ASHA American Speech-Language-Hearing Association

JSLHR

Research Article

Comparison of Respiratory Calibration Methods for the Estimation of Lung Volume in Children With and Without Neuromotor Disorders

Meghan Darling-White[a]

[a] Department of Speech, Language, and Hearing Sciences, University of Arizona, Tucson

ARTICLE INFO

Article History:
Received June 17, 2021
Revision received September 25, 2021
Accepted October 19, 2021

Editor-in-Chief: Bharath Chandrasekaran
Editor: Cara E. Stepp

https://doi.org/10.1044/2021_JSLHR-21-00333

ABSTRACT

Purpose: The primary purpose of this study was to validate common respiratory calibration methods for estimating lung volume in children.

Method: Respiratory kinematic data were collected via inductive plethysmography from 81 typically developing children and nine children with neuromotor disorders. Correction factors for the rib cage and abdomen were calculated using three different methods: (a) least squares method with both rib cage and abdomen corrections (LsqRC/AB), (b) least squares method with rib cage correction only (LsqRC), and (c) a standard 2:1 rib-cage-to-abdomen ratio (Banzett). Correction factors for the LsqRC/AB and LsqRC methods were calculated with and without the use of the speech-like breathing calibration task. Lung volume estimation errors were calculated by comparing the estimated lung volumes based on the correction factors and the actual lung volumes acquired from a spirometer, normalized to each participant's vital capacity.

Results: For typically developing children, the LsqRC/AB method resulted in significantly smaller lung volume estimation errors compared with other methods. Lung volume estimation errors decreased as age increased for each method. For the children with neuromotor disorders, the LsqRC/AB and LsqRC methods resulted in significantly smaller lung volume estimation errors than the Banzett method but were not significantly different from one another. There were no significant differences in lung volume estimation errors for the LsqRC/AB and LsqRC methods when the correction factors were calculated with and without the speech-like breathing calibration task.

Conclusion: The LsqRC/AB method exclusively utilizing the rest breathing calibration task is the most accurate and efficient respiratory calibration method for use with children with and without neuromotor disorders at this time.

The respiratory system can be viewed as a two-part system in which changes to the shape of the rib cage and abdomen contribute to changes in lung volume (Konno & Mead, 1967). Each time the rib cage and abdomen move, they displace volume. When summed, the volumes displaced by the rib cage and abdomen equal the volume displaced by the lungs. Kinematic techniques, such as respiratory inductive plethysmography, allow scientists to capture circumferential changes (as measured in volts) of the rib cage and abdomen during speech production. The raw voltages from the rib cage and abdomen are then converted to liters to estimate lung volume through the use of respiratory calibration methods. Respiratory calibration methods work by calculating separate correction factors for the rib cage and abdomen that, when summed accurately, estimate lung volume (in liters; e.g., Banzett et al., 1995; Chadha et al., 1982; Huber et al., 2005; Konno & Mead, 1967). Lung volume estimates must be mathematically derived since an individual cannot speak while breathing in and out of a spirometer. Thus, the lung volume estimation error inherent in a given methodology is an important variable to understand while designing an experiment and interpreting data.

Correspondence to Meghan Darling-White: darlingwhite@email.arizona.edu. ***Disclosure:*** *The author has declared that no competing financial or nonfinancial interests existed at the time of publication.*

Not all respiratory calibration methods are created equal, and some result in significantly more lung volume estimation error than others (McKenna & Huber, 2019). The literature regarding the accuracy of respiratory calibration methods for estimating lung volume during speech breathing has been studied exclusively in adult populations. Given the changes that occur to speech breathing during development, it is problematic to assume that the accuracy of respiratory calibration methods for estimating lung volume during speech breathing will be the same in children and adults. Infants and young children tend to utilize the abdomen to a greater extent than the rib cage when changing lung volume compared with older children and adults (Boliek et al., 1996, 1997, 2009). This gradually changes with age, where the contribution of the rib cage increases and the contribution of the abdomen decreases (Hoit et al., 1990; Reilly & Moore, 2009). The exact age at which rib cage and abdomen contributions reach adult-like is still unknown but likely occurs between the ages of 10 and 14 years (Hoit et al., 1990; Stathopoulos & Sapienza, 1997). Any respiratory calibration method utilized in children must be flexible enough to account for the changing rib cage and abdomen contributions during development since small differences in rib cage and abdomen correction factors can potentially lead to significant changes in lung volume estimates.

One potential consequence for the absence of knowledge regarding the accuracy of respiratory calibration methods in children is the general lack of peer-reviewed studies regarding speech breathing in children with neuromotor disorders, particularly cerebral palsy (CP) and Down syndrome (DS). Children from both groups of neuromotor disorders often demonstrate respiratory physiologic impairments, such as changes in chest wall tone and/or respiratory muscle weakness, which potentially impact speech breathing behavior (e.g., da Silva et al., 2010; Ersoz et al., 2006; Hardy, 1961, 1964; Wang et al., 2012). Despite the documented respiratory physiologic impairment and the fact that the majority of the most common perceptual features characterizing speech in these groups of children may relate to speech breathing impairment (e.g., Jones et al., 2019; Kent et al., 2021; Rutherford, 1944; Workinger & Kent, 1991), there are no peer-reviewed studies examining speech breathing via kinematic procedures in children with DS and very few documenting speech breathing via kinematic procedures in children with CP (Edgson et al., 2021; Redstone, 2004), making the design of interventions to address speech breathing impairment in children with neuromotor disorders nearly impossible.

Reducing the error in lung volume estimates is essential to the design of interventions to address speech breathing impairment. The respiratory system provides the steady, driving pressure required for speech production via the interaction of passive recoil and active muscle forces. Speech breathing is considered efficient when passive recoil forces are utilized to a greater extent than active muscle forces during speech production. The anatomic and physiologic changes to the respiratory system demonstrated by children with CP and children with DS may create an imbalance in speech breathing forces, where active muscle forces are utilized to a greater degree than passive recoil forces (Edgson et al., 2021). When this occurs, speech production is less effective, more effortful, and fatiguing. Interventions that directly impact speech breathing behavior attempt to restore a more efficient balance of passive recoil and active muscle forces (Darling-White & Huber, 2017). Such interventions rely on accurate estimates of passive recoil and active muscle forces, which are determined by the amount of air in the lungs (i.e., lung volume) at any given point in the expiratory phase of the speech breathing cycle.

The primary purpose of this study was to examine the accuracy of three common respiratory calibration methods, two variations of the least squares method and the Banzett method, in children with and without neuromotor disorders. Typically developing (TD) children were included in this investigation, because without a methodology that minimizes lung volume estimation error and can be easily and accurately replicated in children regardless of neuromotor status, it is difficult to collect, analyze, and interpret speech breathing data from children with neuromotor disorders within the appropriate developmental context. The accuracy of each respiratory calibration method was examined separately for the two groups since lung volume estimation errors for each respiratory calibration method differ based on neuromotor status in adults (McKenna & Huber, 2019). Examining the accuracy of current respiratory calibration methods for estimating lung volume during speech breathing in children with and without neuromotor disorders will lay the foundation for future work examining speech breathing in children and the development of interventions to address speech breathing impairment in children with neuromotor disorders.

The least squares method of respiratory calibration was chosen, because it consistently results in smaller lung volume estimation errors than other methods (Chadha et al., 1982; McKenna & Huber, 2019; Stromberg et al., 1993). A primary difference and potential reason for the superiority of the least squares method in adult populations is that it is the only method that calculates the correction factors for the rib cage and abdomen via direct comparisons with lung volumes collected via a digital spirometer during the same task (Chadha et al., 1982). The most recent version of the least squares method utilizes two calibration tasks, rest breathing and speech-like breathing, to calculate the corrections factors for the rib cage and abdomen (e.g., Darling-White & Huber, 2017; Huber et al., 2005; Huber & Darling, 2011; Huber &

Spruill, 2008; Sadagopan & Huber, 2007). While connected to the respiratory kinematic equipment, participants breathe through a digital spirometer for 1.5 min of quiet breathing (i.e., rest breathing) and then silently read a sentence, such as "You buy Bobby a puppy now if he wants one" one time per exhale for 1.5 min (i.e., speech-like breathing) while breathing through a digital spirometer. These tasks are not physiologically taxing and the majority of participants are able to complete them regardless of age or respiratory physiologic status. The correction factors for the rib cage and abdomen are then calculated via the Moore-Penrose pseudoinverse function such that the sum of the known contributions from rib cage and abdomen equal the known lung volume.

Two variations of the least squares method were examined in this study to ensure that the most accurate and efficient version of this method is being utilized with children with and without neuromotor disorders. The first variation solved for both the rib cage and the abdomen correction factors (LsqRC/AB) and the second variation solved for the rib cage factor while the abdomen factor is set to a constant value of 1 (LsqRC). When comparing these two variations of the least squares method, McKenna and Huber (2019) found that the difference in lung volume estimation error was significant in young adults (with the LsqRC/AB method being more accurate than the LsqRC method) but not significant in older adults or individuals with Parkinson's disease. The authors hypothesized that the lack of difference for the older adults and individuals with Parkinson's disease was due to age- and disease-related respiratory physiologic changes that lead to reductions in coordination between the rib cage and abdomen and unstable and inconsistent abdomen signals. The stability and consistency of abdomen signals in children with neuromotor disorders may also be impacted by respiratory physiologic impairment, thus, highlighting the importance of examining the two different versions of the least squares method in these populations.

The other respiratory calibration method that this study examined was the Banzett method. The Banzett method employs a 2:1 standard ratio in which the rib cage correction factor is set to 2 and the abdomen correction factor is set to 1 (Banzett et al., 1995). While in adults, studies have used a third method, the isovolume method for estimating lung volumes, this method was not used in this study. The isovolume method relies on the completion of a maneuver that requires the ability to displace volume back and forth between the rib cage and abdomen while holding one's breath, which can be difficult to accurately and reliability complete, particularly for children who demonstrate cognitive-linguistic impairment, which is common in CP and DS (Boliek et al., 2009). As a result of the difficulty in collecting isovolume maneuvers from children, some authors (Boliek et al., 1996, 1997, 2009; Parham et al., 2011) have used spontaneously produced paradoxical movements of the rib cage and abdomen to calibrate for estimated lung volume in children. However, the isovolume method requires that the glottis or lips be closed and that the lung volume not change during the maneuver (Konno & Mead, 1967). During spontaneous paradoxical movements, lung volume is very often changing, impacting the validity of these estimates; thus, these kinds of movements were not considered in our calibrations. Given the prior literature demonstrating the difficulty of collecting isovolume maneuvers in children (Connaghan et al., 2004; Moore et al., 2001; Redstone, 2004) and that McKenna and Huber (2019) demonstrated that the lung volume estimation error did not significantly differ between the Banzett method and the isovolume method in adult populations with and without neuromotor disorders, the Banzett method was used as an appropriate stand-in for the isovolume method.

On the basis of the findings from McKenna and Huber (2019), the following hypotheses were proposed: (a) For TD children, the LsqRC/AB method would result in significantly smaller lung volume estimation errors than the LsqRC or the Banzett methods; and (b) for children with neuromotor disorders, the LsqRC/AB and the LsqRC methods would result in significantly smaller lung volume estimation errors than the Banzett method, but the LsqRC/AB and the LsqRC methods would not be significantly different from one another.

When collecting data from children, it is important to streamline the process, especially when respiratory kinematic techniques require children to sit as still as possible during data collection. Given the hypotheses that the two variations of the least squares method would result in the lowest lung volume estimation errors, the secondary purpose of this study was to examine the lung volume estimation errors of the variations of the least squares method when calculated utilizing both calibration tasks, rest breathing and speech-like breathing, versus when calculated utilizing only one calibration task, rest breathing. It is not possible to employ speech production tasks in order to calculate the correction factors for the rib cage and abdomen using the least squares method, because this method directly compares the position of the rib cage and abdomen to the lung volumes collected via a digital spirometer during the calibration tasks and it is not possible to speak while breathing in and out of a digital spirometer. Respiratory function during the speech-like breathing task acts as a proxy for respiratory function during speech production (e.g., quick inhalation followed by long and slow exhalation). In theory, the inclusion of both the rest breathing and speech-like breathing tasks when calculating the calibration factors for the rib cage and abdomen allows for the sampling of rib cage and abdomen positions over a wider variety of lung volumes allowing for more accurate lung volume estimates (Reich & McHenry, 1990). However, the speech-like breathing task requires reading skills and may be difficult for children, especially those with cognitive-linguistic impairment or young children, to perform. If exclusive use of the rest breathing task could result in the same lung volume estimation accuracy as the combined use of the rest breathing and speech-like breathing tasks, then we could streamline the process when collecting respiratory kinematic data from children. No hypothesis was made regarding the use of both the rest breathing and speech-like breathing tasks versus the rest breathing task alone when estimating lung volume in children with and without neuromotor disorders as this was a novel question and had no precedence in the literature.

Method

Participants

Study procedures were approved by the University of Arizona Human Subjects Review Board (Protocol 16055837A005). Recruitment occurred via community postings and public websites that prompted parents or guardians to contact the research team if interested. Legal guardians provided written consent and participants provided verbal assent prior to initiating data collection. Participants were compensated $30 for their time.

Eighty-one TD children (36 boys, 45 girls) participated in this study. The mean age of TD children was 12;4 (years;months) with a range of 8;2–17;5. According to parent-reported information about race, 4.94% of TD children were Asian, 6.17% of TD children were Black or African American, 12.35% of TD children were more than one race, 1.23% of TD children had unknown racial identity, and 75.31% of TD children were White. According to parent-reported information about ethnicity, 17.28% of TD children were Hispanic or Latino.

For inclusion, all TD children were fluent speakers of American English; had no history of speech, language, hearing, or learning problems; had no history of head, neck, or chest surgery; and demonstrated normal lung function based on their age, sex, height, and weight. All TD children, except one, demonstrated normal hearing as determined by a bilateral pure-tone hearing screening at 20 dB HL for 500, 1000, 2000, and 4000 Hz. One of the 10-year-old male participants had a threshold of 25 dB HL for 500 Hz bilaterally. These elevated thresholds were likely the result of recent bilateral ear infections. He was included in the study because he did not have a history of hearing problems per parent report and passed at 20 dB HL for all other frequencies. Each TD child demonstrated average or above average language scores as evidenced by the core language score of the Clinical Evaluation of Language Fundamentals–Fifth Edition (CELF-5; Wiig et al., 2013). All TD children demonstrated typical speech production skills and voice quality, based on the perceptual assessment of the author, a certified speech-language pathologist. To examine lung function, each TD child produced a vital capacity (VC) and forced vital capacity (FVC) maneuver while breathing into a digital spirometer (VacuMed Discovery Handheld Spirometer). For the VC maneuver, children were asked to breathe in as much air as they could and then breathe out as much air as they could. For the FVC maneuver, children were asked to breathe in as much air as they could, then breathe out as hard and fast as possible. The author held the digital spirometer during the task and coached children to produce each task to their maximum capability. All TD children demonstrated normal lung function as evidenced by VC and FVC values that were $\geq$ 80% of the expected values based on age, sex, height, and weight coded into the spirometer (VacuMed Discovery Handheld Spirometer).

Nine children with neuromotor disorders (two boys, seven girls) participated in this study. Seven children were diagnosed with CP, and two children were diagnosed with DS. The mean age of children with neuromotor disorders was 12;2 with a range of 8;3–14;10. According to parent-reported information about race, 1.11% of children with neuromotor disorders were Asian, 0% of children with neuromotor disorders were Black or African American, 1.11% of children with neuromotor disorders were more than one race, and 77.78% of children with neuromotor disorders were White. According to parent-reported information about ethnicity, 0% of children with neuromotor disorders were Hispanic or Latino.

All children with neuromotor disorders were fluent in American English and had no history of head, neck, or chest surgery. M08CP's native language was Chinese. At the time of data collection, M08CP was fluent in American English and able to follow all directions to participate in the study. All children with neuromotor disorders passed the bilateral pure-tone hearing screening at 20 dB HL for 500, 1000, 2000, and 4000 Hz except F09CP and F05DS. F09CP did not cooperate in the hearing screening. There were no concerns regarding hearing status per parent report and F09CP had no history of failed hearing screenings. F05DS had an elevated threshold of 25 dB at 500 Hz in the right ear. Lung function was tested in the manner described above though normal lung function was not an inclusionary criterion for children with neuromotor disorders. Five of the nine children with neuromotor disorders demonstrated normal lung function as evidenced by VC and FVC values that were $\geq$ 80% of expected values based on age, sex, height, and weight coded into the spirometer (VacuMed Discovery Handheld Spirometer). F07CP and F05DS demonstrated normal FVC values, but demonstrated VC values that were slightly below the normal range, 70% and 77%, respectively. F01CP and F09CP did not cooperate with the lung function testing. None of these participants were diagnosed with asthma or other chronic respiratory illnesses per parent report.

Demographic characteristics of children with neuromotor disorders including age, the presence or absence of language impairment, the presence or absence of speech motor impairment, gross motor function (children with CP only), and adaptive function (children with DS only) are presented in Table 1. These demographic characteristics were used to characterize the severity of the impairment in our participants to allow comparisons across studies and not used as inclusionary or exclusionary criteria. Presence or absence of language impairment was determined by the core language score of the CELF-5 (Wiig et al., 2013). The decision was made not to complete standardized language testing with M08CP as he was not expected to score within an average range for a child his age regardless of language impairment status given that he had been learning American English for approximately 3 years. There were no parent reports of language impairment in his native language or any difficulty learning or comprehending the English language. Presence or absence of speech motor impairment (i.e., dysarthria) was determined by the author, who collected these data, using standard clinical procedures. For the children with CP, gross motor function was characterized by describing tonal/movement abnormalities (e.g., spastic and ataxic) and topographical distribution (e.g., diplegia and hemiplegia) as well as the Gross Motor Function Classification System (GMFCS), a standard clinical measure specifically designed for children with CP (Palisano et al., 1997). The GMFCS classifies gross motor abilities, with an emphasis on sitting and walking, into five levels with GMFCS Level I representing children with little to no gross motor impairment and GMFCS Level V representing children with profound gross motor impairment. For the children with DS, the Vineland Adaptive Behavior Scales–Third Edition (Vineland-3; Sparrow et al., 2016) was used as a standardized measure of adaptive behavior (the things that we do to function in our everyday lives). The Vineland-3 is a parent-report measure that provides an adaptive behavior composite (ABC) score based on three domains: communication, daily living skills, and socialization. The ABC is expressed as a standard score with a mean of 100 and standard deviation of 15.

Equipment and Data Collection Procedure

Participants were part of a larger study that consisted of two 60- to 90-min sessions that occurred approximately 1 week apart. The data presented in this study were collected at the Motor Speech Research Laboratory at the University of Arizona within the first 30 min of one of the sessions. Participants were free of allergies or cold symptoms on the day of respiratory kinematic data collection.

Respiratory kinematic data were collected using respiratory inductive plethysmography (Inductotrace system, Ambulatory Monitoring Inc.). Two elastic bands were used to transduce the movement of the rib cage and the abdomen. The rib cage band was placed around the rib cage, inferior to the axilla. The abdominal band was placed around the abdomen at the level of the navel, inferior to the floating ribs. Respiratory kinematic data were digitized via LabChart (ADInstruments) using a sampling rate of 1 kHz/s.

After proper placement of the bands, participants performed a series of calibration tasks in an upright, seated position. Participants were seated in a Rifton Activity Chair with armrests and a footrest, which allowed for a 90° angle at the elbows, hips, and knees. All participants were able to maintain this position without the use of bolsters or restraints. Calibration tasks pertinent to this study included

Table 1. Participant demographic information.

Participant	Age	Language impairment	Speech motor impairment	Type of CP	GMFCS	Adaptive behavior composite of Vineland-3
F01CP	13;5	Severe impairment	Yes	Spastic diplegia	II	n/a
F02CP	14;6	No impairment	No	Spastic hemiplegia	I	n/a
M04CP	11;9	No impairment	No	Spastic	I	n/a
F05CP	14;10	No impairment	Yes	Spastic	II	n/a
F07CP	9;2	Moderate impairment	Yes	Spastic quadriplegia	II	n/a
M08CP	13;8	Did not complete	Yes	Spastic quadriplegia	II	n/a
F09CP	8;3	Borderline impairment	Yes	Mixed–ataxic and hypotonic quadriplegia	III	n/a
F04DS	10;7	Severe impairment	Yes	n/a	n/a	78
F05DS	13;6	Severe impairment	Yes	n/a	n/a	67

Note. Age is provided in years;months. Language impairment classifications are based on the core language score of the Clinical Evaluation of Language Fundamentals–Fifth Edition (Wiig et al., 2013). CP = cerebral palsy; GMFCS = Gross Motor Function Classification System (Palisano et al., 1997); Vineland-3 = Vineland Adaptive Behavior Scales–Third Edition; F = female; M = male; M04CP and F05CP did not report the topographical distribution of their spasticity; DS = Down syndrome; n/a = not applicable.

rest breathing and speech-like breathing tasks. During the rest breathing task, participants wore nose clips and were instructed to sit quietly while breathing through a digital spirometer for 1.5 min of quiet breathing, split across two 45-s trials. All children in the study were able to successfully complete the rest breathing calibration task. For the speech-like breathing task, participants wore nose clips and were instructed to read the sentence, “You buy Bobby a puppy now if he wants one,” silently to themselves one time per exhale for 1.5 min while breathing through a digital spirometer, split across two 45-s trials. Participants were asked to read the sentence aloud prior to the start of the task to verify that they could read. Participants were also asked to explain the task to the author to demonstrate comprehension of the instructions prior to task initiation. If the participant was unable to read or comprehend the instructions for the speech-like breathing task, the participant was instructed to imitate the author during a deep breathing exercise to ensure a wide variety of lung volumes were sampled during the task. This occurred on two occasions (one participant with CP and one participant with DS), but all other participants completed the speech-like breathing task without difficulty. The first author held the digital spirometer for all participants during each respiratory calibration task to prevent movement artifacts from influencing the respiratory data. Participants were given breaks between each respiratory calibration task to prevent fatigue.

Measurements

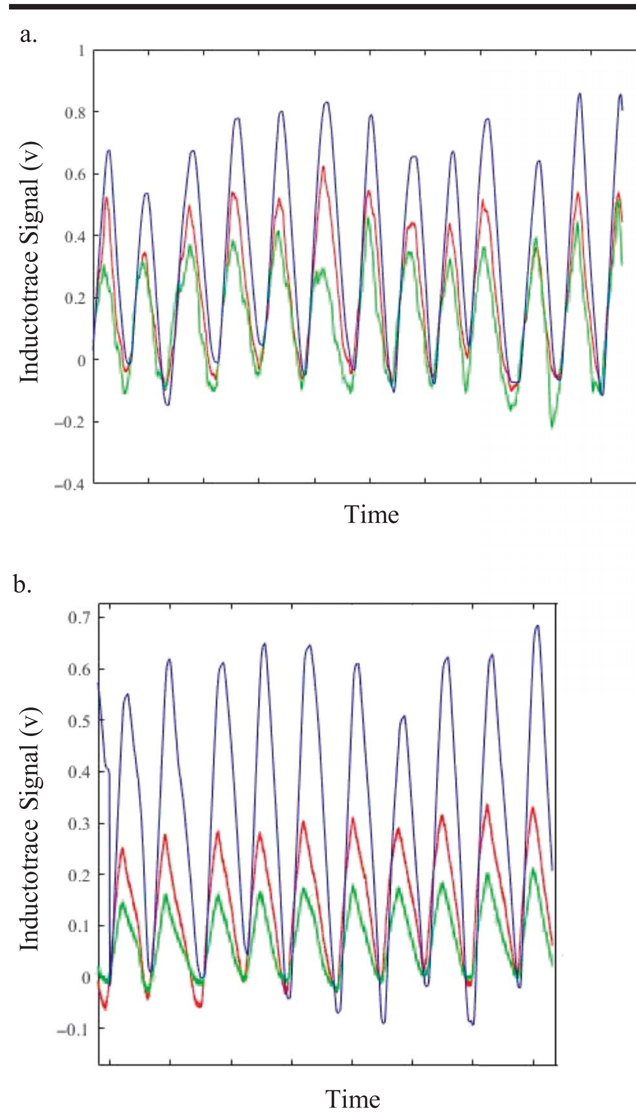
The following procedures were modeled on the methodology presented in McKenna and Huber (2019), which examined the accuracy of respiratory calibration methods in young adults, older adults, and people with Parkinson’s disease. Lung volume estimation errors were determined for the following methods: LsqRC/AB with and without the inclusion of the speech-like breathing task, LsqRC with and without the inclusion of the speech-like breathing task, and the Banzett method. The correction factors for the rib cage and abdomen for each method were calculated prior to the calculation of the lung volume estimation errors.

All data were measured using a custom, semiautomated program in MATLAB. Prior to all measurements, the program allowed for visual inspection of the spirometer signal in order to correct for drift during the recording. Drift is a common and well-documented acquisition problem (McKenna & Huber, 2019; Stathopoulos et al., 2014). When identified, drift was corrected using the detrend function in MATLAB, which subtracts a best-fit line from the drifting data. Data from the rest breathing and speech-like breathing tasks were then normalized to end expiratory level, which was defined as the troughs of three rest breaths at the beginning of each recording. The program then prompted the user to identify the beginning of the task and the end of the task. Measurements were made from all breaths that occurred between those points. Figure 1 provides representative examples of the data collected (postend expiratory level normalization) during the rest breathing task for a TD child and a child with CP.

Calculation of Rib Cage and Abdomen Correction Factors

LsqRC/AB. The correction factors for the rib cage and abdomen were calculated using data from the rest breathing and speech-like breathing tasks. A Moore-Penrose pseudoinverse function solves for the correction factors for the rib cage signal (k_1) and the abdomen signal (k_2) that reduce the

Figure 1. Representative examples of the data collected (postend expiratory level normalization) during the rest breathing task for a typically developing 13-year-old (a) and a 13-year-old with cerebral palsy (b). The rib cage signal is represented in red. The abdomen signal is represented in green. The spirometer signal is represented in blue.



error between lung volume estimates and actual lung volumes captured by the spirometer using the following formula:

$$\text{Spirometer } (L) = k_1(\text{Rib cage}) + k_2(\text{Abdomen}) \quad (1)$$

LsqRC. The same calculations described above for the LsqRC/AB method were used when calculating the correction factors for the LsqRC with one notable exception; the correction factor for the abdomen signal was set to a constant value of 1 using the following formula:

$$\text{Spirometer } (L) = k_1(\text{Rib cage}) + 1(\text{Abdomen}) \quad (2)$$

LsqRC/AB–RB only and LsqRC–RB only. To examine the need for both the rest breathing and the speech-like breathing calibration tasks in the calculation of the rib cage and abdomen correction factors, the correction factors were calculated following the same procedures outlined above for the LsqRC/AB and LsqRC methods using only the rest breathing calibration task.

Banzett. The Banzett method employs a standard 2:1 standard ratio in which the rib cage correction factor is set to 2 and the abdomen correction factor is set to 1. The correction factors are the same for all participants and are not calculated using special equations or calibration tasks.

Calculation of Lung Volume Estimation Errors

Using the correction factors calculated above, the rib cage and abdomen signals were summed to get an estimated lung volume. An absolute mean lung volume estimation error was then calculated by comparing the estimated lung volumes based on the correction factors and the actual lung volumes acquired from the spirometer. This value was normalized to each participant's VC to allow for comparison across participants despite differences in body size using the following formula:

$$\begin{aligned}&\text{Lung Volume Estimation Error } (\%\text{VC}) \\ &\quad = \text{Absolute Mean Lung Volume Estimation Error } (\text{L})/ \\ &\quad\ \ \text{VC } (\text{L}) \qquad (3)\end{aligned}$$

VC values for all participants, except two, were obtained directly from the spirometer used to test lung function prior to data collection. For the children with CP that did not cooperate with lung function testing (F01CP and F09CP), VC was indirectly estimated (using a customized semiautomated program in MATLAB) from at least two VC maneuvers collected while wearing the Inductotrace bands. The VC maneuvers were collected in the same manner as described during lung function testing. More information about this indirect estimation method for F01CP and F09CP is provided in the Limitations section below.

Statistical Analysis

Research questions of interest focused on (a) differences in lung volume estimation error across methods (LsqRC/AB, LsqRC, and Banzett) and (b) differences in lung volume estimation error when correction factors were calculated via the least squares method utilizing both calibration tasks, rest breathing and speech-like breathing, (LsqRC/AB and LsqRC) versus when calculated utilizing only one calibration task, rest breathing (LsqRC/AB–RB only and LsqRC–RB only). Statistical analyses were conducted separately for each group of children (TD and neuromotor disorders) because lung volume estimation error differs by neuromotor status in adults (McKenna & Huber, 2019). The level of significance was set as $p \leq .01$ for all statistical tests.

TD Children

A general linear mixed-model analysis of variance was calculated to analyze lung volume estimation errors. The main effect variables were method and sex. Age was modeled as a covariate. Age and sex were included in the statistical model to ensure that any differences in lung volume estimation error could not simply be explained by development or sex. Interaction effects of Method × Age and Method × Sex were examined in the model as well. Tukey's honestly significant difference post hoc tests were used to examine statistically significant pairwise comparisons for factors with more than two categorical levels (Method, Method × Sex). When the covariate, age, was significant, linear regressions were completed to assess the nature of the relationship between age and the dependent variables. If there was a significant interaction between age and method and/or sex, linear regressions were completed for each level of the categorical variable.

Children With Neuromotor Disorders

A general linear mixed-model analysis of variance was calculated to analyze lung volume estimation errors. The main effect variable was method. Age and sex were eliminated from the model for children with neuromotor disorders due to the small number of children in the group.

Results

TD Children

There was a significant main effect of method, $F(4, 312) = 54.99$, $p < .0001$, and age, $F(1, 78) = 57.91$, $p < .0001$, but no significant main effect of sex, $F(1, 78) = 0.02$, $p = .903$. There was a significant interaction effect for Method × Age, $F(4, 312) = 30.72$, $p < .0001$, but no

Table 2. Pairwise comparisons by group.

Group	Contrast	Mean difference	*SE*	*p*
Typically developing children	Banzett vs. LsqRC	9.86	0.79	< .0001*
	Banzett vs. LsqRC/AB	14.61	0.79	< .0001*
	LsqRC/AB vs. LsqRC	−4.75	0.79	< .0001*
	LsqRC/AB–RB only vs. LsqRC/AB	0.43	0.79	.983
	LsqRC–RB only vs. LsqRC	0.61	0.79	.938
Children with neuromotor disorder	Banzett vs. LsqRC	8.33	2.25	.007*
	Banzett vs. LsqRC/AB	12.34	2.25	< .0001*
	LsqRC/AB vs. LsqRC	4.01	2.25	.40
	LsqRC/AB–RB only vs. LsqRC/AB	1.08	2.25	.998
	LsqRC–RB only vs. LsqRC	0.68	2.25	.988

Note. *SE* = standard error; LsqRC = least squares method with rib cage correction only; LsqRC/AB = least squares method with both rib cage and abdomen corrections; RB only = method was calculated using only the rest breathing calibration task.

*$p \leq .01$.

significant interaction effect for Method × Sex, $F(4, 312) = 0.49$, $p = .740$.

Pairwise comparisons are presented by group in Table 2. Lung volume estimation errors are presented by group and method in Table 3. The LsqRC/AB method resulted in significantly smaller lung volume estimation errors than the LsqRC or the Banzett methods. The LsqRC method also resulted in significantly smaller lung volume estimation errors than the Banzett method. There were no significant differences in lung volume estimation errors for the LsqRC/AB and LsqRC methods when the correction factors were calculated using both the rest breathing and speech-like breathing calibration tasks versus when calculated using only the rest breathing calibration task.

Regression statistics describing the relationship between method and age for lung volume estimation error are presented in Table 4. The lung volume estimation errors for each method were significantly positively correlated with age. The lung volume estimation errors linearly decreased as age increased for each method. Lung volume estimation errors are presented by age and method in Table 5. Figure 2 depicts the linear relationship between the LsqRC/AB–RB only method and age. As the relationship between each respiratory calibration method and age for lung volume estimation error was the same, only one figure depicting the relationship was provided.

Children With Neuromotor Disorders

There was a significant main effect of method, $F(4, 32) = 9.28$, $p < .0001$. Pairwise comparisons are presented by group in Table 2. Lung volume estimation errors are presented by group and method in Table 3. The LsqRC/AB and LsqRC methods resulted in significantly smaller lung volume estimation errors than the Banzett method. There was no significant difference between the LsqRC/AB and LsqRC methods. There were no significant differences in lung volume estimation errors for the LsqRC/AB and LsqRC methods when the correction factors were calculated using both the rest breathing and speech-like breathing calibration tasks versus when calculated using only the rest breathing calibration task. Lung volume estimation errors for each child with a neuromotor disorders are presented by method in Table 6.

Discussion

This study compared the accuracy of three common respiratory calibration methods, two variations of the least squares method (LsqRC/AB and LsqRC) and the Banzett method, for estimating lung volume during speech breathing in children with and without neuromotor disorders. In support of the proposed hypotheses, the data revealed that

Table 3. Mean lung volume estimation errors (standard deviations) by method and group.

Age	Banzett	LsqRC/AB	LsqRC/AB–RB only	LsqRC	LsqRC–RB only
Typically developing children	18.95 (14.28)	4.39 (1.45)	4.83 (1.74)	9.19 (4.46)	9.82 (4.79)
Children with neuromotor disorder	17.26 (9.92)	4.92 (1.58)	6.00 (2.45)	8.93 (3.67)	9.61 (3.97)

Note. LsqRC/AB = least squares method with both rib cage and abdomen corrections; RB only = method was calculated using only the rest breathing calibration task; LsqRC = least squares method with rib cage correction only; the unit of measurement for all values is in percent vital capacity.

Table 4. Regression statistics describing the relationship between method and age for lung volume estimation errors for typically developing children.

Method	p	R^2
Banzett	< .0001*	.27
LsqRC/AB	< .0001*	.24
LsqRC	< .0001*	.25
LsqRC/AB–RB only	.0007*	.14
LsqRC–RB only	.0001*	.17

Note. LsqRC/AB = least squares method with both rib cage and abdomen corrections; LsqRC = least squares method with rib cage correction only; RB only = method was calculated using only the rest breathing calibration task.

*$p \leq .01$.

(a) the LsqRC/AB was the most accurate method (with significantly smaller lung volume estimation errors) for estimating lung volume in TD children and (b) the LsqRC/AB and LsqRC were more accurate than the Banzett method when estimating lung volume in children with neuromotor disorders, but the variations of the least square method were not significantly different from one another. The accuracy of each respiratory calibration method was significantly related to age in that lung volume estimation errors linearly decreased as age increased in for TD children. Since each respiratory calibration method was initially designed and validated on young healthy adults (Banzett et al., 1995; Chadha et al., 1982), this finding is not surprising. Discussion of the current results will be presented in the context of the adult literature, as this is the first study to report lung volume estimation errors for any respiratory calibration method utilized in children with or without neuromotor disorders.

Data from this study bolster claims from the adult literature that the least squares method, particularly the LsqRC/AB variation, is the most accurate respiratory calibration method in use at this time (Chadha et al., 1982; McKenna & Huber, 2019; Stromberg et al., 1993). The superiority of the least squares method is likely due to the fact that it is the only method that calculates the correction factors for the rib cage and abdomen by comparing estimated lung volumes to actual lung volumes acquired from a spirometer during the same task. By calculating each correction factor (rib cage and abdomen) separately, the LsqRC/AB method is flexible enough to account for the changing contributions of the rib cage and abdomen to lung volume change throughout the lifespan. The Banzett method, on the other hand, utilizes a set ratio (2:1) to discuss rib cage and abdomen contributions and does not allow for these lifespan changes within its calculation. It is possible that a different ratio could reduce lung volume estimation errors across the lifespan, but it is likely that this ratio would differ depending on age and neuromotor status.

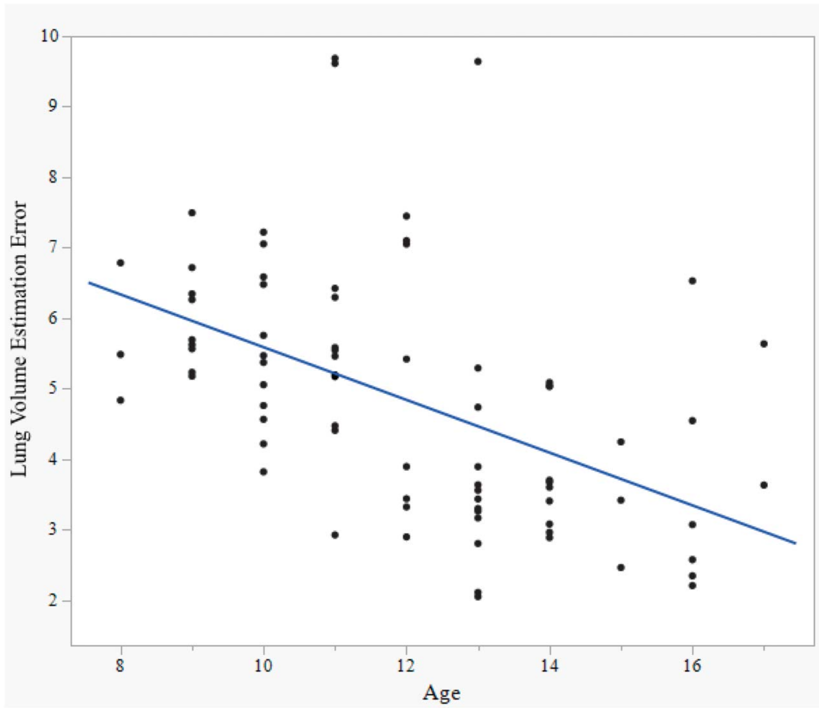
The lack of statistical difference between the LsqRC/AB and LsqRC methods in children with neuromotor disorders mirrors the results from individuals with Parkinson's disease presented in McKenna and Huber (2019). Taken together, these studies suggest that abdominal contributions do not significantly impact changes in lung volume in individuals with neuromotor disorders. Despite these converging results, the low number of participants with neuromotor disorders in each study (n = 13 in McKenna and Huber [2019] and n = 9 in this study) suggests that these results be interpreted with caution. When using the LsqRC/AB method, previous work in adults with and without neuromotor disorders indicates that lung volume change in the range of 2%VC–5%VC can lead to clinically significant differences in speech breathing variables such as lung volume excursion (Huber, 2008; Huber & Darling, 2011). Examination of the individual differences from children with neuromotor disorders between the lung volume estimation errors resulting from the LsqRC/AB and LsqRC methods indicates mean differences ranging from 1.27%VC and 9.47%VC. Approximately half (five of nine) of the children with neuromotor disorders demonstrated an error difference of greater than 2%VC across the estimation methods with the LsqRC/AB

Table 5. Mean lung volume estimation errors (standard deviations) by method for typically developing children.

Age	n	Banzett	LsqRC/AB	LsqRC/AB–RB only	LsqRC	LsqRC–RB only
8-year-olds	3	41.40 (21.61)	5.45 (0.73)	5.70 (0.99)	14.39 (3.50)	13.42 (2.73)
9-year-olds	9	29.07 (7.31)	5.58 (0.71)	6.01 (0.76)	14.49 (4.03)	15.31 (5.12)
10-year-olds	13	30.29 (22.28)	5.41 (1.16)	5.61 (1.11)	11.84 (6.51)	12.44 (6.92)
11-year-olds	13	22.34 (10.04)	5.12 (1.04)	5.90 (1.98)	9.13 (2.31)	9.59 (3.04)
12-year-olds	9	12.94 (5.27)	4.65 (1.85)	4.88 (1.88)	8.33 (2.86)	9.08 (3.80)
13-year-olds	13	12.53 (4.24)	3.45 (1.04)	3.91 (1.94)	7.71 (1.88)	8.62 (2.57)
14-year-olds	10	9.98 (4.70)	3.34 (0.73)	3.85 (0.88)	6.30 (1.56)	6.74 (1.55)
15-year-olds	4	5.29 (1.18)	3.08 (0.81)	3.15 (0.86)	4.83 (1.88)	5.00 (2.45)
16-year-olds	5	10.83 (1.79)	3.06 (1.29)	3.55 (1.69)	6.35 (2.53)	6.90 (2.76)
17-year-olds	2	11.24 (7.91)	3.12 (0.07)	4.64 (1.42)	5.96 (2.13)	8.99 (0.22)

Note. n = number of participants. LsqRC/AB = least squares method with both rib cage and abdomen corrections; RB only = method was calculated using only the rest breathing calibration task; LsqRC = least squares method with rib cage correction only; the unit of measurement for all values is in percent vital capacity.

Figure 2. The linear relationship between lung volume estimation error (%VC) and age for the LsqRC/AB–RB only method.



resulting in a smaller lung volume estimation error. In the context of the 2%VC–5%VC clinically significant margin of error, it is recommended that future studies examining speech breathing in children with neuromotor disorders utilize the LsqRC/AB method as the preferred respiratory calibration method until the differences in lung volume estimation error between the LsqRC/AB method and LsqRC method can be evaluated in a larger cohort. It is also recommended that the same respiratory calibration method be used when comparing different groups of speakers (McKenna & Huber, 2019). Given the superiority of the LsqRC/AB technique in TD children, the LsqRC/AB method should be utilized for children with neuromotor disorders when examining differences in speech breathing between these groups.

When using any respiratory calibration method, it is important to consider the potential for clinically significant differences in speech breathing variables to be the result of differences in lung volume estimation error as opposed to the result of differences in age and/or neuromotor status. As data from this study show that the LsqRC/AB method should be utilized for children with and without neuromotor disorders, it is important to focus on errors for that respiratory calibration method. There is no established range of minimally acceptable lung volume estimation error in the

Table 6. Lung volume estimation errors for each child with neuromotor disorder.

Participant	Age	Banzett	LsqRC/AB	LsqRC/AB–RB only	LsqRC	LsqRC–RB only
F01CP	13;5	7.51	5.37	5.60	6.60	6.76
F02CP	14;6	7.48	3.14	3.52	7.84	9.43
M04CP	11;9	24.33	3.79	3.91	12.24	11.90
F05CP	14;10	10.92	4.08	4.20	5.63	4.77
F07CP	9;2	11.51	4.58	5.49	10.13	10.49
M08CP	13;8	26.22	5.10	11.14	8.31	12.40
F09CP	8;3	18.37	2.74	2.75	4.96	4.78
F04DS	10;7	41.23	6.09	7.15	8.13	9.35
F05DS	13;6	3.12	3.13	3.66	4.88	4.97

Note. Age is provided in years;months. LsqRC/AB = least squares method with both rib cage and abdomen corrections; RB only = method was calculated using only the rest breathing calibration task; LsqRC = least squares method with rib cage correction only; F = female; M = male; CP = cerebral palsy; DS = Down syndrome; the unit of measurement for all values is in percent vital capacity.

respiratory kinematic literature. The only other study to normalize lung volume estimation error to VC, McKenna and Huber (2019) reported errors ranging from 2.1%VC for young adults to 4.6%VC for individuals with Parkinson's disease. Mean lung volume estimation errors from each age cohort (see Table 5) and the children with neuromotor disorders (4.23%VC) fall within this range. In addition, mean differences in lung volume estimation error for the LsqRC/AB method between each age cohort (calculated using data from Table 5; range: 0.02%VC–2.52%VC) and between TD children and children with neuromotor impairment were below the clinically significant margin of error (2%VC–5%VC) discussed above. This is a further indication that the LsqRC/AB technique is an accurate and valid technique for children ages 8 years and older with or without neuromotor impairment and will lead to identification of clinically significant differences related to development and/or neuromotor status as opposed to differences in lung volume estimation error. Future work is needed to examine the LsqRC/AB technique in children younger than 8 years old who can reasonably participate in the calibration tasks.

Methodological approaches to the study of speech breathing need to be accurate and efficient. Respiratory plethysmography as a technique is highly sensitive to positional changes of the body (e.g., sitting vs. standing and arm movements) and, therefore, requires the participant to remain in the same position the entire data collection process. Minimizing the amount of time a child is required to remain as still as possible to collect data is essential for a successful research protocol. The secondary purpose of this study was to examine the lung volume estimation errors of both variations of the least squares method when calculated with and without the use of the speech-like breathing task. The data indicate that the use of the speech-like breathing calibration task during the calculation of correction factors for the rib cage and abdomen does not significantly improve the accuracy of lung volume estimation error for either variation of the least squares method in children with and without neuromotor disorders. Differences in lung volume estimation error between estimates made with the speech-like breathing calibration task and without it were below the clinically significant margin of error described above (2%VC–5%VC) for all age groups of TD children and for all but one (M08CP) child with neuromotor disorders.

The accuracy of the least squares methods with and without the use of the speech-like breathing task has not been studied in children or adults. Theoretically, the speech-like breathing task samples a wider variety of lung volumes than the rest breathing task, which would then allow for more accurate lung volume estimates during speech breathing. However, this does not appear to be the case in children with and without neuromotor disorders. One possibility for this finding is that this task is more cognitively demanding than the rest breathing task and that children, especially those with cognitive-linguistic impairment or who cannot read, do not perform this task much differently than the rest breathing task. However, all children in the TD group could read, were in the typical range of cognitive-linguistic abilities, and followed the directions to complete the speech-like breathing task adequately. Furthermore, all but two children with neuromotor impairments were able to complete the speech-like breathing task without difficulty. Another possibility for this finding is that the least squares method is robust enough to estimate lung volume without the addition of the speech-like breathing task. As the TD cohort in this study is large, the speech-like breathing calibration task can likely be eliminated from future research protocols involving TD children. The data from eight of the nine children with neuromotor disorders follow the patterns in the TD data pointing to the likelihood that this task can be eliminated from future research protocols involving children with neuromotor disorders following larger scale studies examining the need for the speech-like breathing task in children with neuromotor disorders.

Limitations

The primary limitation of this study was that the isovolume method was not examined. Despite the fact that the isovolume method is the most widely utilized respiratory calibration method in children, there are no published studies regarding its accuracy estimating lung volume in children with which to compare these findings. In this study, the Banzett method was chosen as an appropriate stand-in for the isovolume method. Similar to the Banzett method, the isovolume method does not calculate the correction factors for the rib cage and abdomen via direct comparisons with lung volumes collected via a digital spirometer during the same task. Additionally, lung volume estimates based on the Banzett method do not differ from lung volume estimates based on the isovolume method in adult populations (Banzett et al., 1995; McKenna & Huber, 2019). The Banzett method is also easier to calculate than the isovolume method. The isovolume maneuver that the method depends upon is notoriously difficult for children to complete, especially for those with cognitive-linguistic deficits. Several studies examining speech breathing in children report uncalibrated (e.g., raw) lung volume data due to the issues with isovolume implementation (Connaghan et al., 2004; Moore et al., 2001; Redstone, 2004). However, it is possible that this relationship between the isovolume method and the Banzett method differs in children than what has been reported in adults.

Another limitation of this work is the exclusion of body size metrics, such as height and weight, in the regression analyses. Height and weight were collected via parent report, but were not independently verified and therefore not included in statistical analyses. The R^2 values describing the relationship between lung volume estimation errors and age range from .25 to .42, indicating that age is not the only variable contributing to the variance in lung volume estimation error. Future research should include body size metrics for a more complete understanding of the factors that contribute to lung volume estimation errors.

A final limitation of this study was the use of VC estimates from the VC maneuvers collected while wearing the Inductotrace bands to normalize lung volume estimation error in the children with CP that did not cooperate with lung function testing (F01CP and F09CP). In order to estimate VC from the Inductotrace bands, a decision had to be made about which set of calibration factors to utilize. Both variations (with and without the speech-like breathing task) of the LsqRC/AB method were considered as this was the method that resulted in the least amount of lung volume estimation error in the TD children and the majority of the children with neuromotor disorders. Estimates of VC from kinematic data and not from direct measurements of lung volume via a spirometer could introduce error into the measure. However, lung volume estimation errors for each participant followed the statistical and individual data trends for children with neuromotor disorders regardless of which calibration factors were utilized. Thus, this estimation method was deemed acceptable. The lung volume estimation errors for F01CP and F09CP published in this study were calculated from the LsqRC/AB–RB only method.

Conclusions

The LsqRC/AB method is the most accurate respiratory calibration method for use with children with and without neuromotor disorders. This method is easy to collect and minimizes lung volume estimation errors from children across a wide variety of age (8 years and older), cognitive-linguistic status, and physical impairment. In TD children and for all but one child with neuromotor disorders in this study, the use of the speech-like breathing tasks did not improve calibration accuracy, suggesting that researchers could choose to use just the rest breathing task to improve efficiency and feasibility of collecting respiratory data in children. These findings will allow researchers to conduct future work regarding speech breathing in these populations with the knowledge that any clinically significant differences are likely the result of actual physiologic differences between cohorts and not just the result of differences in lung volume estimation error, thus laying the foundation for the design and implementation of interventions to address speech breathing impairment in children with neuromotor disorders.

Acknowledgments

Research reported in this publication was supported by Grant R03DC015607, awarded to the author, from the National Institute on Deafness and other Communication Disorders of the National Institutes of Health. The content is solely the responsibility of the authors and does not necessarily reflect the official views of the National Institutes of Health. The author would like to thank Victoria S. McKenna, Brianna R. Kiefer, and Jessica E. Huber for their assistance with the custom, semi-automated MATLAB program. The author would like to thank the children and their families who participated in this research as well as the graduate and undergraduate students at The University of Arizona who assisted with data collection.

References

Banzett, R. B., Mahan, S. T., Garner, D. M., Brughera, A., & Loring, S. H. (1995). A simple and reliable method to calibrate respiratory magnetometers and respitrace. *Journal of Applied Physiology, 79*(6), 2169–2176. https://doi.org/10.1152/jappl.1995.79.6.2169

Boliek, C. A., Hixon, T. J., Watson, P. J., & Jones, P. B. (2009). Refinement of speech breathing in healthy 4- to 6-year-old children. *Journal of Speech, Language, and Hearing Research, 52*(4), 990–1007. https://doi.org/10.1044/1092-4388(2009/07-0214)

Boliek, C. A., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1996). Vocalization and breathing during the first year of life. *Journal of Voice, 10*(1), 1–22. https://doi.org/10.1016/S0892-1997(96)80015-4

Boliek, C. A., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1997). Vocalization and breathing during the second and third years of life. *Journal of Voice, 11*(4), 373–390. https://doi.org/10.1016/S0892-1997(97)80033-1

Chadha, T. S., Watson, H., Birch, S., Jenouri, G. A., Schneider, A. W., Cohn, M. A., & Sackner, M. A. (1982). Validation of respiratory inductive plethysmography using different calibration procedures. *American Review of Respiratory Disease, 125*(6), 644–649.

Connaghan, K. P., Moore, C. A., & Higashakawa, M. (2004). Respiratory kinematics during vocalization and nonspeech respiration in children from 9 to 48 months. *Journal of Speech, Language, and Hearing Research, 47*(1), 70–84. https://doi.org/10.1044/1092-4388(2004/007)

da Silva, V. Z. M., de França Barros, J., de Azevedo, M., de Godoy, J. R. P., Arena, R., & Cipriano, G., Jr. (2010). Bone mineral density and respiratory muscle strength in male individuals with mental retardation (with and without Down syndrome). *Research in Developmental Disabilities, 31*(6), 1585–1589. https://doi.org/10.1016/j.ridd.2010.05.003

Darling-White, M., & Huber, J. E. (2017). The impact of expiratory muscle strength training on speech breathing in individuals with Parkinson's disease: A preliminary study. *American Journal of Speech-Language Pathology, 26*(4), 1159–1166. https://doi.org/10.1044/2017_AJSLP-16-0132

Edgson, M. R., Tucker, B. V., Archibald, E. D., & Boliek, C. A. (2021). Neuromuscular and biomechanical adjustments of the speech mechanism during modulation of vocal loudness in children with cerebral palsy and dysarthria. *Neurocase, 27*(1), 30–38. https://doi.org/10.1080/13554794.2020.1862240

Ersoz, M., Selcuk, B., Gunduz, R., Kurtaran, A., & Akyuz, M. (2006). Decreased chest mobility in children with spastic cerebral palsy. *The Turkish Journal of Pediatrics, 48*(4), 344–350.

Hardy, J. C. (1961). Intraoral breath pressure in cerebral palsy. *Journal of Speech and Hearing Disorders, 26*(4), 309–319. https://doi.org/10.1044/jshd.2604.309

Hardy, J. C. (1964). Lung function of athetoid and spastic quadriplegic children. *Developmental Medicine & Child Neurology, 6*(4), 378–388. https://doi.org/10.1111/j.1469-8749.1964.tb08139.x

Hoit, J. D., Hixon, T. J., Watson, P. J., & Morgan, W. J. (1990). Speech breathing in children and adolescents. *Journal of Speech and Hearing Research, 33*(1), 51–69. https://doi.org/10.1044/jshr.3301.51

Huber, J. E. (2008). Effects of utterance length and vocal loudness on speech breathing in older adults. *Respiratory Physiology & Neurobiology, 164*(3), 323–330. https://doi.org/10.1016/j.resp.2008.08.007

Huber, J. E., Chandrasekaran, B., & Wolstencroft, J. J. (2005). Changes to respiratory mechanisms during speech as a result of different cues to increase loudness. *Journal of Applied Physiology, 98*(6), 2177–2184. https://doi.org/10.1152/japplphysiol.01239.2004

Huber, J. E., & Darling, M. (2011). Effect of Parkinson's disease on the production of structured and unstructured speaking tasks: Respiratory physiologic and linguistic considerations. *Journal of Speech, Language, and Hearing Research, 54*(1), 33–46. https://doi.org/10.1044/1092-4388(2010/09-0184)

Huber, J. E., & Spruill, J. (2008). Age-related changes to speech breathing with increased vocal loudness. *Journal of Speech, Language, and Hearing Research, 51*(3), 651–668. https://doi.org/10.1044/1092-4388(2008/047)

Jones, H. N., Crisp, K. D., Kuchibhatla, M., Mahler, L., Risoli, T., Jr., Jones, C. W., & Kishnani, P. (2019). Auditory-perceptual speech features in children with Down syndrome. *American Journal on Intellectual and Developmental Disabilities, 124*(4), 324–338. https://doi.org/10.1352/1944-7558-124.4.324

Kent, R. D., Eichhorn, J., Wilson, E. M., Suk, Y., Bolt, D. M., & Vorperian, H. K. (2021). Auditory-perceptual features of speech in children and adults with down syndrome: A speech profile analysis. *Journal of Speech, Language, and Hearing Research, 64*(4), 1157–1175. https://doi.org/10.1044/2021_JSLHR-20-00617

Konno, K., & Mead, J. (1967). Measurement of the separate volume changes of rib cage and abdomen during breathing. *Journal of Applied Physiology, 22*(3), 407–422. https://doi.org/10.1152/jappl.1967.22.3.407

McKenna, V. S., & Huber, J. E. (2019). The accuracy of respiratory calibration methods for estimating lung volume during speech breathing: A comparison of four methods across three adult cohorts. *Journal of Speech, Language, and Hearing Research, 62*(8), 2632–2644. https://doi.org/10.1044/2019_JSLHR-S-18-0478

Moore, C. A., Caulfield, T. J., & Green, J. R. (2001). Relative kinematics of the rib cage and abdomen during speech and nonspeech behaviors of 15-month-old children. *Journal of Speech, Language, and Hearing Research, 44*(1), 80–94. https://doi.org/10.1044/1092-4388(2001/008)

Palisano, R., Rosenbaum, P., Walter, S., Russell, D., Wood, E., & Galuppi, B. (1997). Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Developmental Medicine & Child Neurology, 39*(4), 214–223. https://doi.org/10.1111/j.1469-8749.1997.tb07414.x

Parham, D. F., Buder, E. H., Oller, D. K., & Boliek, C. A. (2011). Syllable-related breathing in infants in the second year of life. *Journal of Speech, Language, and Hearing Research, 54*(4), 1039–1050. https://doi.org/10.1044/1092-4388(2010/09-0106)

Redstone, F. (2004). The effects of seating position on the respiratory patterns of preschoolers with cerebral palsy. *International Journal of Rehabilitation Research, 27*(4), 283–288. https://doi.org/10.1097/00004356-200412000-00005

Reich, A. R., & McHenry, M. A. (1990). Estimating respiratory volumes from rib cage and abdominal displacements during ventilatory and speech activities. *Journal of Speech and Hearing Research, 33*(3), 467–475. https://doi.org/10.1044/jshr.3303.467

Reilly, K. J., & Moore, C. A. (2009). Respiratory movement patterns during vocalizations at 7 and 11 months of age. *Journal of Speech, Language, and Hearing Research, 52*(1), 223–239. https://doi.org/10.1044/1092-4388(2008/06-0215)

Rutherford, B. R. (1944). A comparative study of loudness, pitch, rate, rhythm and quality of the speech of children handicapped by cerebral palsy. *Journal of Speech Disorders, 9*(3), 263–271. https://doi.org/10.1044/jshd.0903.263

Sadagopan, N., & Huber, J. E. (2007). Effects of loudness cues on respiration in individuals with Parkinson's disease. *Movement Disorders, 22*(5), 651–659. https://doi.org/10.1002/mds.21375

Sparrow, S. S., Cicchetti, D. V., & Saulneir, C. A. (2016). *Vineland Adaptive Behavior Scales* (3rd ed.). Pearson.

Stathopoulos, E. T., Huber, J. E., Richardson, K., Kamphaus, J., DeCicco, D., Darling, M., Fulcher, K., & Sussman, J. E. (2014). Increased vocal intensity due to the Lombard effect in speakers with Parkinson's disease: Simultaneous laryngeal and respiratory strategies. *Journal of Communication Disorders, 48,* 1–17. https://doi.org/10.1016/j.jcomdis.2013.12.001

Stathopoulos, E. T., & Sapienza, C. M. (1997). Developmental changes in laryngeal and respiratory function with variations in sound pressure level. *Journal of Speech, Language, and Hearing Research, 40*(3), 595–614. https://doi.org/10.1044/jslhr.4003.595

Stromberg, N. O., Dahlback, G. O., & Gustafsson, P. M. (1993). Evaluation of various models for respiratory inductance plethysmography calibration. *Journal of Applied Physiology, 74*(3), 1206–1211. https://doi.org/10.1152/jappl.1993.74.3.1206

Wang, H. Y., Chen, C. C., & Hsiao, S. F. (2012). Relationships between respiratory muscle strength and daily living function in children with cerebral palsy. *Research in Developmental Disabilities, 33*(4), 1176–1182. https://doi.org/10.1016/j.ridd.2012.02.004

Wiig, E. H., Secord, W. A., & Semel, E. (2013). *Clinical evaluation of language fundamentals: CELF-5*. Pearson.

Workinger, M. S., & Kent, R. D. (1991). Perceptual analysis of the dysarthrias in children with athetoid and spastic cerebral palsy. In *Dysarthria and apraxia of speech: Perspectives on management* (pp. 109–126). Brookes.