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Research Article

Oscillometric Markers of Knee-Shaped Expiratory Loops in Children with Recurrent Respiratory Symptoms

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Abstract

Background: The "knee pattern" is a recognizable convex inflection in the expiratory limb of the flow-volume curve, often associated with variable central airway obstruction, sometimes illustrated as a normal variant, but also described in children with asthma, raising questions about its clinical relevance.

Objective: To evaluate whether within-breath oscillometric parameters, particularly the standardized resistance shift (ΔsR), can identify knee-pattern morphology in children with recurrent respiratory symptoms.

Methods: Ninety children (mean age 11.9 ± 3.2 years) underwent spirometry and 8 Hz oscillometry; 27 displayed knee-shaped loops, while 63 served as controls. Inspiratory and expiratory resistance and reactance were measured, with differences expressed as ΔR, ΔX, ΔsR and ΔsX.

Results: Children with the knee pattern had fewer asthma diagnoses and less parental smoking exposure, but more exacerbations and greater use of corticosteroids and antibiotics. Compared to controls, they showed higher FEV_1/FVC ratios, elevated ΔR and ΔsR and reduced bronchodilator responsiveness. Logistic regression identified ΔsR, absence of asthma diagnosis and corticosteroid use as independent predictors. ROC analysis of ΔsR yielded an AUC of 0.73, with a threshold of 0.69 providing high specificity (96.8%).

Conclusion: ΔsR distinguished knee-shaped expiratory loops and may complement visual inspection by improving diagnostic confidence. Its link with exacerbations and treatment use suggests potential value as a marker of recurrent respiratory morbidity in children.

Keywords: Knee Pattern; Pediatric Spirometry; Oscillometry; Central Airway Obstruction; Asthma, Δsr; Tracheomalacia; Bronchodilator Response; Flow-Volume Loop Morphology; Within-Breath Impedance

Abbreviations

R: Respiratory resistance; X: Respiratory reactance; FEV1: Forced Expiratory Volume in 1 second; FVC: Forced Vital Capacity; BMI: Body Mass Index; SDB: Sleep-Disordered Breathing; GER: Gastroesophageal Reflux; ICs: Inhaled Corticosteroids; SABA/LABA: Short/Long-Acting Β-Agonist; COPD: Chronic Obstructive Pulmonary Disease; CAO: Central Airway Obstruction; ROC: Receiver Operating Characteristic; AUC: Area Under Curve; ANOVA: Analysis of Variance

Introduction

The "knee pattern" is a recognized, though frequently misinterpreted, convex inflection in the expiratory limb of the flow-volume curve [1-3]. This long-recognized morphology is thought to reflect maximal expiratory flow limitation within the intrathoracic upper airways [4-6]. It typically consists of a horizontal or downward-sloping linear segment, sometimes following an initial peak, culminating in a convex inflection attributed to elastic lung recoil. This linear portion is believed to coincide with the onset of a "choke point" in major intrathoracic airways, most often at high lung volumes [4]. The pattern becomes more pronounced during spirometry performed with neck flexion in adults [5]. As the lungs empty, diminished interdependence among airway segments may lead to multiple choke points in peripheral branches, producing the steep flow decline characteristic of the "knee" morphology [4].

The prevalence of this pattern remains uncertain. Studies in young adults report a high prevalence, approaching two-thirds of individuals by age 18, more commonly in females and declining with age, whereas a large pediatric study (n = 1,950) observed a markedly lower rate of just 5.9% [7,8]. This variability likely reflects both population differences and the inherent challenges of visually identifying subtle expiratory loop features. Its clinical significance remains debated. Some authors regard the knee pattern as a normal variant and even international guidelines have illustrated knee-shaped curves as "normal" [1,3,9]. Angular expiratory loops have also been described in patients with asthma [7].

Nonetheless, several studies have linked the knee pattern to variable central airway obstruction, particularly tracheomalacia [8,10,11]. In an Australian pediatric cohort with chronic respiratory symptoms and knee-shaped spirometry, bronchoscopy revealed tracheomalacia in 65.4% of cases [8], defined as a reduction >50% in tracheal cross-sectional area during tidal expiration [12]. These children typically exhibited a brief expiratory peak, followed by a plateau and a steep flow-drop-hallmarks of the knee pattern [8]. The plateau may reflect the abrupt collapse of malacic upper airways, while the knee likely results from rapid, recoil-driven emptying during the effort-independent phase of expiration.

This behavior may be quantifiable during quiet breathing using oscillometry, particularly through measurements of inspiratory and expiratory resistance (Ri and Re, respectively) [13]. Their difference, ΔR (Re − Ri), may serve as a mechanical signature of expiratory collapse. We hypothesize that ΔR is significantly elevated in children exhibiting knee-shaped spirometry compared to those whose expiratory curves lack this angular morphology.

The primary objective of this study is to compare oscillometry-derived impedance parameters in pediatric patients with and without knee-pattern flow-volume curves, all presenting with recurrent respiratory symptoms. Secondary objectives include assessing bronchodilator response and identifying clinical, functional and anthropometric predictors of knee-pattern prevalence.

Methodology

Study Design

Retrospective, observational.

Participants/Subjects

We retrospectively analyzed spirometry and oscillometry data collected between 2022 and 2025 from pediatric patients evaluated at the Pediatric Pulmonology Unit of our center. Inclusion criteria required that both tests be performed during the same clinical session, with oscillometry conducted using the pediatric monofrequency mode (8 Hz) of the Resmon Pro Full device as described below.

Data Collection

Two investigators independently reviewed flow-volume loops for the presence of a knee-shaped pattern, defined by a convex inflection observed both at baseline and after bronchodilator administration. Loops lacking this morphology, classified as "normal" or "scooped" according to Shin, et al., were selected as controls, while ambiguous tracings were excluded [7]. Representative examples of knee-shaped and control flow-volume loops are shown in Fig. 1.

Clinical data and therapeutic history over the preceding 12 months were extracted from medical records. Informed consent was obtained. The local ethics committee exempted the study from formal review. Knee and non-knee loops were pooled and two investigators independently assessed the presence of the knee pattern (yes/no). Loops were assessed visually and by measuring inflection angles using a protractor. Inter-rater agreement was calculated and discrepancies were resolved by consensus. Intra-rater agreement was also evaluated through repeated assessments. Loops exhibiting the knee pattern were further classified according to Boonjindasup, et al., based on the presence of a pre-plateau "scoop" and whether the inflection angle exceeded 150° [8]. The pre-plateau scoop was evaluated visually; a plateau not preceded by a scoop or preceded only by minor flow oscillations before the plateau was deemed "without a scoop".

Measurements

Spirometry was performed using the Quark PFT system (Cosmed Srl, Rome, Italy); acceptability of measurements was determined in accordance with international standards [14]. Dynamic volumes and flow rates were expressed as percentages of predicted values [15]. Oscillometry was conducted using the Resmon Pro Full device (ResTech, Milano, Italy), with patients (cheeks supported by the operator and wearing a nose clip) breathing quietly in triplicate sets of 10 breaths, free of artifacts and with a Coefficient of Variation (CV) ≤15% between replicates as recommended [13]. Tracings were manually inspected by the operator and the final value was computed as the mean of accepted breaths. Oscillometry measurements preceded the spirometric maneuvers, both at baseline and 15 minutes after inhaled albuterol 200 mcg via spacer.

Measured parameters included both absolute and z-score values (denoted by the prefix "s") for inspiratory and expiratory resistance (R) and reactance (X) [16]. Within-breath differences were calculated as $\Delta R = Re - Ri$ and $\Delta X = Xe - Xi$, expressed in $cmH_2O/L/s$. Standardized differences were also computed: $\Delta sR = sRe - sRi$ and $\Delta sX = sXe - sXi$.

Data Analysis

Based on prior data, we estimated the sample size required to detect a minimum between-group difference of 0.3 $cmH_2O/L/s$ in ΔR, assuming a mean of 0.70 and a standard deviation of 0.68. With a type I error (α) of 0.05, power of 80% ($1-\beta$) and a sampling ratio of 2.5, the calculated total sample size was 90 subjects-64 in one group and 26 in the other [17]. Cohen's D was interpreted as follows: <0.2 = small, 0.2-0.5 = medium, >0.8 = large effect size.

Continuous variables were expressed as means ± standard deviation or medians with Interquartile Ranges (IQRs), depending on distribution (Kolmogorov-Smirnov test). Between-group comparisons were performed using the Mann-Whitney U test or Kruskal-Wallis ANOVA with Bonferroni correction. Categorical variables were analyzed using the χ^2 test or Fisher's exact test, as appropriate. Inter- and intra-rater agreement was assessed using Cohen's kappa (κ), with κ values of 0.80-1.00 indicating excellent agreement and 0.00-0.20 indicating poor agreement. Spearman's rank correlation was used to evaluate associations. Logistic regression was employed to identify predictors of the knee pattern. Receiver Operating Characteristic (ROC) curve analysis assessed the discriminative performance of within-breath impedance differences, with cutoff values determined by the Youden index. All statistical analyses were conducted using SPSS version 28 (SPSS Inc., Chicago, IL), with significance set at $p < 0.05$.

Results

Among 350 pediatric patients who underwent both spirometry and oscillometry, 27 subjects (7.7%) exhibited a distinct inflection in the expiratory limb of the flow-volume curve at both baseline and post-bronchodilator. In accordance with sample size calculations, we consecutively selected 63 spirometry loops without a knee pattern to serve as controls. The final study population comprised 90 subjects (mean age 11.9 ± 3.2 years; range 5-18 years).

In a subset of 54 spirometry loops (27 knee-pattern and 27 non-knee), inter-rater agreement was substantial (κ = 0.74, 95% CI: 0.55-0.89) and intra-rater agreement was excellent (κ = 0.93, 95% CI: 0.81-1.00).

Compared to controls, patients with a knee pattern were less frequently diagnosed with asthma or exposed to parental smoking. Yet, their clinical records disclosed higher rates of respiratory exacerbations and use of oral corticosteroids and antibiotics in the preceding year (Table 1).

Across the entire cohort, ΔR was negatively correlated with age and height ($r = -0.39$ and -0.34, respectively; $p < 0.001$). However, this relationship was not observed when using the standardized within-breath difference ΔsR. Spearman's correlation between ΔR and ΔsR was high ($r = 0.83$, $p < 0.001$). The effect size for the difference in ΔsR between groups was −1.022 (95% CI: −1.494 to −0.544), indicating a large effect.

The knee-pattern group demonstrated significantly higher FEV_1/FVC ratios, ΔR and ΔsR values, but lower bronchodilator responses by both spirometry and oscillometry compared to non-knee patients (Table 2). All 27 knee-pattern loops exhibited inflection onset at or beyond mid-FVC, with 24 showing a descending expiratory plateau before the inflection point, characterized by a gradual decline in flow rather than a horizontal segment. To explore morphological variation within the knee-pattern group, these loops were further stratified by the presence (n = 15) or absence (n = 12) of a pre-plateau scoop and by inflection sharpness either sharp (n = 12) or wide (n = 15). No significant differences in spirometry or oscillometry parameters were observed among these subgroups at baseline or after bronchodilator administration. For instance, ΔsR values without vs with a scoop were 0.66 ± 0.93 and 0.51 ± 0.59; wide vs sharp knee angle: 0.66 ± 0.93 and 0.51 ± 0.59; p = 0.922 for both comparisons. Notably, all subgroups defined by scoop presence or inflection angle showed significantly elevated ΔsR values compared to controls (Fig. 2). Binary logistic regression identified ΔsR, absence of asthma diagnosis and oral corticosteroid use as independent predictors of the knee pattern (Table 3), after excluding potential confounders (e.g., age, sex, height, BMI, atopy, inhaled corticosteroids and smoke exposure). The model was statistically significant ($\chi^2 = 30.7$, $p < 0.001$), explained 41% of the variance (Nagelkerke R^2) and correctly classified 80.0% of cases. The odds of exhibiting a knee pattern increased with the absence of asthma (OR = 5.3, 95% CI: 1.6-17.6) and higher ΔsR (OR = 4.6, 95% CI: 1.5-13.6) and decreased with lower oral corticosteroid use (OR = 0.22, 95% CI: 0.07-0.71). To evaluate the discriminative ability of ΔsR in identifying the knee pattern, we performed ROC curve analysis. ΔsR was selected over raw ΔR due to its standardized nature, which minimizes the influence of age and anthropometric variation. The Area Under the Curve (AUC) was 0.73, indicating acceptable predictive performance consistent with clinical utility for rule-in diagnostics (Fig. 3). An optimal threshold of 0.69 yielded very high specificity (96.8%) and moderate sensitivity (44.4%). The adjusted Negative Predictive Value (NPV) and Positive Predictive Value (PPV) for the observed prevalence of the knee pattern (7.7%) were 95.4% and 53.9%, respectively. These findings suggest that ΔsR may serve as a clinically useful marker for identifying knee-pattern morphology, complementing its independent association observed in the logistic regression model.

Demographics	**Without "Knee" (n=63)**	**With "Knee Pattern" (n=27)**	***p*-value**
Gender (M/F)	34/29	18/9	0.264
Age, years	12.2±3.2	11.3±3.1	0.216
Height, cm	150.9±17.5	148.1±16.6	0.423
Weight, kg	51.0±19.4	49.6±19.1	0.708
BMI percentile	69.9±28.1	78.3±26.1	0.078
Clinical history, n (%)			
Atopy	48 (76.2)	17 (63.0)	0.199
Parents smoke	33 (52.4)	7 (25.9)	0.021
Asthma diagnosis	47 (74.6)	10 (37.0)	<0.001
Rhinitis	41 (65.1)	18 (66.7)	0.885
Eczema	14 (22.2)	6 (22.2)	1.000
SDB	15 (23.8)	5 (18.5)	0.580
Exercise-induced symptoms	30 (47.6)	12 (44.4)	0.782
GER symptoms	9 (14.3)	3 (11.1)	1.000
Stridor past 12 months	1 (1.6)	3 (11.1)	0.079
Exacerbations past 12 months[1]	13 (20.6)	11 (40.7)	0.048
Therapy past 12 months, n (%)			
-Oral corticosteroids	16 (25.4)	14 (51.9)	0.015
-Antileukotriens	24 (38.1)	11 (40.7)	0.813
-Antihistamines	27 (42.9)	16 (59.3)	0.153
-ICs+SABA	33 (52.4)	15 (55.6)	0.782
-ICs+S/LABA ≥3 months	19 (30.2)	6 (22.2)	0.441
-Biological therapy	3 (4.8)	2 (7.4)	0.634
-Antibiotics	9 (14.3)	10 (37.0)	0.015

SDB: sleep-disordered breathing; GER: gastroesophageal reflux; ICs: inhaled corticosteroids; SABA/LABA: short-/long-acting β-agonists. [1] Defined as at least one acute episode of dyspnea requiring oral corticosteroids or emergency care within the past 12 months. Statistical differences were assessed using the Mann-Whitney test or Fisher's exact test.

Table 1: Subject characteristics by "knee pattern" in expiratory loops.

Baseline	Without "Knee" (n=63)	With "Knee Pattern" (n=27)	*p*-value
FEV_1%	94.9±16.2	100.8±16.5	0.090
FVC%	99.3±13.2	98.5±13.8	0.884
FEV_1/FVC (%)	83.4±9.3	89.0±7.1	0.004
FEF_{25-75}%	85.4±27.5	95.7±21.4	0.054
sRi	1.00±1.52	0.54±1.42	0.269
sRe	1.00±1.44	1.11±1.65	0.676
sXi	-1.06±1.24	-0.59±1.09	0.081
sXe	-0.81±1.44	-0.60±1.41	0.446
ΔR, cmH_2O/L/s	0.73±0.50	1.33±1.01	0.004
ΔX, cmH_2O/L/s	-0.50±0.61	-0.63±0.78	0.765
ΔsR	0.00±0.47	0.58±0.75	<0.001
ΔsX	0.25±0.85	-0.00±0.92	0.309
Bronchodilator response			
Rise in FEV_1 (%)	8.7±8.2	3.1±5.3	0.001
Rise in FEF_{25-75} (%)	22.6±17.4	8.4±12.5	<0.001
Fall in sRi	-1.53±0.99	-0.52±1.28	<0.001
Fall in sRe	-1.09±0.88	-0.32±1.71	0.018
Rise in sXi	1.06±0.91	0.57±0.87	0.035
Rise in sXe	0.06±1.23	-0.87±1.79	0.021
Inspiratory and expiratory resistance (R) and reactance (X) are expressed as z-scores ("s" prefix). Δ: within-breath difference (Re - Ri or Xe - Xi) expressed in CmH_2O/L/s. Δs: standardized within-breath differences (sRe - sRi or sXe - sXi). Statistical differences were assessed using the Mann-Whitney test.			

Table 2: Respiratory function by "knee pattern" in expiratory loops.

Variable	B	SE	Wald	g.l.	*p*-value	Exp (B)	95% C.I. for Exp (B)
Asthma absence	1.676	0.608	7.608	1	0.006	5.344	1.624-17.583
ΔsR	1.520	0.556	7.477	1	0.006	4.572	1.538-13.590
No oral Cs use	-1.535	0.610	6.330	1	0.012	0.215	0.065-0.712
Constant	-1.054	0.478	4.857	1	0.028	0.348	-
Asthma absence: no clinical diagnosis of asthma. ΔsR: difference between z-scores of expiratory and inspiratory resistance (sRe - sRi). No oral corticosteroid (Cs) use: no reported use in the past 12 months. Exp (B): Odds ratio with 95% confidence interval. The regression model excluded other potential confounders reported in demographics, clinical history and therapy over the past 12 months (see text and Table 1).							

Table 3: Logistic regression predictors of "knee pattern".

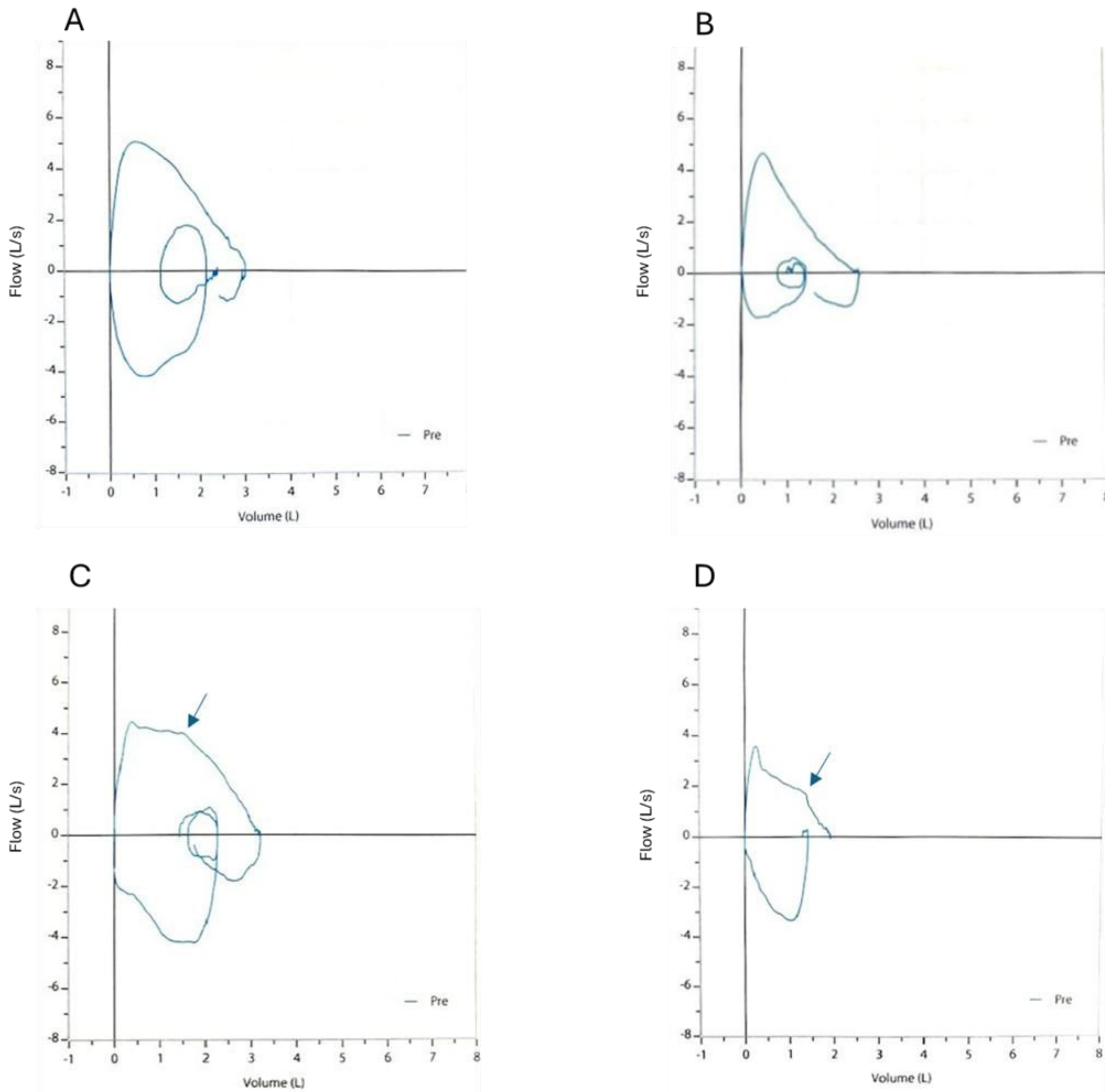

Figure 1: Examples of spirometry flow-volume loops. A: "Normal"; B: "Scooped" (or concave); C: "Knee" pattern without a pre-plateau scoop; D: "Knee" pattern with a pre-plateau scoop. Arrows indicate the "knee".

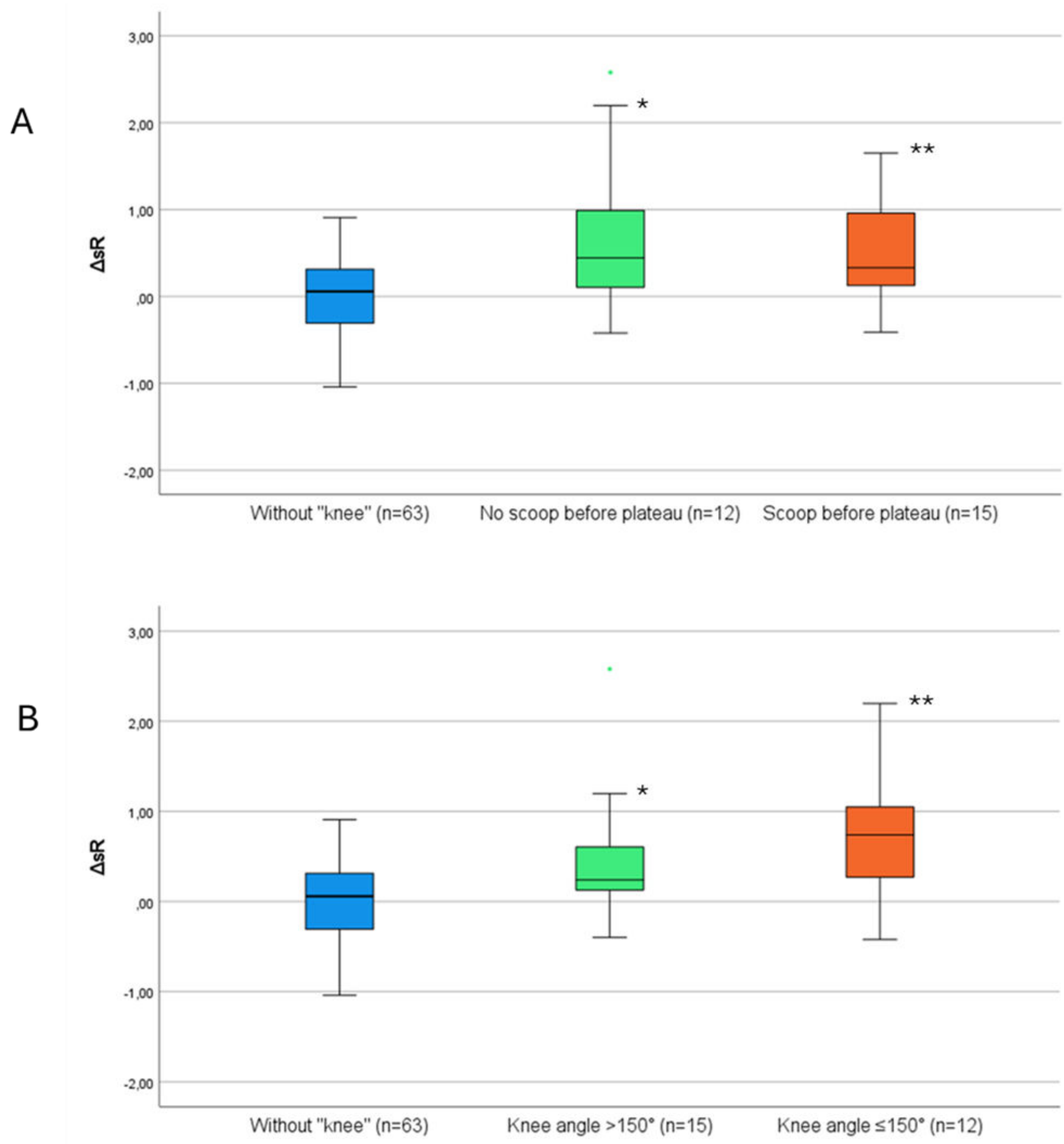

Figure 2: Comparison of ΔsR values in subgroups of patients with "knee" pattern loops, stratified by the presence or absence of a scoop before the expiratory plateau (A) and by the angle of inflection of the "knee": "wide" >150° and "sharp" ≤150° (B), compared to controls without a "knee"-shaped spirometry. ΔsR = sRe - sRi.

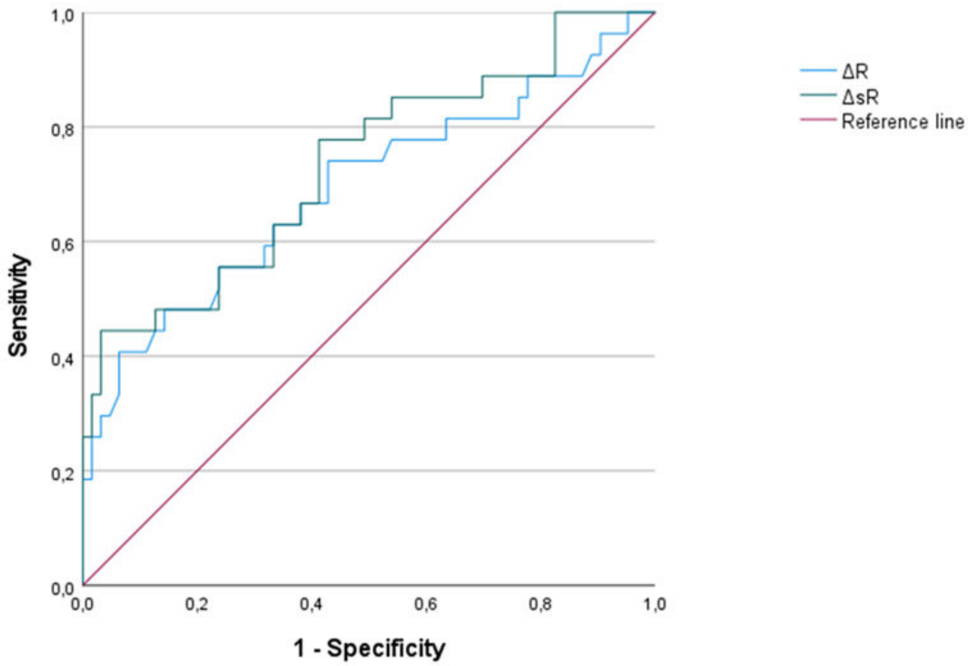

Figure 3: Receiver Operating Characteristic (ROC) curves for the within-breath difference in R (ΔR) and its standardized measure (Δz-sR) in identifying the knee-pattern spirometry. AUCs: 0.69 ($p = 0.004$) and 0.73 ($p < 0.001$), respectively. ΔR = Re − Ri ; ΔsR = sRe - sRi.

Discussion

This study identifies the within-breath oscillometric parameter ΔsR as a promising marker for distinguishing pediatric patients with knee-pattern spirometry. Beyond its statistical association, ΔsR emerged as an independent predictor of this morphology, with ROC analysis demonstrating acceptable discriminative performance (AUC = 0.73). Although sensitivity was modest, the high specificity (96.8%) suggests that a ΔsR value ≥ 0.69 strongly supports the presence of a knee-shaped expiratory loop, offering a useful rule-in tool for bronchoscopy referral when supported by clinical context.

The use of z-scores helped mitigate age-related confounders, enhancing the interpretability of impedance values in pediatric populations. Collectively, these findings support the utility of within-breath oscillometry specifically standardized resistance shifts-in quantifying a traditionally visual spirometric phenotype. Separate measurements of inspiratory and expiratory resistance (Ri, Re) and reactance (Xi, Xe) at 8 Hz did not distinguish between patients with and without the knee pattern. By contrast, within-breath variations in resistance-particularly when expressed as z-score deltas-proved more sensitive to changes in upper intrathoracic airway mechanics.

Resistance (R), the impedance component in-phase with flow, reflects frictional losses along the airways and is influenced by airway diameter, tissue collapsibility and endoluminal secretions [13,18]. Typically, R increases during expiration and decreases during inspiration [19,20], generating a ΔR. In conditions such as floppy central airways, expiratory resistance may be accentuated, resulting in elevated ΔR values.

Reactance (X), the impedance component that is out-of-phase with flow and in-phase with volume, primarily reflects elastance-a measure of the combined stiffness of lung and chest wall tissues-since inertance at 8 Hz is negligible. X is sensitive to the volume of communicating lung units [21], making it a useful marker of airway closure [22]. ΔX tends to widen during peripheral airway closure at low lung volumes and is altered in conditions with expiratory flow limitation, such as COPD or exercise-induced airway hyperresponsiveness [17,23]. The absence of significant differences in ΔX within our cohort supports the hypothesis that the knee pattern originates from central rather than peripheral airway dynamics.

These physiological insights are consistent with previous clinical observations by Shin et al., who reported higher FEV_1/FVC ratios and mid-expiratory flow rates in patients with knee-pattern spirometry, along with a lower prevalence of asthma diagnoses [7]. Similarly, our cohort demonstrated elevated FEV_1/FVC, borderline FEF_{25-75} values, reduced bronchodilator responsiveness and fewer asthma cases within the knee-pattern group. Taken together, spirometric and oscillometric findings in this subgroup diverge from the patterns typically associated with small airway obstruction [24,25]. Beyond these physiological distinctions, the presence of knee-shaped expiratory loops was also associated with higher rates of respiratory exacerbations and increased use of oral corticosteroids and antibiotics in the preceding year. Clinical history-when interpreted alongside abnormal spirometry loops and elevated ΔsR values-may assist clinicians in determining whether further diagnostic interventions, such as bronchoscopy, are warranted. Although the knee pattern appears less frequent in asthmatic children, it may coexist with asthma, suggesting that floppy central airways could represent a comorbidity rather than an alternative diagnosis. Given the absence of a universally accepted definition of the knee pattern, we selected loops based on abnormally angled contours and previously published pediatric criteria [8]. To ensure consistency, we required repeatable measures and excluded ambiguous or intermediate tracings. This approach strengthens the validity of our comparisons and may provide a functional framework for future studies evaluating oscillometry in patients whose spirometry and clinical presentation suggest central airway involvement.

Neither the presence of a pre-plateau scoop nor the degree of inflection in flow-volume curves significantly affected oscillometry outcomes within knee-pattern subgroups. All patients reported mild to moderate respiratory symptoms and none had underlying chronic disease. Although the scoop has been associated with tracheomalacia, we lacked bronchoscopic data to confirm anatomical differences. Importantly, both the scoop and knee angle are features observed during forced expiratory maneuvers, whereas oscillometry measurements are obtained during quiet breathing. Forced vital capacity maneuvers may better reveal the mechanical consequences of variable central airway obstruction as choke points migrate peripherally [4]. In contrast, within-breath FOT parameters such as ΔsR may complement spirometry by assessing central airway dynamics without requiring forced maneuvers-a particularly advantageous approach in pediatric populations.

Despite growing interest, pediatric data on impedance in variable central airway obstruction remain sparse. Hamlington, et al., studied 50 patients with Down syndrome, 72% of whom had co-occurring conditions such as congenital heart disease, dysphagia with aspiration, obstructive sleep apnea and tracheomalacia. Among the subgroup who underwent bronchoscopy, six patients with tracheomalacia showed no significant differences in R and X z-scores compared to 18 patients without tracheomalacia [26]. The heterogeneity of clinical characteristics and small sample size complicate the physiological interpretation of oscillometry results in this population.

Studies in adults have explored oscillometry in central airway obstruction due to neoplastic, inflammatory and other etiologies [27-29]. One study reported elevated Ri and Re and reduced Xi in CAO patients but found no significant differences in within-breath parameters such as ΔR or ΔX compared to patients with COPD. Additionally, CAO patients exhibited less pronounced within-breath changes in resonance frequency (ΔFres) than those with COPD characterized by airway wall thickening [27]. Verbanck, et al., proposed a regression-based index, ΔR/ΔV, for assessing tracheal stenosis, but its reliance on multiple maneuvers-including repeated quiet and rapid breaths at similar tidal volumes-may limit feasibility in pediatric populations [28]. Handa, et al., compared variable and fixed CAO, reporting elevated R and X during both respiratory phases in patients with variable CAO, although within-breath differences were not evaluated [29]. These adult studies underscore the novelty of our findings and highlight the need for pediatric-specific methodologies.

This study is the first to evaluate within-breath oscillometry parameters in children with knee-pattern spirometry, offering a novel approach to characterizing central airway dynamics. Our results suggest that ΔsR is a feasible and informative metric that complements spirometry in evaluating suspected central variable obstruction, particularly when traditional measures are inconclusive.

Limitations

This study presents several limitations. Its exploratory and retrospective design restricts anatomical interpretation and may introduce bias, particularly in symptom reporting-whether from children, caregivers or through variable physician documentation, which may be incomplete or inconsistently classified. Additionally, retrospective spirometry assessments may lack contextual alignment with clinical records, potentially affecting patient classification and therapeutic decisions. Visual evaluation of angled spirometry loops remains inherently subjective. Although ambiguous tracings were excluded to enhance diagnostic clarity, this may have introduced selection bias. Furthermore, ΔR was calculated from mean inspiratory and expiratory values, which are susceptible to flow dependence. Intra-breath assessments of Ri and Re at zero flow currently unavailable on our device-would offer greater precision and mitigate this limitation [30]. Despite these constraints, our primary aim was to assess the feasibility of within-breath oscillometry measurements in children presenting with atypically angled flow-volume loops. These findings lay the groundwork for future prospective studies in pediatric populations who may benefit from endoscopic evaluation. Incorporating imaging or bronchoscopic data in future research could help validate the anatomical correlates of ΔsR and refine its diagnostic utility.

Conclusion

In children with recurrent respiratory symptoms, elevated ΔsR may help identify those with knee-pattern spirometry suggestive of central airway collapse. This non-invasive metric offers a practical adjunct to clinical evaluation when spirometry is inconclusive, supporting decisions about further investigation or bronchoscopy referral. By quantifying a visual spirometric phenotype, ΔsR enhances diagnostic precision and expands the utility of oscillometry in pediatric respiratory care.

Conflict of Interest

The authors declare no conflicts of interest that may have influenced the research, authorship or publication of the article.

Financial Disclosure

This research did not receive any grant from funding agencies in the public, commercial or not-for-profit sectors.

Ethical Statement

This project was exempt from IRB review as it did not qualify as human subject research under federal regulations.

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We thank nurse Anna Calavita, for her assistance in the pulmonary function laboratory.

Consent To Participate

Informed consent was obtained from the participant involved in this study.

Data Availability and Consent of Patient

Informed consent was obtained from the participant involved in this study.

Author’s Contribution

Informed consent was obtained from the participant involved in this study.

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