

Scientific Paper

The Utility of the TKEO Parameter in the assessment of thoracic respiratory movements

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Abstract

Introduction: Chronic obstructive pulmonary disease (COPD) and dysphonia are prevalent disorders associated with altered respiratory patterns, posing significant diagnostic and therapeutic challenges. Accurate and efficient assessment of thoracic respiratory movements is essential for individualized therapy and monitoring. The Teager-Kaiser Energy Operator (TKEO), originally developed for speech analysis, offers a single-parameter approach to evaluate both amplitude and frequency characteristics of biosignals. This study aimed to determine the utility of TKEO in assessing thoracic respiratory patterns in healthy individuals, COPD patients, and those with dysphonia.

Material and methods: Sixty-one participants were enrolled: 30 healthy controls, 16 with COPD, and 15 with dysphonia. Thoracic and abdominal respiratory movements were recorded using Respiratory Inductive Plethysmography (RIP) in both standing and seated positions. The TKEO parameter was calculated from the displacement signals, and its values were compared with conventional respiratory parameters (inspiratory and expiratory depths) obtained via RIP. Statistical analysis included the Kruskal-Wallis test and Spearman's rank correlation to assess group differences and parameter relationships.

Results: In the seated position, TKEO values and conventional respiratory parameters significantly differentiated between healthy subjects, COPD, and dysphonia groups ($p < 0.01$). Healthy and COPD subjects exhibited higher diaphragmatic activity, while dysphonia patients showed a dominant upper rib pattern. TKEO values closely paralleled traditional respiratory measures, with strong to very strong positive correlations observed across all groups and positions (Spearman's ρ , $p < 0.001$). In the standing position, group differences were less pronounced, but TKEO still reflected underlying respiratory patterns.

Conclusions: TKEO is a sensitive and efficient parameter for assessing thoracic respiratory movements, correlating strongly with established respiratory metrics. Its application may accelerate and refine the diagnosis of respiratory pattern disorders in clinical practice. Further research should explore TKEO's integration with artificial intelligence-based diagnostic tools and its utility in larger, age-matched cohorts.

Keywords: Teager-Kaiser Energy Operator (TKEO), Thoracic respiratory movements, Respiratory Inductive Plethysmography (RIP), COPD and dysphonia

Introduction

The rising prevalence of health conditions, coupled with an improved understanding of their aetiology, underscores the need for personalized therapies and, consequently, the development of precise and effective therapeutic techniques. Enhancing the diagnostic process is vital for therapy implementation, individualization, and monitoring. Within modern medicine, the advancement of diagnostic technologies allows

for an accurate evaluation of therapy, improves the probability of successful treatment, and as a result, becomes a crucial component in improving the quality of health care.

An example of such development in diagnostics is the Kaiser-Teager energy operator (TKEO). TKEO facilitates the estimation of a system's mechanical energy through the analysis of the displacement signal, allowing for the evaluation of both signal frequency and amplitude using a singular parameter.

Chronic obstructive pulmonary disease (COPD) and dysphonia are among the disorders that present a therapeutic challenge and a major social issue, due to their financial burden on healthcare systems. Patients with COPD often experience sudden exacerbations of the disease that require urgent medical intervention. These exacerbation episodes can lead to prolonged hospitalisations and higher healthcare costs¹.

Dysphonia, also commonly referred to as impaired voice production, has been reported to affect nearly one third of people². Voice disorders have a significant impact on society and patients' quality of life. Individuals with dysphonia may experience difficulties in managing daily activities and communicating which potentially leads to loss or limitation of professional opportunities³. Regardless of various etiologies of these conditions, a common component among these patients is the disturbance of respiratory patterns^{4,5}.

This study proposes Teager-Kaiser energy operator (TKEO) as a device for investigating thoracic respiratory movements in the context of these two conditions. TKEO was chosen for its capability to evaluate both the frequency and amplitude of

identify motion artifacts in real time. Compared to manual determination, it achieved 81.3% accuracy in artifact detection.

In 2022, Imirzalioglu conducted an analysis of seismocardiography in which the TKEO operator was used for quantitative assessment of the impact of respiration on heartbeats. This study demonstrated how physiological modulations affect the interaction between respiration and seismocardiogram morphology. Significant differences were detected between seismocardiographic responses induced by exhalation and inhalation, which were distinguished using the Teager-Kaiser energy operator¹⁴.

The aim of our study was to explore the use of TKEO in the evaluation of respiratory patterns.

Material

Sixty-one subjects were eligible for measurement, including: 30 healthy subjects, 16 subjects with diagnosed obstructive pulmonary disease and 15 subjects with dysphonia (**Table 1**).

Table 1. Characteristics of subjects qualified for the study (group size, gender and age).

Group name	Total number	Average age (in years)	Number of women	The percentage distribution of women	The average age of women (In years)	Number of men	The percentage distribution of men	Average age of men (in years)
Control group (healthy subjects)	30	25.1	14	47%	23.3	16	53%	26.7
Study group 1 (COPD)	16	67.8	3	19%	68.3	13	81%	67.6
Study group 2 (dysphonia)	15	56.4	6	40%	61.7	9	60%	52.9

signals using a single parameter. Its initial application was in speech analysis, which can be credited to the work of Hubert M. Teager and Shushan M. Teager nearly 4 decades ago⁶. At that time, the authors highlighted its use in speech analysis based on the audio signal, an application that remains effective to this day⁷. Another application related to speech function is the classification of speech disorders based on pathology type and its aetiology. This was demonstrated in the studies by Hammami et al., which classified psychogenic and laryngeal voice disorders⁸.

In the year 1990, Kaiser⁹ introduced an algorithm for calculating the energy operator and theoretical foundation for continuous and discrete signals. Currently the energy operator, also referred to as the Kaiser-Teager energy operator is widely applied in medicine. Shokouhyan et al.¹⁰ demonstrated that the TKEO technique could efficiently remove the electrocardiogram (ECG) and motion artifacts compared with the simple classical filtering approach. Long¹¹ proposed a blood glucose detection algorithm based on Teager-Kaiser. Zeng et al. proved the usefulness of TKEO in providing algorithm for the automatic detection of heart valve disorders¹². In 2017, Młynczak¹³ introduced a new method for detecting motion artefacts in impedance pneumography signals, commonly used for measuring respiratory activity. This method employs the Kaiser-Teager energy operator and accelerometer signals to

38 men took part in the survey, representing approximately 62% of all respondents, and 23 women, representing 38% of all people surveyed.

Due to significant differences between the control and study group, relevant to the present study, it was deemed necessary and reasonable to establish specific inclusion and exclusion criteria for each group. **Tables 2 and 3**.

Table 2. Inclusion criteria for groups: control and study 1 and 2.

Control group (healthy subjects)	Study group 1 (COPD)	Study group 2 (dysphonia)
Informed consent to participate in the study.		
Men and women.		
No use of psychoactive substances or psychotropic drugs.		
No chronic and frequent consumption of alcohol.		
Non smokers.	No known specific postural defects or other respiratory or vocal diseases.	
No known postural defects.	Diagnosed chronic obstructive pulmonary disease.	Diagnosed dysphonia.
No known respiratory diseases.	No current exacerbation of COPD.	No known COPD and other respiratory diseases.
No known vocal diseases.	No known COPD.	No surgeries in vocal tract.

Table 3. Exclusion criteria for groups: control and study 1 and 2

Control group	Study group 1 (COPD)	Study group 2 (dysphonia)
Lack of informed consent for participation in the study.		
Musculoskeletal disorders affecting body posture.		
Acute or chronic respiratory diseases that impair breathing and sound generation.		
Orthopedic contraindications (which may affect research outcomes, e.g., cervical dystonia, rib fractures, etc.).		
Nicotine dependence		
Individuals under the influence of psychoactive substances.		
Intellectual limitations of the participant that prevent them from making independent decisions and understanding the conducted research.		
Cold or active illness affecting the quality and outcome of the research.		

The study was approved by the Bioethics Committee, located at the Regional Chamber of Medicine in Krakow, with the reference 165/KBL/OIL/2018.

Methods

The Respiratory Inductive Plethysmograph (RIP) method and the Teager energy operator were used to evaluate thoracic respiratory movements.

The Kaiser-Teager energy operator (TKEO)

The operator was introduced as early as 40 years ago by Hubert M. Teager and Shushan M. Teager as a means used to analyse speech from an audio signal⁶. However, it was applied in the present study because of its ability to estimate the mechanical energy of a system through knowledge of the displacement signal.

Defining the TKEO operator is possible in a number of ways. In this study, the continuous form is used:

$$\psi(x) = \dot{x}(t)^2 - x(t) \cdot \ddot{x}(t)$$

In which:

- $x(t)$ is the displacement signal,
- $\dot{x}(t)$ is the first time derivative of the displacement signal (velocity),
- $\ddot{x}(t)$ is the second derivative after the time of the displacement signal (acceleration).

In our study, the signal representing the abdominal and thoracic tract tension was analysed in each case according to the schematic method shown in **Figure 1**.

The procedure involves calculating the first and second derivatives of the entire signal. Then the mathematical operations of product, difference and sum were performed according to the Energy Operator formula. In the final step, the average value of Energy Operator is calculated. The process consists of determining the TKEO for a signal in LabVIEW. Initially, the first and second derivatives of the signal are calculated. Following this, mathematical operations are applied, specifically computing the difference between the square of the first derivative and the product of the signal and its second derivative. The subsequent step involves calculating the average TKEO by summing the results of these mathematical operations and dividing by the number of samples. Finally, the procedure returns the arithmetic mean of the TKEO. This sequence operates automatically, without user interaction, allowing for continuous signal monitoring and TKEO calculation.

The detailed analysis of the respiratory pattern used parameters:

Av (average amplitude of local minimums = average expiratory depth),

Ap (average amplitude of local maximums = average inhalation depth),

Avp (average inter-peak value = average depth of breath),

Tv [s], (average expiratory time = mean duration of exhalation)

Tp [s], (average inspiratory time = mean duration of inhalation),

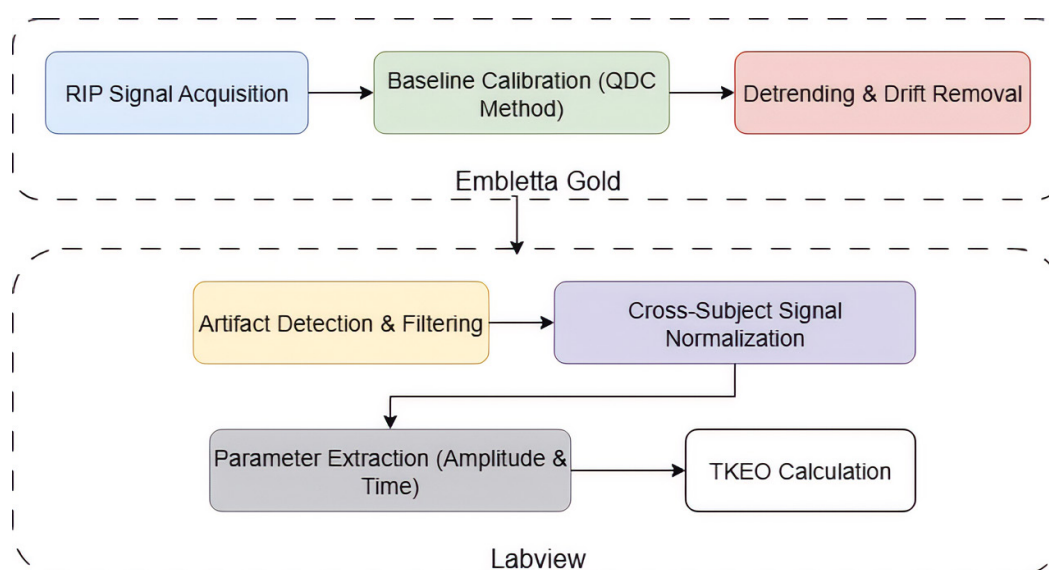


Figure 1. Data processing workflow for Kaiser-Teager Energy Operator (TKEO) analysis.

Tvp [s], (average breath period = total duration of respiratory cycle), TKEO - Teager Kaiser energy operator.

To verify the effectiveness of using the TKEO operator in assessing respiratory patterns, the results of obtained measurements were compared with those obtained using the Respiratory Inductive Plethysmograph system Embla Embletta Gold.

RIP technology

The Respiratory Inductive Plethysmograph (RIP) enables measurement of both frequency and amplitude of chest respiratory movements from two respiratory patterns: the thoracic (upper rib) pattern (Th) and the abdominal-diaphragmatic pattern (Ab). This is achieved using the XactTrace inductive method with the Embla Embletta Gold system. XactTrace sensors are placed on two respiratory effort belts (inductive bands) positioned according to the manufacturer's recommendations—under the armpits, at the level of the nipple line (Th), and approximately 3 cm above the navel (Ab) (**Figure 2**). Band tension is individually adjusted to fit snugly but without compressing the skin. Baseline calibration was performed using the Quantitative Diagnostic Calibration (QDC) method, involving 3–5 minutes of natural resting breathing in the measurement posture, to calculate a calibration coefficient by the least squares method. During signal processing, slow baseline drifts were removed by detrending, and signal segments with motion artifacts were filtered out. Signals were normalized across subjects to the mean tidal volume obtained during calibration to enable group comparisons. Although differences in body types and potential band displacement may affect volume accuracy, no significant distortions due to these factors were observed in this study. A diagram of the placement of the inductive bands along with the connected equipment is shown in **Figure 2**.

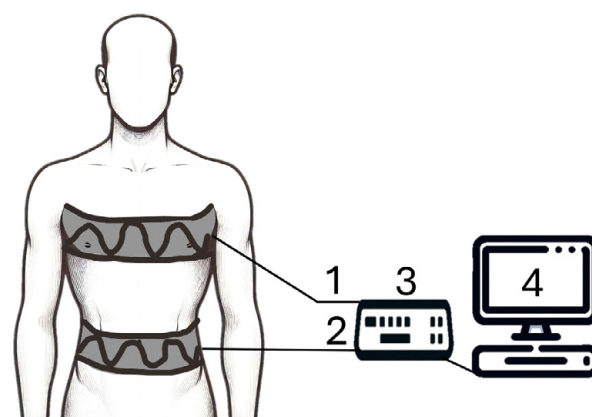


Figure 2. Induction tape layout diagram (1- induction tape for Th tract; 2- induction tape for Ab tract) with connection to equipment (3- Embletta Gold).

The test results were obtained during the measurements in the form of graphs, an example of which is shown in **Figure 3**.

Statistical methods

All statistical analyses were performed using non-parametric procedures due to deviations from normality in the respiratory parameters.

Between-group differences (healthy, dysphonia, COPD) were assessed separately for the free standing and free seated positions using the Kruskal-Wallis test. When a statistically significant effect was detected, post-hoc pairwise comparisons were conducted using Dunn's test with Bonferroni adjustment for multiple comparisons (overall $\alpha = 0.05$).

To assess the association between the TKEO parameter and respiratory measures, Spearman's rank correlation coefficients were calculated. Correlations were computed independently for the free-standing and free-seated positions.

Statistical significance was set at $p < 0.05$. All analyses were performed using IBM SPSS Statistics 25.

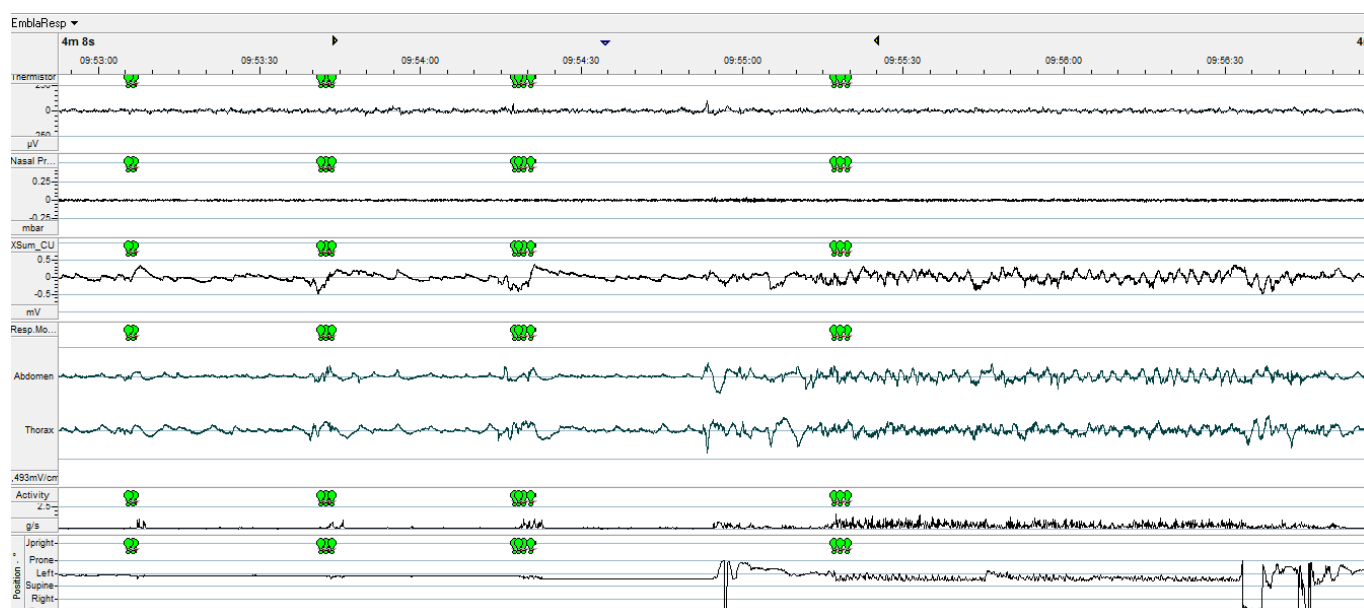


Figure 3. An example of a graph recording during a RIP measurement in the seated position.

Results

In order to analyze the accuracy of using the TKEO parameter for evaluating respiratory patterns, it was decided to compare its results with those obtained using the RIP method, specifically with breath depth (Av, Ap, Avp) and breathing time (Tv, Tp, Tvp) in the respective patterns. The analysis was conducted in two positions: standing and seated.

Free standing position

Table 4 provides the results of a study in which the average ranks for the three groups in the free standing position were compared: healthy people, people with dysphonia and people with chronic obstructive pulmonary disease (COPD). No statistically significant results were obtained in this context. However, it can be observed that in both healthy subjects and those with COPD, higher results were obtained for the diaphragmatic (Ab) tract, while for those with dysphonia in the upper rib (Th) tract. In all groups, TKEO scores were higher for the diaphragmatic tract, which, for the control group and those with COPD, coincides with the other results of the respiratory parameters. In people with dysphonia, the results were heterogeneous. This may indicate a mixed respiratory tract in these individuals.

Table 4. Respiratory pattern parameters in the free standing position.

Variable	Average rank			Significance level (p)
	Healthy subjects	Dysphonia	COPD	
Ab Av	27.90	30.93	35.27	0.408
Ab Ap	28.07	31.47	34.40	0.502
Ab Avp	28.00	31.07	34.93	0.450
Ab TKEO	27.33	32.47	34.87	0.347
Th Av	27.60	31.47	35.33	0.364
Th Ap	28.10	31.20	34.60	0.492
Th Avp	27.67	31.67	35.00	0.396
Th TKEO	27.47	29.27	37.80	0.165

Free seated position

Table 5 provides the results of a study in which the average ranks for the three groups in the free seated position were compared: healthy people, people with dysphonia and people with chronic obstructive pulmonary disease (COPD). In this context, statistically significant correlations were identified between the adopted position and the observed respiratory pattern.

Following significant post-hoc results were obtained: In the Ab tract, comparisons of values between the healthy - dysphonia and healthy - COPD groups appeared to be significantly statistical. The Ab Av value was significantly lower in the healthy group than in the dysphonia group ($p = 0.002$) and than in the COPD group ($p < 0.000$); the Ab Ap value was significantly lower in the healthy group than in the dysphonia group ($p = 0.002$) and than in the COPD group ($p < 0.000$);

Table 5. Respiratory patterns parameters in the free seated position

Variable	Average rank			Significance level (p)
	Healthy subjects	Dysphonia	COPD	
Ab Av	19.00	38.13	45.87	0.000
Ab Ap	19.17	38.07	45.60	0.000
Ab Avp	19.07	38.00	45.87	0.000
Ab TKEO	19.27	38.33	45.13	0.000
Th Av	21.77	30.53	47.93	0.000
Th Ap	23.40	28.53	46.67	0.000
Th Avp	22.50	29.40	47.60	0.000
Th TKEO	23.97	27.00	47.07	0.000

Ab Avp was significantly lower in the healthy group than in the dysphonia group ($p = 0.002$) and than in the COPD group ($p < 0.000$); Ab TKEO was significantly lower in the healthy group than in the dysphonia group ($p = 0.002$) and than in the COPD group ($p < 0.000$). In Th Av, comparisons were statistically significant between the healthy-COPD and the dysphonia-COPD groups. Th Av value was significantly higher in the COPD group than in the healthy group ($p < 0.001$) and than in the dysphonia group ($p = 0.019$); Th Ap value was significantly higher in the COPD group than in the healthy group ($p < 0.001$) and than in the dysphonia group ($p = 0.013$); Th Avp was significantly higher in the COPD group than in the healthy group ($p < 0.001$) and than in the dysphonia group ($p = 0.013$); Th TKEO was significantly higher in the COPD group than in the healthy group ($p < 0.001$) and than in the dysphonia group ($p = 0.005$).

In all groups, a shift in the dominant respiratory pattern was observed when transitioning to the standing position. Both the control group and individuals with COPD exhibited a more active diaphragmatic pattern in this posture, while the upper rib pattern was dominant in those with dysphonia. In all cases, the TKEO parameter results (higher scores) aligned with those of other respiratory parameters (inspiratory depth, expiratory depth, and overall respiration). All results were statistically significant.

Spearman's rank correlation coefficients between TKEO and other respiratory parameters are presented in **Tables 6 and 7**.

Statistically significant results were obtained between the TKEO associated with a specific pattern and other respiratory parameters within that same pattern. All statistically significant correlations were positive, indicating that as one parameter increased, the corresponding parameter also increased. The remaining correlations were found to be statistically insignificant.

In terms of the free standing upright position for statistically significant results, the correlations were very strong in the group of healthy people in the abdominal tract and strong correlations in the rib tract; in the group of people with dysphonia in both tracts, the correlations were very strong; in the COPD group, the correlations were very strong between Th. Av and Th. TKEO and strong between Th. Ap, Th. Avp and Th. TKEO.

Table 6. Spearman's ρ coefficients between selected parameters in the free standing position

Variable	Healthy		Dysphonia		COPD	
	Ab. TKEO	Th. TKEO	Ab. TKEO	Th. TKEO	Ab. TKEO	Th. TKEO
Ab. Av	0.92**	0.02	0.96**	0.11	0.98**	-0.03
Ab. Ap	0.94**	-0.01	0.98**	0.06	0.98**	-0.01
Ab. Avp	0.93**	0.01	0.97**	0.05	0.98**	-0.03
Ab. TKEO	-	0.03	-	0.06	-	-0.03
Th. Av	-0.08	0.80**	-0.05	0.91**	0.00	0.91**
Th. Ap	-0.15	0.80**	0.00	0.92**	-0.05	0.83**
Th. Avp	-0.12	0.79**	-0.07	0.91**	-0.04	0.88**
Th. TKEO	0.03	-	0.06	-	-0.03	-

** - Correlation is statistically significant at $p < 0.001$

Table 7. Spearman's ρ coefficients between selected parameters in the free seated position

Variable	Healthy		Dysphonia		COPD	
	Ab. TKEO	Th. TKEO	Ab. TKEO	Th. TKEO	Ab. TKEO	Th. TKEO
Ab. Av	0.94**	0.19	0.97**	0.11	0.96**	-0.13
Ab. Ap	0.94**	0.22	0.98**	0.14	0.97**	-0.10
Ab. Avp	0.95**	0.24	0.97**	0.11	0.96**	-0.15
Ab. TKEO	-	0.31	-	0.07	-	-0.10
Th. Av	0.23	0.90**	0.08	0.96**	0.02	0.92**
Th. Ap	0.20	0.90**	0.09	0.96**	0.07	0.88**
Th. Avp	0.21	0.91**	0.10	0.96**	0.02	0.90**
Th. TKEO	0.31	-	0.07	-	-0.10	-

** - Correlation is statistically significant at $p < 0.001$

For the free seated position, statistically significant correlations between TKEO and other respiratory parameters in the same trajectory were very strong for all groups, except for one correlation in the COPD group where the correlation between Th. Ap and Th. TKEO was strong.

Discussion

The diagnosis of respiratory dysfunction involves assessing the patient's symptoms using available questionnaires and analyzing the respiratory pattern through measuring devices or direct observation and palpation¹⁵. In pursuit of patient welfare, the most objective, accurate, and rapid methods of examination continue to be sought.

Teager-Keiser energy operator (TKEO) has found its application in the assessment of numerous clinical events and manifestations^{7,11,16}. In physiotherapy diagnostics, especially in the context of respiratory function assessment, a precise instrument for analyzing thoracic respiratory movements is crucial. The ability to evaluate signal parameters by one operator not only increases the effectiveness of the analysis, but also enhances its accuracy, which is essential for monitoring therapeutic progress and making informed clinical decisions.

To conduct the chest mobility measurements, inductive plethysmography was employed, using the Embletta Gold

Embla equipment. This device was initially designed to diagnose breathing disorders during sleep, with the option for home use. This intended purpose and method of use forced the need to simplify the operation of the equipment, ensuring its use is easy and intuitive¹⁷. Additionally, the device is multipurpose which allows for a wide range of applications, enabling it to be used both for sleep apnea analysis and for monitoring respiratory rate. For these reasons along with the objectivity of its measures, its availability and its mobility due to its compact size, this device was chosen for use in this study. Another advantage of this system is that Embletta's technology, which utilizes respiratory inductive plethysmography (RIP), aligns with the recommendations of the American Academy of Sleep Medicine (AASM)¹⁸. This method is often used in scientific research, which indicates its high methodological value. Its utility has been demonstrated, among others, in a study by Courtney et al. where measurements from the upper rib and diaphragmatic breathing paths were analysed in the seated position¹⁹. The effectiveness of using the RIP system in Embletta technology for respiratory rate analysis has also been demonstrated in studies, including those by Iles et al.²⁰, Duran-Cantolla et al.¹⁸, Droiticour et al.²¹.

Our research has shown that by using RIP technology, the patient's respiratory movements can be precisely monitored and recorded. This technology, based on respiratory impedance, allows accurate tracking of changes in thoracic and abdominal volumes associated with breathing, which is crucial for further analysis. Based on the recorded time signals, it was possible to calculate the signal energy (TKEO) for both the diaphragmatic and upper-rib pathways, allowing for a more detailed evaluation of the respiratory pattern and diagnostics of possible respiratory disorders.

Previous studies have found that even brief changes in posture can significantly impact variables that characterize breathing. Given that we spend the majority of our time either standing or sitting, our study incorporated measurements in both positions, maintaining a neutral and unforced posture.

The findings we obtained validate the effectiveness of the Teager-Kaiser Energy Operator (TKEO) in the analysis of thoracic respiratory movements, particularly in the context of diagnosing patients with chronic obstructive pulmonary disease (COPD) and dysphonia. The TKEO has proven to be highly sensitive instrument in assessing both the amplitude and frequency of respiratory patterns, allowing precise monitoring of respiratory dynamics. In healthy subjects and patients with COPD, increased diaphragmatic tract activity was observed in the standing position, potentially indicating superior control of respiratory mechanics in this group. In comparison, the upper rib tract was predominant in subjects with dysphonia, suggest-

ing possible impairment in diaphragmatic control. The statistically significant positive correlations between TKEO and other respiratory parameters indicate that an increase in one parameter corresponded to an increase in the other. In the healthy group, these correlations were very strong in the abdominal tract and strong in the ribcage tract. Similarly, in the dysphonia and COPD groups, the correlations were also very strong, underscoring the reliability of TKEO in these populations.

Our results partially align with those reported by Młyńczak and Cybulski¹³. The differences may be attributed to the use of a different type of electrodes and their placement (chest and arm), as well as the method employed (impedance pneumography). In their study, they also utilized electrode readings to obtain amplitude and frequency data. Subsequently, they applied the TKEO scheme as a nonlinear operator to measure instantaneous changes in the energy of signals composed of a single frequency that varies over time. When using TKEO, they obtained 81.3 percent accuracy (80.9 percent sensitivity and 81.6 percent specificity) compared to manual tagging, i.e. based on the comparison of operator and accelerometer signals. This demonstrates the high reliability of TKEO as a method in the analysis of respiratory movements. However, in contrast to our study, they only analysed the supine position and the imitation of body position changes during sleep¹³.

Notably, Młyńczak and Cybulski¹³ also highlighted that analysis with TKEO allows for real-time monitoring of changes in respiratory signal characteristics. This is extremely important in the context of rapid diagnosis and monitoring the efficacy of therapy. The results of our study suggest that TKEO may be useful in personalizing therapy, particularly for patients requiring rapid and accurate assessment of respiratory function. The application of TKEO in the analysis of chest respiratory patterns not only accelerates diagnostics but also allows for more precise monitoring of the patient's condition. Further research could focus on comparing TKEO with other diagnostic techniques and extending the study to other patient groups. It should be initiated with manual analysis of respiratory signals by the experts. Based on their assessments, thresholds of TKEO values could be set to serve as diagnostic indicators. This approach offers promising possibilities for increasing efficiency and precision in the diagnosis of respiratory diseases.

Conclusions

While the present study focused on the potential of TKEO for respiratory assessment, it should be noted that conventional

approaches such as spectral analysis and cycle-based parameters (e.g., breath-by-breath timing and amplitude measures) are commonly used in both clinical and research contexts. Compared with these techniques, TKEO offers the advantage of condensing both amplitude and frequency information into a single parameter, which simplifies analysis and may facilitate continuous monitoring. At the same time, TKEO does not replace conventional methods but rather complements them. Spectral analysis provides detailed frequency-domain information, while cycle-based metrics allow for direct clinical interpretation of inspiratory and expiratory phases. Future studies should therefore include direct comparisons between TKEO and these established approaches to better delineate the specific strengths and possible limitations of the method.

Limitations

It is necessary to point out certain limitations of the presented research. The first is the small size of the study population. In future, the measurements should be repeated and on a larger number of people. Another limitation is the significant age differences of the respondents between different groups. It seems reasonable to gather age-matched groups in the next phase of research to eliminate the influence of age and aging processes on the characteristics studied. Another limitation is that the study did not directly compare TKEO with conventional respiratory assessment methods such as spectral analysis or cycle-based parameters. Such comparisons would be valuable for clarifying the added diagnostic value of TKEO. While TKEO demonstrates particular sensitivity to transients and offers continuous, single-parameter monitoring of both amplitude and frequency, conventional techniques like spectral analysis and cycle-based approaches retain established strengths in specific domains. Spectral analysis excels in providing long-term frequency information but can miss rapid changes, whereas cycle-based methods supply widely recognized, standardized clinical metrics but may overlook short-lived disturbances. TKEO is more responsive to artifact detection and rapid pattern shifts, yet its heightened sensitivity can make it prone to noise and necessitate robust preprocessing. As summarized in the **table 8**, each method presents distinct advantages and limitations, indicating that hybrid approaches or explicit comparisons could further inform clinical diagnostics and support optimal method selection for specific applications.

Table 8. Comparison of respiratory signal assessment methods: main advantages, limitations, and recommended applications

Method	Strengths	Limitations	Recommended Use
TKEO	Sensitive to transients	Sensitive to noise	Artifact detection, rapid transient analysis
Spectral Analysis	Long-term frequency	Misses short	Stable signal monitoring
Cycle-Based Parameters	Standard clinical metrics	May overlook rapid events	Periodically stable signals

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