the person who is blowing air in the straw with the inverted tree branch shape. The results of the MPT indicating the effect of flex sensor during phonation showed the longer MPT in the straw with wider widths and deeper depths and the shorter MPT in the straw with narrower widths and thinner depths. This indicates that the thermocouple and the flex sensors in the straw with inverted tree branch shape can provide clinically consistent and reliable results for voice therapy and training.

The effects of the widths and depths of straw in the water resistance phonation have already been verified in other studies [7,19-21]. The previous studies recommended tubes between 26 and 28 cm in length with a diameter of 9 mm for adults and between 24 and 26 cm in length with a diameter of 8 mm [21]. Another study recommended continuous phonation with tube ends submerged in 1 to 7 cm for LaxVox technique, 1 to 2 cm of water for the patients with hyperfunctional voice disorders, or tube ends submerged at a depth of 15 cm of water for the patients with insufficient vocal fold closure [19]. Measuring the amplification rate of the water level change in the three 35 cm-long silicone tubes with different diameters (5, 7, and 10 mm) immersed at four different water depths (2, 4, 7, and 10 cm), the amplification rate of the water level change ranged from 2.46 to 13.29%. When this study measured the temperature change by the thermocouple sen-

sor and the maximum phonation time by the flex sensor, this study confirmed that the narrower the tube diameter and the shallower the water depth, the lower the water resistance was. The only difference between our study and previous studies was the fact that our study used two different shapes of inverted tree branch and tree branch. With the straw with inverted tree branch shape, the above statement was true. The straws with inverted tree branch shape provide the ease of use, that there was no air flow reaching on the face of the person who is blowing air. Therefore, this study demonstrated that physical factors—including straw shape, diameter, and water volume—significantly influence the functional mechanism of voice training tools, as assessed by quantitative temperature measurements. Specifically, it identified aerodynamic differences associated with straw geometry (tree branch vs. inverted tree branch), which affected internal air-flow, pressure, and heat transfer. These findings may serve as foundational data for future research on vocal fold vibration and expiratory resistance.

Furthermore, the results provide a basis for optimizing the design of Lax Vox or straw phonation devices by identifying structural configurations that yield more stable and reproducible outcomes.

Clinically, the observation that straw diameter and water volume influence thermal responses suggests that these tools can potentially be customized based on individual patient characteristics such as phonatory strength or lung capacity. This highlights the potential of such devices to be adapted as personalized therapeutic tools in voice therapy.

Although there are some advantages in the development of the real-time biofeedback system for voice therapy and training, we should mention the efficiency and effectiveness of the thermocouple and flex sensors used in this study. When the current study used the thermocouple sensor, we assumed that the temperature changes provided by the sensor are proportional to the pressure changes of exhalation. Based on the assumption, the thermocouple sensor was connected to a voice therapy straw to measure exhalatory pressure during breathing exercises. If the temperature changes by the sensor are completely proportional to pressure changes, the thermocouple sensor measuring temperature variations caused by airflow during exhalation in real time showed consistent and reliable results compared to those of previous studies. However, since the thermocouple sensor is an indirect method measuring the pressure changes in the straw during exhalation, our study did not measure if there are some relationships

between the temperature change and the pressure change of the straws during exhalation. Therefore, some studies of the relationship in the near future should be performed.

There are some considerations in the use of the flex sensor to detect abdominal movements during diaphragmatic breathing. The sensor in this study is inserted at both sides of the waist band expanding and contracting during diaphragmatic breathing. The sensor was not perfectly attached to the entire waistband. This indicates that the flex sensor can perfectly not reflect the subtle and small changes in the abdominal breathing of the entire waistband. In addition, the semi-elastic band provides relatively accurate information about abdominal breathing. However, we were unable to provide various sizes of the semi-elastic band depending on the subject's waist size. Therefore, more accurate studies in the near future should be performed to solve the problems.

The abdominal movements during diaphragmatic breathing were detected using a flexible thin film pressure sensor. The placement of the sensors was optimized to the regions at both sides of the waist that expand and contract during breathing, ensuring real-time detection of flexural changes induced by diaphragmatic breathing. The semi-elastic band (09-657, Wondan Inc., Korea) was selected as diaphragmatic breathing measurement band, to which the sensors were attached for data acquisition. The semi-elastic band was deemed to be most suitable for measuring breathing, as it provided accurate data while minimizing discomfort for participants.

Furthermore, this study used the limited number of participants. Due to the limited numbers of the subjects, we were unable to provide clinical information of the normal and abnormal standards of the temperature detected by the thermocouple sensor and the abdominal movements during diaphragmatic breathing detected by the flex sensor. Particularly, we need to obtain more clinical data of the patients with hyperfunctional or hypofunctional voice disorders.

Finally, the long-term goal of this study was to develop a real-time biofeedback system providing self-monitoring or self-evaluating for patients with voice disorders. As we mentioned early, the total biofeedback system composed of three subsystems of the temperature changes connected to a phonation therapy straw which is proportional to the pressure change during breathing, a flexible thin film pressure sensors to measure the abdominal movements during diaphragmatic breathing, and an EGG to measure the changes of contact area of vocal fold through the electrode attached to the neck.

Of these three components, this study measured two components: the temperature changes detected by the thermocouple sensor and the abdominal movements detected by the flex sensor. Although the present study focused on validating the effectiveness of the thermocouple and flex sensors, future development will aim to integrate additional biosignal monitoring components such as sensors for vocal fold contact (e.g., electroglottography) and subglottic pressure sensors to enable more comprehensive and multidimensional monitoring of phonatory function. Furthermore, expanding the system for use in home-based self-training settings may support long-term voice maintenance and self-guided rehabilitation. We are expecting the development of a holistic biofeedback system for voice therapy and training in the near future.

In conclusion, the integration of real-time measurement tools such as a respiration belt with a flex sensor and a thermocouple-based oral pressure monitoring system into voice therapy protocols offers significant clinical implications. Monitoring abdominal wall movement during phonation provides direct feedback on the engagement and coordination of the respiratory subsystem, particularly diaphragmatic breathing. This is essential for patients with voice disorders, as inefficient or maladaptive breathing patterns—such as shallow thoracic breathing—are commonly associated with hyperfunctional phonation and vocal fatigue.

Furthermore, the application of a thermocouple sensor to indirectly assess intraoral pressure through temperature variation during water resistance phonation (e.g., LaxVox technique) offers a novel and objective approach to quantify phonatory effort. As pressure regulation is a critical aspect of effective voice production, especially in SOVTEs, real-time visualization of pressure-related temperature changes can aid in both diagnostic assessment and therapeutic biofeedback.

Clinically, these tools facilitate self-monitoring, self-regulation, and individualized training, which are crucial for improving treatment adherence and outcomes. For clinicians, these measurements provide quantifiable data to tailor intervention strategies, monitor progress, and document therapeutic efficacy over time. This is particularly valuable for populations with functional voice disorders, such as muscle tension dysphonia, or neurogenic conditions, where subtle respiratory-phonatory coordination issues may not be readily visible through perceptual assessment alone.

The combination of these sensors may thus contribute to the development of a comprehensive, sensor-based biofeedback system that enhances traditional voice therapy by incor-

porating real-time, patient-specific physiological data.

In conclusion, the developed biofeedback system effectively captured and visualized physiological signals related to respiration and phonation in real time. The system demonstrated high sensitivity, stability, and user comfort, making it a promising tool for voice therapy and training. Future studies with larger and more diverse participant groups are recommended to further validate the system's efficacy and explore its potential applications in clinical settings.

FUNDING

This study was supported by the 2024 Regional Innovation-based University Research Activity Support Program through Daegu Technopark (DGTP) funded by Daegu Metropolitan City, Republic of Korea.

REFERENCES

1. Titze IR. Principles of voice production. Prentice Hall. 1994.
2. Verdolini K, Ramig LO. Review: occupational risks for voice problems. *Logopedics Phoniatrics Vocology*. 2001;26:37-46.
3. Stemple JC, Glaze LE, Gerdeman B. Clinical voice pathology: theory and management. Plural Publishing. 2020.
4. Boone DR, McFarlane SC. The voice and voice therapy (9th ed.). Pearson Education. 2020.
5. Ma EPM, Yiu EML. The effects of self-controlled feedback on learning of a "relaxed phonation task". *Journal of Voice*. 2001;27:723-728.
6. Ziegler A, Dastolfo C, Hersan R. Perceptions of voice therapy from patients diagnosed with primary muscle tension dysphonia and benign mid-membranous vocal fold lesions. *Journal of Voice*. 2010;28:742-752.
7. Choi SH, Lim GB, Chae HR, Youn JI. Development and usability of biofeedback system for water resistance therapy using sensor. *Clinical Archives of Communication Disorders*. 2021;6:104-112.
8. Maryn Y, Bodt MD, Cauwenberge PV. Effects of biofeedback in phonatory disorders and phonatory performance: a systematic literature review. *Applied Psychophysiology & Biofeedback*. 2006;31:65-83.
9. Allen KD. EMG biofeedback treatment of dysphonias and related voice disorders. *The Journal of Speech and Language Pathology - Applied Behavior Analysis*. 2007;2:149-157.
10. Kirkpatrick A, McLester JR. Teaching lower laryngeal position with EMG biofeedback. *Journal of Singing*. 2012;68:253-260.
11. Marks MK, South M, Carter B. Measurement of respiratory rate and timing using a nasal thermocouple. *Journal of Clinical Monitoring*. 1995;11:159-164.
12. Malik S, Ahmad M, Punjiya M, Sadeqi A, Baghini MS, Sonkusale S. Respiration Monitoring Using a Flexible Paper-Based Capacitive

- Sensor. 2018 IEEE SENSORS, 2018;1-4.
13. Hussain T, Ullah S, Fernández-García R, Gil I. Wearable sensors for respiration monitoring: a Review. *Sensors (Basel)* 2023;23: 7518.
14. Titze IR. Voice training and therapy with a semi-occluded vocal tract: rationale and scientific underpinnings. *Journal of Speech - Language & Hearing Research*. 2006;49:448-459.
15. Stemple JC. A holistic approach to voice therapy. *Seminars in Speech & Language*, 2005;26:131-137.
16. Granqvist S, Simberg S, Hertegard S, Holmqvist S, Larsson H, Linderstad PA, et al. Resonance tube phonation in water: high-speed imaging, electroglottographic and oral pressure observations of vocal fold vibrations- a pilot study. *Logopedics Phoniatrics & Vocology*. 2015;40:113-121.
17. Giggins OM, Persson UM, Caulfield B. Biofeedback in rehabilitation. *Journal of NeuroEngineering and Rehabilitation*. 2013;10:60.
18. An JH, Choi SH, Lee K, Choi CH, Youn JI. Clinical applications of facial sensor biofeedback: implications for voice therapy or vocal training. *Communication Sciences & Disorders*. 2022;27:420-431.
19. Simberg S, Laine A. The resonance tube method in voice therapy: description and practical implementations. *Logopedics & Phoniatrics Vocology*. 2007;32:165-170.
20. Andrade PA, Wistbacka G, Larsson H, et al. The flow and pressure relationships in different tubes commonly used for semi-occluded vocal tract exercises. *Journal of Voice*. 2016;30:36-41.
21. Wistbacka G, Andrade PA, Simberg S, Hammarberg B, Södersten M, Švec JG, et al. Resonance tube phonation in water—the effect of tube diameter and water depth on back pressure and bubble characteristics at different airflows. *Journal of Voice*. 2018;32:126.e11-126.e22.