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Research Article

Magnitude of Neck-Surface Vibration as an Estimate of Subglottal Pressure During Modulations of Vocal Effort and Intensity in Healthy Speakers

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Purpose: This study examined the relationship between the magnitude of neck-surface vibration (NSV_{Mag}; transduced with an accelerometer) and intraoral estimates of subglottal pressure (P'_{sg}) during variations in vocal effort at 3 intensity levels.
Method: Twelve vocally healthy adults produced strings of /pɑ/ syllables in 3 vocal intensity conditions, while increasing vocal effort during each condition. Measures were made of P'_{sg} (estimated during stop-consonant closure), NSV_{Mag} (measured during the following vowel), sound pressure level, and respiratory kinematics. Mixed linear regression was used to analyze the relationship between NSV_{Mag} and P'_{sg} with respect to total lung volume excursion, levels of lung volume initiation and termination, airflow, laryngeal resistance, and vocal efficiency across intensity conditions.
Results: NSV_{Mag} was significantly related to P'_{sg} ($p < .001$), and there was a significant, although small, interaction between NSV_{Mag} and intensity condition. Total lung excursion was the only additional variable contributing to predicting the NSV_{Mag}–P'_{sg} relationship.
Conclusions: NSV_{Mag} closely reflects P'_{sg} during variations of vocal effort; however, the relationship changes across different intensities in some individuals. Future research should explore additional NSV-based measures (e.g., glottal airflow features) to improve estimation accuracy during voice production.

A central component of the diagnosis and management of voice disorders is the assessment of aerodynamic measures that reflect respiratory and glottal function (Awan et al., 2014; Roy et al., 2013). A commonly used clinical voice measure is subglottal pressure (P_{sg}), which is critical for voice production and is often aberrant in individuals with phonatory abnormalities (e.g., glottal insufficiency, muscle tension dysphonia; Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989; Netsell, Lotz, & Shaughnessy, 1984; Stemple, Glaze, & Klaben, 2012; Wingate, Brown, Shrivastav, Davenport, & Sapienza, 2007). Unfortunately, techniques that measure P_{sg} directly are invasive, which has prompted a need to develop a clinically feasible, noninvasive tool that can estimate P_{sg} for the management of voice disorders. In the current study, we test the hypothesis that an indirect but close estimate of P_{sg} can be inferred from the magnitude of neck-surface vibrations (NSV_{Mag}) during vowels, as derived from the signal of a neck-mounted accelerometer—a portable, inexpensive, and noninvasive device. Toward this end, we have investigated the relationship between NSV_{Mag} and intraoral-based estimates of P_{sg} during modulations of voice quality and intensity.

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P_{sg} Estimates and NSV_{Mag}

P_{sg} “acts as the force building up below the adducted vocal folds, rising until it overcomes vocal fold resistance and sets the folds into oscillation” (Stemple et al., 2012, p. 158).

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Although P_{sg} can be measured directly using a tracheal puncture or esophageal balloon (Isshiki, 1963; Ladefoged & McKinney, 1963; Van den Berg, 1956), both methods are considered too invasive for clinical voice therapy. To address this problem, researchers have developed less invasive methods to estimate P_{sg} from intraoral pressure (e.g., airflow interruption, labial interruption; Bard, Slavit, McCaffrey, & Liptin, 1992; Jiang, Leder, & Bichler, 2006; Smitheran & Hixon, 1981). For example, the labial interruption method uses production of a bilabial stop consonant to estimate P_{sg} during an adjacent vowel production (e.g., /pi/; Holmberg, 1980; Lofqvist, Carlborg, & Kitzing, 1982; Smitheran & Hixon, 1981). A bilabial stop consonant requires closure of the lips and velopharyngeal port and abduction of the vocal folds. During a long enough consonant, this anatomical configuration results in equalization of pulmonary pressure above and below the glottis and allows for indirect estimation of P_{sg} from a pressure measurement in the oral cavity. Clinicians can use intraoral estimate of P_{sg}, referred to throughout this paper as P'_{sg}, to identify inefficient voice use (Mehta & Hillman, 2007) and to quantify therapeutic outcomes (Lim et al., 2007; Wingate et al., 2007). Although less invasive than a tracheal puncture, the labial interruption method lacks ecological validity because it requires an artificial set of speech tasks (e.g., /pi pi pi pi pi/), repeated at a slow rate without pausing between syllables (Hertegard, Gauffin, & Lindestad, 1995; Holmberg, Perkell, & Hillman, 1984). This type of speech task can be challenging for individuals with poor kinesthetic awareness and individuals with cognitive deficits. Therefore, there is a need to develop measurement techniques to estimate P_{sg} for vowels during more natural conversational speech. Such a technique could then be incorporated into ambulatory monitoring devices for biofeedback in individuals with, or at risk for, voice disorders (Llico et al., 2015; Mehta, Zanartu, Feng, Cheyne, & Hillman, 2012).

A high-bandwidth accelerometer has received attention in its utility as an ambulatory monitoring device. The accelerometer is an electromechanical sensor that captures acceleration (the second derivative of the displacement) of NSVs during phonation. The sensor is typically placed superior to the sternal notch and inferior to the cricoid cartilage, where it can be affixed to the skin of the neck with double-sided adhesive tape. With this placement, NSV_{Mag} has been shown to correlate with sound pressure level (SPL) within a range of up to ± 6 dB in most speakers (Svec, Titze, & Popolo, 2005). Fundamental frequency can also be estimated from the NSV signal (Askenfelt, Gauffin, Sundberg, & Kitzing, 1980; Stevens, Kalikow, & Willemain, 1975; Szabo, Hammarberg, Hakansson, & Sodersten, 2001); however, it has been more challenging to relate measures of spectral tilt from the NSV signal to their acoustic counterparts (Mehta, Van Stan, & Hillman, 2016; Zanartu, Ho, Mehta, Hillman, & Wodicka, 2013).

Recent work of Zanartu et al. (2013) has indicated that specific glottal aerodynamic measurements can be estimated from the NSV signal using a subglottal impedance-based inverse filtering (IBIF) technique. This technique estimates a glottal waveform from the NSV signal that is comparable with glottal volume velocity waveforms derived from inverse filtering the airflow captured with a pneumotachographic oronasal mask (Glottal Enterprises; Rothenberg, 1973). The participants in the study by Zanartu et al. (2013) produced sustained vowels in the modal, modal-loud, breathy, and falsetto vocal modes while simultaneous recordings were made of oral airflow, electroglottographic, and NSV signals. Results indicated that NSV signals can be used to estimate the peak-to-peak amplitude of the oscillatory component of the glottal airflow signal (AC flow) and maximum flow declination rate (MFDR; R^2 values of .97 and .98, respectively). Further work by Mehta et al. (2015) evaluated the IBIF technique developed by Zanartu et al. (2013), but from measures made during a reading passage. Findings indicated that the IBIF scheme could be used to reliably extract MFDR from the NSV signal in connected speech contexts as well.

It follows that being able to estimate P_{sg} from the NSV signal would enhance the capabilities of an ambulatory monitoring device. Previous work has indicated that NSV_{Mag}, calculated as the root-mean-square of the NSV signal during the vowel that follows a bilabial stop consonant, correlates strongly with P'_{sg}. In a recent study by Fryd, Van Stan, Hillman, and Mehta (2016), vocally healthy participants produced syllable strings from a loud vocal intensity decreasing to a soft intensity (decrescendo) in the context of different consonant–vowel combinations (/pa/, /pi/, /pu/) and pitches (low, comfortable, high). The results indicated high within-speaker relationships between NSV_{Mag} and P'_{sg} (r^2 = .68–.93) for all manipulations of vowel, pitch, and intensity, and the individual relationships between NSV_{Mag} and P'_{sg} were consistently stronger (higher r^2) than those between NSV_{Mag} and vocal intensity (dB SPL).

Although vocally healthy speakers have been shown to exhibit strong relationships between P'_{sg} and vocal intensity (Baker, Ramig, Sapir, Luschei, & Smith, 2001; Bjorklund & Sundberg, 2016; Bouhuys, Mead, Proctor, & Stevens, 1968; Isshiki, 1963), individuals with voice disorders often exhibit elevated P'_{sg} without concurrent changes in vocal intensity (Hillman et al., 1989). That imbalance results in changes to overall vocal efficiency (a ratio of the acoustic power output to the driving aerodynamic input; Mehta & Hillman, 2007), with lower efficiency evident in individuals with voice disorders (Friedman, Hillman, Landau-Zemer, Burns, & Zeitels, 2013; Zietels, Burns, Lopez-Guerra, Anderson, & Hillman, 2008). Likewise, increased vocal effort does not necessarily correlate with the perception of loudness (Lane, Catania, & Stevens, 1961). Rather, increasing effort may be a compensatory behavior to maintain the same vocal intensity in the presence of changes in vocal fold tissue properties and/or reduced muscular endurance (McCabe & Titze, 2002). Vocal effort is one of the most common symptoms reported by individuals with high voice demands (de Alvear, Baron, & Martinez-Arquero, 2011) and may be a potential indicator of vocal inefficiency.

Described as "an exertion" of the voice (Baldner, Doll, & van Mersbergen, 2015), excessive vocal effort has been closely linked to vocal fatigue (Chang & Karnell, 2004; McCabe & Titze, 2002) and perceptual correlates of strain, breathiness, and roughness (Holmberg, Doyle, Perkell, Hammarberg, & Hillman, 2003; Kempster, Gerratt, Abbott, Barkmeier-Kraemer, & Hillman, 2009). There are many physiological strategies that have been shown to contribute to excessive vocal effort besides increasing P'_{sg}, such as increases in extrinsic and/or intrinsic laryngeal muscular tension (Angsuwarangsee & Morrison, 2002; McKenna, Heller Murray, Lien, & Stepp, 2016; Redenbaugh & Reich, 1989; Stepp et al., 2011), supraglottal compression (Stager, Bielamowicz, Regnell, Gupta, & Barkmeier, 2000), and transglottal airflow (Rosenthal, Lowell, & Colton, 2014). Characterizing excessive vocal effort is complex and requires consideration of respiratory, laryngeal, aerodynamic, and acoustic parameters as well as their potential interactions.

Research Questions

Fryd et al. (2016) provided promising evidence for being able to estimate P'_{sg} from the NSV signal; thus, a logical next step would be to examine that relationship during voice productions that may not exhibit a reliable relationship between vocal intensity and P'_{sg}. Therefore, the aim of this study was to examine the relationship between NSV_{Mag} and P'_{sg} during modulations of vocal effort across different vocal intensities in vocally healthy individuals. Due to the complex relationship between respiratory and laryngeal functions, we also sought to determine how additional measures of respiration and laryngeal efficiency (lung volume initiation, lung volume termination, total lung volume excursion, airflow, vocal efficiency, and laryngeal resistance) might account for variation in the relationship between NSV_{Mag} and P'_{sg}. Thus, we addressed the following research questions:

1. What is the relationship between NSV_{Mag} and P'_{sg} across a range of vocal productions that vary in vocal effort?
2. How does vocal intensity interact with the relationship between NSV_{Mag} and P'_{sg} during a range of effortful productions?
3. To what extent and how do additional respiratory and laryngeal efficiency measures account for the variation in the NSV_{Mag}–P'_{sg} relationship?

Method

Participants

Twelve participants aged 19–28 years (M = 22.3 years, SD = 2.9 years; six men and six women) completed the study. Participants were healthy speakers of American English, without any history of speech, language, hearing, neurological, voice, or pulmonary disorders (e.g., asthma). All participants reported no history of singing training (beyond middle school), playing of wind instruments, or smoking. They were screened by a certified speech-language pathologist for typical vocal quality via perceptual assessment. We chose to enroll vocally healthy individuals because they can produce wide ranges of vocal intensities and excessive vocal effort. Healthy individuals can also act as their own controls so their effortful voice productions can be compared with their typical voice productions. All participants consented to the protocol, which was approved by the institutional review board of Boston University.

Instrumentation and Calibration

Participants were fit with a headset microphone (Shure WH20; placed 7 cm from the lips at a 45° angle from midline) and a BU series 21771 accelerometer[1] (Knowles Electronic) placed superior to the sternal notch with double-sided adhesive tape. The headset microphone was calibrated with a sound pressure meter (Galaxy Audio, CM-150) placed 7 cm from the lips angled toward the mouth, with acoustic excitation provided by an electrolarynx located at the corner of the mouth. The acoustic signal was digitized with a soundcard (MOTU UltraLite-mk3 Hybrid) at a rate of 44100 Hz and 16 bits, as controlled by SONAR Artist software (Cakewalk). The same microphone signal was recorded a second way through a data acquisition board (DAQ; National Instruments) so that respiratory kinematics and the microphone signal could be time-aligned during signal processing.

The Phonatory Aerodynamic System (PAS; Model 6600; PENTAX Medical) captured intraoral pressure via a catheter placed in the oral cavity. The PAS has a built-in microphone that was used to time-align the PAS signals with the other recorded signals. Calibrated intraoral pressure (in centimeters of water) was sampled at 200 Hz, whereas the PAS microphone signal was sampled at 22050 Hz.

Respiratory kinematics were recorded with a commercially available respiratory inductive plethysmograph system (Inductotrace; Ambulatory Monitoring, Inc.). Participants were fit with two flexible respiratory inductive plethysmography bands (inductobands), each equipped with wires arranged in a way that results in modification of electrical impedance proportional to changes in the bands' length during respiration (Cohn, Watson, Weisshaut, Stott, & Sackner, 1977). One inductoband was placed around the thorax at the level of the rib cage, and the other was placed at the level of the abdomen. To convert the voltage change to a volume estimate in liters, all participants completed a calibration protocol: inspirations and expirations with a 0.8-L spirometer bag, first standing and then sitting (Cohn et al., 1977). Using the least squares method (Inductotrace Instruction Manual; Ambulatory Monitoring, Inc.), rib and abdomen correction factors were calculated. After this

[1]The BU Series 21771 accelerometer has a linear frequency response of up to 2500 Hz, which covers most energy known to be in the NSV signal (Mehta et al., 2016).

calibration, participants remained seated in a slightly reclined position at 120° (approximately 10° reclined from a typical sitting position; Harrison, Harrison, Croft, Harrison, & Troyanovich, 1999) with head and neck support to increase their comfort and limit the amount of body movement over the duration of the study. Participants were advised to remain as still as possible while the inductobands were monitored for potential movement and waveforms were examined for possible movement artifacts. Any movement or change in the bands from their original position would invalidate the calibration procedure. Inductotrace output signals were digitized at a sampling rate of 11025 Hz via a DAQ. The raw voltage data were later converted to liters during data processing.

Protocol and Training

Participants were first instructed to place the tip of the intraoral pressure catheter one third of the way into the oral cavity. They were trained to produce sets of /pɑ/ at a slow rate without pausing between syllables.[2] A single set of /pɑ/ syllables was defined as an initial /ɑ/ vowel, followed by five repetitions of /pɑ/ (i.e., /ɑ pɑ pɑ pɑ pɑ pɑ/). A metronome, set to 92 beats per minute (about 1.5 syllables/s), assisted in training a consistent speech-syllable rate and an utterance duration of approximately 4 s.

A pressure pulse is a single, step-like increase and decrease in intraoral pressure during the /p/ in a /pɑ/ production. The pressure pulse maximum should be "flat" for accurate P_{sg} estimation, as a flat pulse maximum indicates that pressure levels above and below the vocal folds have equilibrated. Participants were able to monitor the shape of the intraoral pressure pulses using the PAS visual display, with a goal to produce a flat top at each /pɑ/ production.

Once participants were able to produce a set of /pɑ/ syllables with the target rate and pulse shape, they were instructed to increase their vocal effort. Productions of vocal effort were elicited by the direction to "produce extra effort in your voice, as if you are pushing your air out. Try to maintain the same volume while increasing your effort." Participants were instructed to maintain the same amount of effort within a set of /pɑ/ syllables but to increase their effort for each consecutive set to reach a personal maximal effort level. Finally, participants received training to vary their vocal intensity. A range of at least ± 6 dB from each participant's comfortable speaking intensity was elicited to produce loud and soft vocal intensities. Individuals were deemed appropriately trained once three sets of /pɑ/ syllables met the criteria of rate, pulse shape, and excessive effort at each vocal intensity level.

[2]Before initiating the experiment described in this study, we completed feasibility testing. We observed an increase in nasality during the production of the more commonly used /æ/ vowel when some of the healthy speakers were increasing vocal effort. Therefore, we chose the /ɑ/ vowel to maintain a tight seal of the velopharyngeal port and the anatomical configuration necessary to obtain accurate P'_{sg}.

Participants began recordings with their comfortable speaking voice with no extra effort, referred to from here on as their baseline measurements. Next, they were instructed to maintain their comfortable vocal intensity while systematically increasing their vocal effort, referred to as the comfortable condition. They were advised to continue increasing their vocal effort until they reached their personal maximal effort. This same strategy was repeated for the loud and soft vocal intensities. As a result, each individual produced a variation in effort levels, extending from the least amount of effort to the maximal vocal effort they were able to produce. All participants performed each task in the same order, and all reported attaining their maximal vocal effort. Each vocal intensity condition (comfortable, loud, and soft) was recorded three times with eight sets per recording, resulting in 24 sets of /pɑ/ syllables per condition. The baseline (comfortable intensity, no extra effort) was recorded twice, for a total of 16 productions.

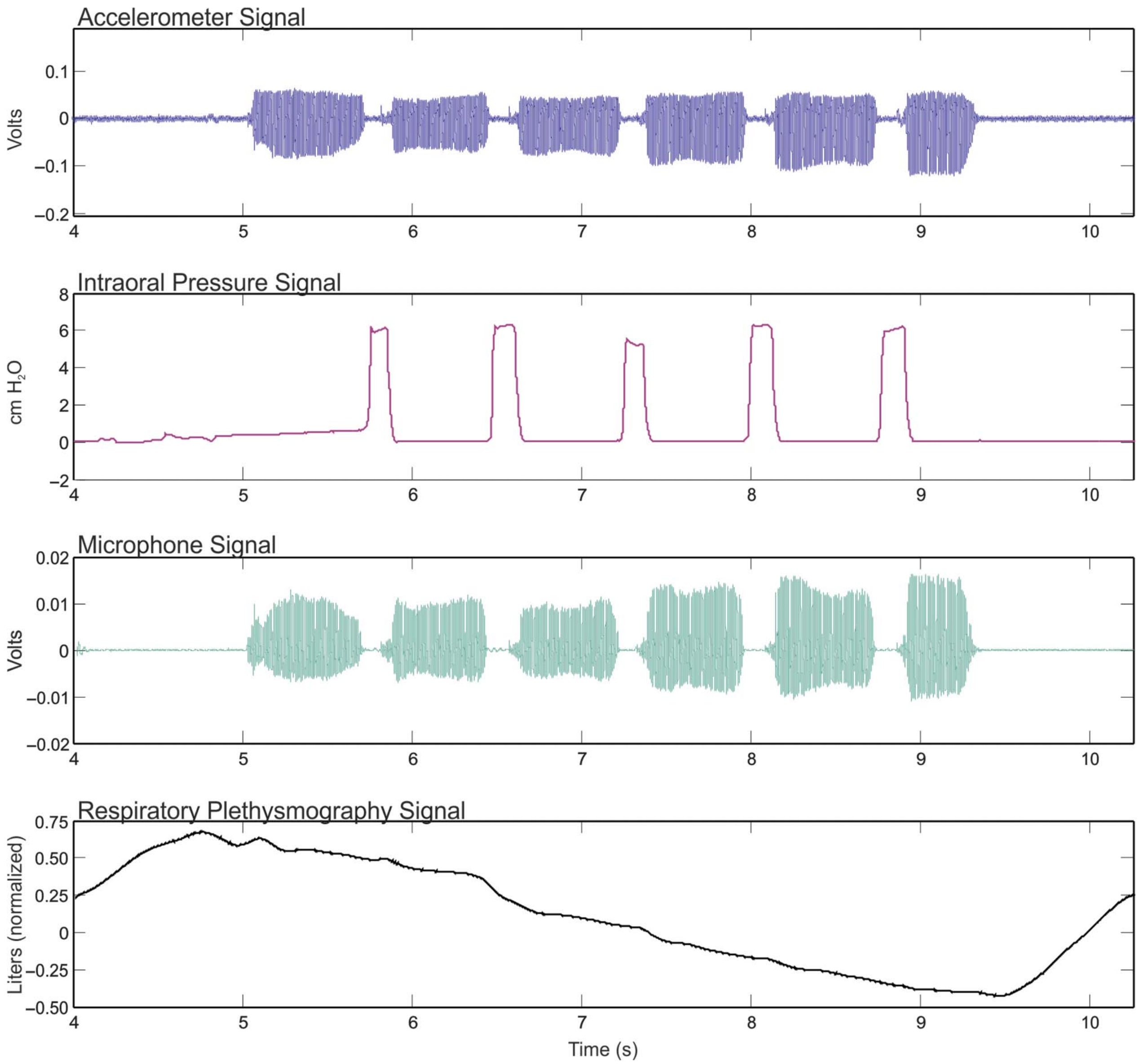
To limit extraneous movements that might impact the respiratory plethysmography signal, participants were given the PAS handheld device for each trial and instructed to only move their forearms while keeping their elbows on the arm rest of the chair. Participants were allowed to rest between recordings. The entire session, including consent, calibration, training, and recordings, lasted approximately 2 hr.

Signal Processing and Data Analysis

All signals were processed, and data were extracted with custom algorithms written in MATLAB 8.1 (MathWorks). Signals were resampled to 44100 Hz and time-aligned using the microphone signals from each recording. Figure 1 provides an example of the time-aligned signals that were used to extract parameters of interest. User-assisted algorithms were developed to extract acoustic, aerodynamic, and respiratory parameters for each set of /pɑ/ syllables. P'_{sg}, NSV_{Mag}, and SPL were averaged across the middle three /pɑ/ productions in each string (i.e., /ɑ pɑ <u>pɑ pɑ pɑ</u> pɑ/) to avoid any beginning or end effects from the first and fifth /pɑ/s. The following parameters were extracted from the raw data:

1. Intraoral pressure:
   (a) P'_{sg} (centimeters of water): This was calculated as the maximum value during the bilabial stop consonant /p/ as an estimate of P_{sg}.
   (b) Variation of the pressure during each pulse (centimeters of water): We extracted points within 5% of the maximum peak of each pressure pulse and determined the standard deviation of those values. The variation is reported as ± 1.96 × *SD*. Each pulse was inspected visually to ensure extraction accuracy.
2. NSV_{Mag} (volts): The raw NSV signal was full-wave rectified and then low-pass filtered with a first-order

Figure 1. An example of the time-aligned signals for a single set of /pɑ/ syllables produced by Participant 4.



Butterworth filter at a cutoff frequency of 12 Hz. To determine the noise floor for each condition for each participant, a 500-ms period of rest was extracted from each filtered NSV signal and averaged. From this, a threshold was calculated for the onset and offset of phonation. Thresholds were set at six to eight times the noise floor, based on visual inspection of the signal-to-noise ratio of the NSV signal (e.g., the signals during the soft condition had a lower signal-to-noise ratio, so their thresholds were set at six times the noise floor to ensure the entire vowel was captured). Each vowel was then extracted beginning at the center of the /ɑ/ and moving outward until the envelope amplitude dropped below the threshold. The root-mean-square of the vowel segment was calculated in the raw NSV signal.

3. Vocal intensity (dB SPL): The high-quality microphone signal was calibrated to dB SPL using reference electrolarynx levels of known SPL.

4. Inductotrace signals: The rib and abdomen signals were multiplied by correction factors determined in the calibration procedure to convert the raw voltage into liters. The calibrated rib and abdomen signals were summed together and normalized by an individual reference value (determined as the

average of three tidal breathing troughs). The calibrated, summed, and normalized respiratory signal was then used for parameter extraction:

(a) Lung volume initiation (liters): The inspiratory peak is the highest point of lung excursion at the beginning of each set of /pɑ/ syllables. The average peak during baseline productions (without additional effort) was subtracted from each inspiratory peak value to account for individual variation and allow for a group analysis.[3] Lung volume initiation is therefore a change (in liters) from baseline.

(b) Lung volume termination (liters): The expiratory trough is the lowest point of lung excursion at the end of each set of /pɑ/ syllables. To determine the difference (in liters) from the baseline, the average baseline trough was subtracted from each expiratory trough value during the conditions with excessive vocal effort.

(c) Total lung excursion (liters): The volume from the inspiratory peak to the expiratory trough for each set of /pɑ/ syllables.

(d) Airflow (liters per second): We determined the average lung volume corresponding to the steady-state portion of the three /ɑ/ vowels and fit a regression line to those averages. We reported the slope of the line as the estimated airflow.

5. Laryngeal efficiency ratios: Vocal efficiency and laryngeal resistance are two ratios that characterize the interplay between the respiratory and laryngeal subsystems during voicing. They have been shown to vary based on gender (Hoit & Hixon, 1992; Holmberg et al., 1984), vocal intensity (Friedman et al., 2013), and vocal mode (e.g., breathy, pressed; Grillo, Perta, & Smith, 2009; Grillo & Verdolini, 2008):

(a) Vocal efficiency ([dB SPL]/[cm H_2O]): The average vocal intensity divided by the average P'_{sg} for each set of /pɑ/ syllables.

(b) Laryngeal resistance ([cm H_2O]/[L/s]): The average P'_{sg} divided by the average airflow for each set of /pɑ/ syllables.

Data were excluded from the analysis for productions when the participant produced too few or too many /pɑ/ syllables within a set, the participant took a breath in the middle of a /pɑ/ set, or the intraoral pressure waveform did not return to 0 cm H_2O between /pɑ/ productions.

All participants were able to produce flat intraoral pressure pulses during their baseline productions, with an average pulse variation of ± 0.17 cm H_2O (range = 0.07–0.29 cm H_2O). The intraoral pressure pulses became less flat as participants increased their vocal effort across intensities, with average pulse variations as follows: soft = ± 0.28 cm H_2O, comfortable = ± 0.34 cm H_2O, and loud = ± 0.51 cm H_2O. The study by Fryd et al. (2016) found no significant differences in statistical calculations when using a plateau cutoff criterion or when using all of the pulses available; therefore, we decided to utilize all intraoral pressure pulses regardless of how flat they were.

[3]Baseline measurements were subtracted from lung volume initiation and lung volume termination because we were unable to add the baseline condition as a covariate into the linear mixed-effects model (due to the nature of the outcome variable and the behavior of baseline measures).

Statistical Analysis

Pearson product–moment correlation coefficients were determined between NSV_{Mag} and P'_{sg} for each participant at each intensity condition (comfortable, loud, and soft) and then for all conditions combined, including baseline productions. A criterion of $r \geq .50$ was used as a marker of at least a moderate positive correlation.

Two separate mixed-effects linear regression models were completed. Model 1 addressed the first research question, which sought to determine the relationship between NSV_{Mag} and P'_{sg} during the production of variations in vocal effort. Therefore, NSV_{Mag} and participant (random factor) were entered as predictor variables for the outcome variable P'_{sg}. Model 2 determined how vocal intensity influenced the relationship between NSV_{Mag} and P'_{sg}. NSV_{Mag}, vocal intensity condition (comfortable, loud, soft), and the interaction between NSV_{Mag} and intensity condition (NSV_{Mag} × Intensity Condition) were fixed predictor variables, whereas participant was entered as a random predictor. The coefficient of determination was calculated for both models, and a statistical comparison between the models was completed via a chi-square analysis to determine if including vocal intensity and the interaction into Model 2 significantly improved the prediction of P'_{sg}.

To address the third research question, we completed six separate mixed linear regression models with six variables (lung volume initiation, lung volume termination, total lung excursion, airflow, vocal efficiency, and laryngeal resistance) to determine how the variables accounted for change in the relationships between P'_{sg} and NSV_{Mag} across different intensities. The variables of interest were averaged within each intensity condition (comfortable, loud, and soft) for each participant, resulting in three average values per participant for each of the six variables. Each model included variable of interest, intensity condition, the interaction effect (Intensity Condition × Variable of Interest), and participant (random). The slopes of the linear relationship between P'_{sg} and NSV_{Mag} for each participant and each condition were the outcome variables for each model.

The statistical models did not include any baseline measurements as these measurements were not made with any increase in vocal effort. The mixed linear regression models were computed using Minitab statistical software (Version 17), whereas post hoc comparisons and the chi-square analyses were computed in the statistical package R (Version 3.2.2). All significance values were set a priori to

$p < .05$, with a Bonferroni–Holm adjustment for post hoc comparisons to account for Type I error.

Results

Participants produced an average of 13.6 usable /pɑ/ sets during their baseline productions, 22.0 comfortable sets, 21.6 loud sets, and 22.1 soft sets. In total, 954 sets of /pɑ/ syllables were available for analysis. Figure 2 provides all NSV_{Mag} and P'_{sg} data points for each participant across all conditions (baseline, comfortable, loud, and soft).

Table 1 reports summary statistics of the aerodynamic, respiratory, and laryngeal efficiency ratios for the baseline /pɑ/ productions. P'_{sg} and airflow were within normal ranges reported previously in healthy male and female speakers during typical vocal productions (Baker et al., 2001; Bernthal & Beukelman, 1978; Holmberg, Hillman, & Perkell, 1988; Murray, 1971; Smitheran & Hixon, 1981; Stemple et al., 2012; Tanaka & Gould, 1983). For example, male and female speakers produced average airflow values of 0.24 and 0.18 L/s, respectively, which are comparable with those produced by male (M = 0.19 L/s, range = 0.10–0.30 L/s) and female (M = 0.14 L/s, range = 0.09–0.21 L/s) speakers in the study by Holmberg et al. (1988). Laryngeal resistance ratios (based on the airflow estimates determined from the respiratory plethysmography signal) also fell within normal ranges of 30–40 (cm H_2O)/(L/s) during baseline productions (Smitheran & Hixon, 1981).

Participants were able to produce the target intensity ranges for comfortable (M = 78.6 dB SPL, SD = 4.3 dB), loud (M = 87.3 dB SPL, SD = 4.2 dB), and soft (M = 72.1 dB SPL, SD = 4.0 dB) productions. Total lung excursion, airflow, and P'_{sg} all showed increasing trends during the progression from soft, to comfortable, to loud conditions, a common occurrence that has been noted previously (Holmberg et al., 1988; Isshiki, 1963; Jiang et al., 1999; Rosenthal et al., 2014). Please see Figure 3 for boxplot distributions of total lung excursion and airflow across each intensity condition. P'_{sg} values were converted to the dB scale ($20 \times \log_{10} [P'_{sg}]$) and correlated with vocal intensity (dB SPL), revealing a moderate-to-strong positive correlation (average r = .71). Vocal intensity increased by an average of 7.4 dB (range = 3.4–10.4 dB) for every doubling (~6-dB increase) of P'_{sg}. Typically, healthy individuals increase vocal intensity by 9–13 dB when increasing P'_{sg} by a factor of 2 (Fryd et al., 2016; Holmberg et al., 1988; Lamarche & Ternstrom, 2008; Sundberg, Titze, & Scherer, 1993; Tanaka & Gould, 1983). However, the participants in our study were trained to increase vocal effort while trying to maintain a constant vocal intensity. This training most likely resulted in the reduced changes in vocal intensity relative to the P'_{sg} increases.

Figure 2. Average P'_{sg} and NSV_{Mag} for each set of /pɑ/ syllables plotted per participant. The loudness conditions (comfortable, loud, and soft) are produced with varied vocal effort, whereas baseline productions are produced without any additional vocal effort. Individual regression lines are placed for the conditions that included vocal effort. P'_{sg} = subglottal pressure estimate; NSV_{Mag} = magnitude of neck-surface vibration.

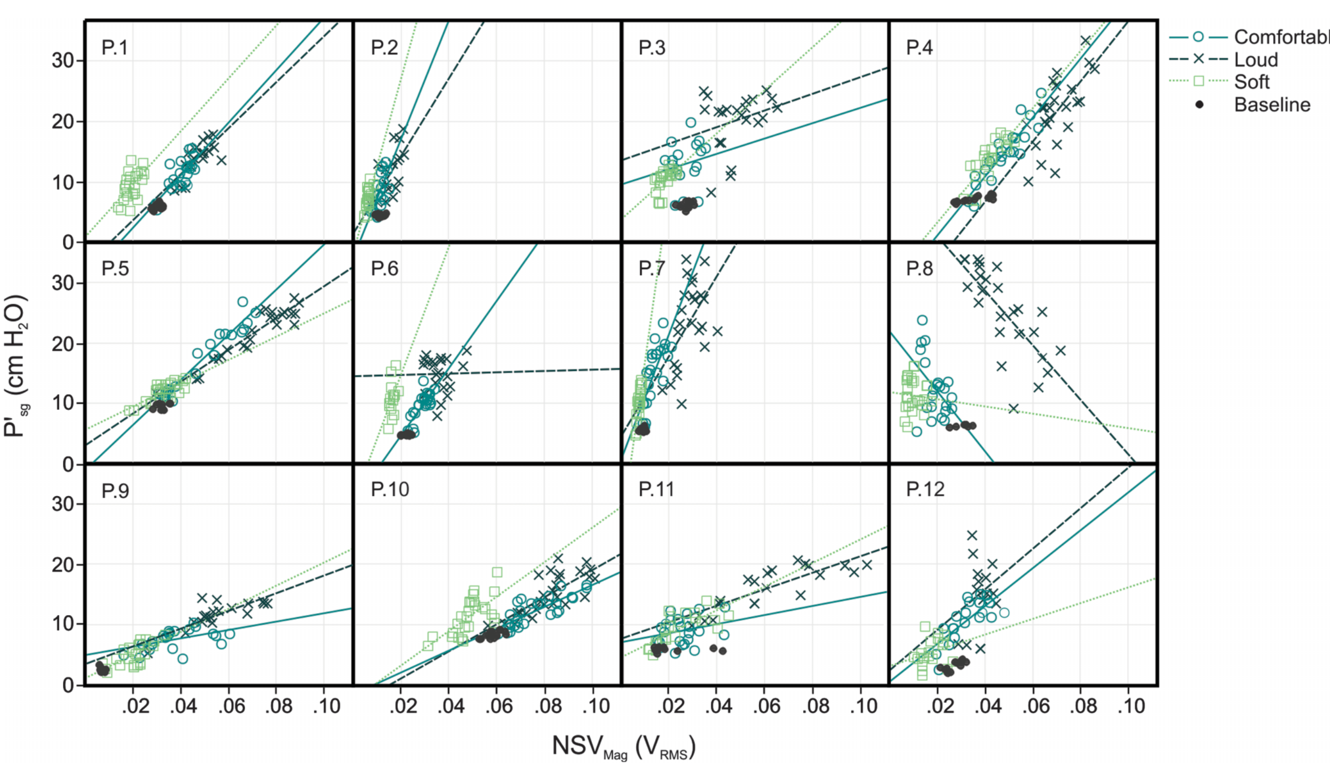


Table 1. Aerodynamic, respiratory, and laryngeal efficiency ratios: mean (standard deviation) during baseline productions.

Variable	All participants (*N* = 12)	Female (*n* = 6)	Male (*n* = 6)
P'_{sg} (cm H_2O)	5.95 (1.86)	5.19 (2.22)	6.71 (0.97)
Total lung excursion (L)	0.94 (0.30)	0.83 (0.28)	1.05 (0.25)
Airflow (L/s)	0.21 (0.07)	0.18 (0.06)	0.24 (0.06)
Vocal efficiency ([dB SPL]/[cm H_2O])	14.11 (5.19)	16.60 (6.48)	11.64 (1.56)
Laryngeal resistance ([cm H_2O]/[L/s])	31.25 (11.58)	30.31 (13.19)	32.21 (10.90)

Note. Baseline productions are at a comfortable speaking intensity with no additional vocal effort. P'_{sg} is the average of the maximum intraoral pressure pulses during a bilabial stop consonant /p/ in a set of /pɑ/ syllables.

Individual Correlation Coefficients

Individual Pearson product–moment correlation coefficients were determined between the NSV_{Mag} and P'_{sg} for each condition and then all conditions combined (comfortable, loud, soft, and baseline productions). Table 2 reports the correlation coefficients for each participant. Nine of the 12 participants (75%) exhibited at least a moderate positive relationship ($r \geq .50$) between NSV_{Mag} and P'_{sg} during the comfortable condition (comfortable speaking volume with increasing vocal effort). The same pattern was observed across each intensity condition with approximately 77% of all possible correlations (12 participants × 4 calculated correlations) meeting the same criterion. All correlations were positive, except for one participant (P8) who exhibited negative relationships between the NSV_{Mag} and P'_{sg} for each intensity condition.

Research Questions 1 and 2: Mixed Regression Models

The two separate linear mixed-effects regression models were used to analyze the intensity conditions (comfortable, loud, and soft) that included vocal effort with 790 /pɑ/ sets included in the analysis (954 total minus the 164 baseline productions). The first regression model (Model 1) explored the relationship between NSV_{Mag} and P'_{sg} during the production of varying vocal effort (all intensities analyzed together). The results indicated that NSV_{Mag} ($F(1, 777) = 729.64$, $p < .001$) and participant ($F(11, 777) = 66.80$, $p < .001$) were both significant predictors of P'_{sg} with large effect sizes of $\eta_p^2 = .48$ and $\eta_p^2 = .49$, respectively (Witte & Witte, 2010). The predictors accounted for 61% of the variance in the model (adjusted $R^2 = .61$).

A second mixed linear regression analysis (Model 2) revealed that NSV_{Mag} ($F(1, 773) = 226.26$, $p < .001$), vocal intensity condition ($F(2, 773) = 43.42$, $p < .001$), and the interaction between NSV_{Mag} and intensity condition ($F(2, 773) = 23.79$, $p < .001$) significantly predicted P'_{sg}. NSV_{Mag} had a medium-to-large effect size ($\eta_p^2 = .23$), vocal intensity condition had a medium effect size ($\eta_p^2 = .10$), and the interaction between the two was small to medium ($\eta_p^2 = .06$). The random effect factor of participant was also significant, with a large effect size ($F(11, 773) = 57.78$, $p < .001$, $\eta_p^2 = .45$). The variables explained 66% of the variance in P'_{sg} (adjusted $R^2 = .66$).

Model 2 revealed a higher coefficient of determination (adjusted $R^2 = .66$) compared with Model 1 ($R^2 = .61$). A chi-square analysis revealed that Model 2 was significantly better than Model 1 in accounting for the variance in P'_{sg} ($\chi^2(6) = 186.27$, $p < .001$).

Main effect post hoc comparisons of the three vocal intensity levels (comfortable, loud, and soft) were significantly different for all comparisons (all adjusted *p*s < .001).

Figure 3. Boxplot of airflow and total lung excursion for each vocal condition.

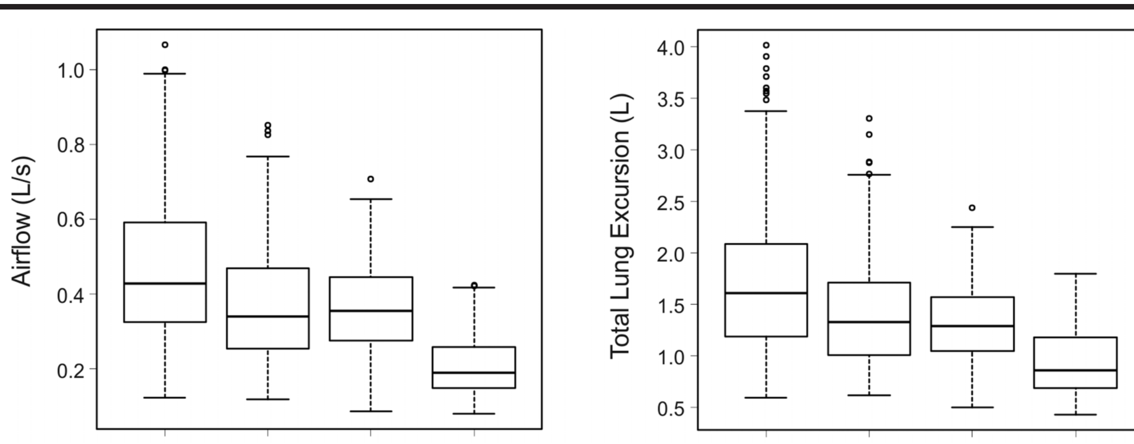


Table 2. Individual Pearson product–moment correlation coefficients (*r*) between P'_{sg} and NSV_{Mag} for each intensity condition alone and for all conditions combined (comfortable, loud, soft, and baseline).

Participant	Comfortable condition (*r*)	Soft condition (*r*)	Loud condition (*r*)	All conditions combined (*r*)
P1	.79	.56	.73	.65
P2	.69	.73	.68	.61
P3	.17	.56	.26	.71
P4	.92	.82	.67	.88
P5	.97	.76	.95	.96
P6	.79	.43	.02	.53
P7	.77	.79	.52	.85
P8	−.45	−.07	−.73	.48
P9	.50	.68	.84	.91
P10	.80	.67	.77	.69
P11	.25	.76	.85	.89
P12	.75	.27	.26	.69

Note. P'_{sg} = subglottal pressure estimate; NSV_{Mag} = magnitude of neck-surface vibration.

Further post hoc testing of the interaction effect indicated that the relationship between P'_{sg} and NSV_{Mag} changed significantly at each intensity level for all comparisons (all adjusted *p*s < .001). Review of the individual slopes revealed that the soft-intensity condition had the steepest slopes (largest beta values during individual linear regressions between NSV_{Mag} and P'_{sg}), and the loud-intensity conditions had shallower slopes (smaller beta values) for most participants. Figure 2 provides a visual display of the regression slopes at each intensity level for each participant.

Research Question 3: Analysis of Respiratory and Laryngeal Efficiency Ratios

We tested six separate mixed linear regression models to examine the relationship between the respiratory and laryngeal efficiency variables of interest (lung volume initiation, lung volume termination, total lung volume, airflow, vocal efficiency, and laryngeal resistance) and the NSV_{Mag}–P'_{sg} condition slopes for each participant. Variables were not combined into one model because some were too highly correlated with one another (e.g., total lung excursion and airflow were highly correlated, $r = .88$). Total lung excursion was the only variable that was found to be a significant predictor of the individual NSV_{Mag}–P'_{sg} intensity condition slopes, with a large effect size ($F(1, 23) = 5.96$, $p = .025$, $\eta_p^2 = .24$); however, airflow and lung volume initiation both approached significance ($p = .06$). The intensity condition and the interaction effects were not significant in any of the six models.

Discussion

This study sought to determine the relationship between NSV_{Mag}, transduced with a neck-mounted accelerometer, and P'_{sg}. Prior research has shown that NSV_{Mag} is an accurate estimate of P'_{sg} during changes in frequency, vowel, and vocal intensity (Fryd et al., 2016). Our study expanded on these prior findings by incorporating increasing amounts of vocal effort, a common symptom in individuals with high voice use, across a range of vocal intensities that may tax the respiratory and laryngeal subsystems differently.

On the basis of the first mixed-effects regression model (Model 1), we determined that NSV_{Mag} was significantly related to P'_{sg} across modulations of vocal effort, with a large effect size. Once the vocal intensity condition and the interaction effect were accounted for in Model 2, the effect size of NSV_{Mag} decreased but remained medium to large. Most importantly, the interaction effect revealed that the relationship between NSV_{Mag} and P'_{sg} varied significantly across vocal intensities. When we calculated individual Pearson product–moment correlation coefficients between NSV_{Mag} and P'_{sg} for all productions, five participants (P4, P5, P7, P9, and P11) exhibited strong correlations ($r = .85$–$.96$), revealing a consistent, linear relationship between the two variables regardless of vocal intensity. In these cases, it may be appropriate to estimate P'_{sg} from NSV_{Mag} across all vocal intensity ranges. The other participants who exhibited moderate correlations (e.g., P1: $r = .65$, P6: $r = .53$) had soft productions that did not appear to follow the same pattern as the other intensity conditions, most likely resulting in the small interaction effect revealed in Model 2.

Post hoc analysis of the interaction effect revealed that soft productions resulted in consistently steeper slopes when compared with the comfortable and loud productions. This means that there was less change in NSV_{Mag} during increases of P'_{sg} when a soft voice was produced with increasing vocal effort. The production of a soft voice has specific glottal characteristics such as a larger prephonatory gap, decreased vocal fold contact time, and reduced impact stress on the vocal folds (Sataloff, 2015). Furthermore, difficulty producing a soft voice can be an indication of voice problems, including vocal fatigue and tissue inflammation (Bastian, Keidar, & Verdolini-Marston, 1990; Halpern, Spielman, Hunter, & Titze, 2009; Hunter & Titze, 2009). In our study, the soft intensity had a lower range of P'_{sg} values (range = 2.5–18.7 cm H_2O) compared with the other vocal intensities. Although at a glance, airflow values were lower than the other two conditions as well; in fact, the results indicate that the airflow expressed during soft productions was proportionally larger than those expressed during the other conditions when examined as a laryngeal resistance ratio (P'_{sg}/airflow). High airflow accompanied by increased stiffness in the vocal folds could result in higher P'_{sg} values but not necessarily increase vocal fold contact. We suspect that the vocal folds had a longer open phase during soft productions, increasing the breathiness of the productions and possibly resulting in reduced NSV_{Mag}. Cheyne, Hanson, Genereux, Stevens, and Hillman (2003) also reported individual variation in NSV_{Mag} during intensity changes (soft-to-loud production). The authors postulated that the NSV signal may have been affected by other parameters at the glottal source, such as vocal fold collision forces. Although we measured additional respiratory kinematic and laryngeal efficiency measures, there are other parameters that could be measured at the glottal source and that could affect the NSV signal.

Our analysis of additional respiratory and laryngeal efficiency ratios indicated that total lung excursion was related to the NSV_{Mag}–P'_{sg} relationship across all intensities. Importantly, airflow approached significance as well (p = .06) and was highly correlated with total lung excursion (r = .88). Unlike respiratory kinematics, specific aerodynamic estimates (AC flow, MFDR) can be accurately derived from the NSV signal using the IBIF technique (Mehta et al., 2015; Zanartu et al., 2013). Different airflow parameters should be investigated further as a potential NSV-based estimate that could improve the accuracy of predicting P'_{sg} across different vocal intensities.

Participant Variation

Participant-specific factors can influence the NSV signal, including skin inertance, skin resistance, skin stiffness, tracheal length, and accelerometer position relative to the larynx (Zanartu et al., 2013). To examine one aspect of potential variation, we calculated the body mass index (BMI) for each participant based on his or her height, weight, age, and gender (Gallagher et al., 2000). All participants were within the "normal" range for BMI (18.5–24.9), except for one participant (P2) whose BMI value fell into the "overweight" range (25.0–29.9). Visual inspection of P2's data revealed the smallest range of NSV_{Mag} values (4.6–21.3 mV) when compared with all the other participants. Thus, it is possible that larger amounts of soft tissue between the vocal folds and the skin surface may attenuate the NSV signal in some speakers.

Further inspection of the data revealed that P8 exhibited atypical correlation patterns compared with the other participants in the study. Although the NSV_{Mag} and P'_{sg} values increased from soft, to comfortable, to loud productions, the relationships within each intensity condition were negatively correlated. The participant's data were reviewed and revealed large lung volume excursions and airflow values on the outer range of all the other male participants' data. Specifically, P8 produced airflow as high as 0.85 L/s during his loud productions, which was on the upper end of the male participant range for this intensity level (M = 0.53 L/s, range = 0.21–1.07 L/s). Also, his vocal efficiency values were close to the lowest in the study (M = 4.1 [dB SPL]/[cm H_2O]), which were only comparable with P7 in the loud condition. P8 also exhibited some difficulty increasing vocal effort without simultaneously increasing pitch; however, Fryd et al. (2016) reported that the NSV_{Mag} could predict P'_{sg} across low, comfortable, and high pitches. Extracting fundamental frequency may in fact assist in explaining the NSV_{Mag}–P'_{sg} variance in this participant but was not examined in this study. Additional work should also investigate extrinsic laryngeal and anterior neck muscle contractions to determine how they may influence NSV_{Mag}. It is conceivable that platysma contraction may reduce NSV_{Mag} during vocal productions that vary in vocal effort.

Limitations and Future Research

We chose to examine healthy participants because they are able to produce a range of vocal effort levels and vocal intensities, thereby acting as their own controls, whereas individuals with voice disorders are often limited in their ability to manipulate changes in their voices. The results of the study align with what is expected in those with voice disorders, as evidenced by lower vocal efficiency values and increased laryngeal resistance when increasing vocal effort, but there are known anatomical and physiological differences between healthy individuals and those with voice disorders that should not be disregarded. Some differences may include glottal configuration, laryngeal structure, compensatory responses, and physiological variation when producing excessive vocal effort. A future step could be to determine the clinical utility of NSV_{Mag} as an estimate of P'_{sg} in individuals with voice disorders to determine if the same relationships and patterns reported here persist in specific patient populations.

Of course, a limitation to this study is that it compares indirect estimates of P_{sg} with NSV_{Mag}. Previous studies report strong relationships between indirect and direct measures of P_{sg} (Bard et al., 1992; Hertegard et al., 1995; Lofqvist et al., 1982), and indirect estimation techniques have the added benefit of being noninvasive, allowing for multiple trials over longer periods and for translation voice clinics. However, Plant and Hillel (1998) argue that P'_{sg} during a bilabial stop plosive may not be reflective of the P_{sg} during the corresponding voiced vowel, especially when the voiced production is in an individual with a voice disorder (e.g., spasmodic dysphonia). Future work should consider evaluating NSV_{Mag} against direct measurements of P_{sg} in individuals with voice disorders who may exhibit more variability in P_{sg} during plosive–vowel combinations.

Finally, our results indicate that it would be possible to develop individual-specific algorithms to estimate P'_{sg} from NSV_{Mag} but that this prediction would only be accurate for individuals who exhibit the same relationship between

NSV_{Mag} and P'_{sg} across all vocal intensities (approximately 50% of individuals in our study). Although the NSV signal itself is relatively impervious to environmental noise, the behavior of the individual producing voice is not. In occupations where ambulatory monitoring may be of benefit (e.g., teachers in classrooms, restaurant workers, coaches), it is possible that elevated environmental noise would elicit a larger range of produced vocal intensities, beyond those of a comfortable speaking voice in a less noisy environment. We determined that total lung volume excursion was related to the change observed in the P'_{sg}–NSV_{Mag} relationship across intensity conditions but is not feasible to measure respiratory kinematics during ambulatory monitoring. Airflow, on the other hand, was strongly correlated with total lung excursion, and AC airflow can be derived from the NSV signal. We recommend that airflow be explored as another measure relevant to the estimation of P'_{sg} from the NSV signal.

Conclusion

The current study sought to determine whether NSV_{Mag} is related to P'_{sg} during variations in vocal effort and, furthermore, whether that relationship is affected by changes in vocal intensity. The results of this study indicate that P'_{sg} can be estimated from NSV_{Mag} in 75% of the participants during voice productions with excessive vocal effort at comfortable speaking volumes. However, once vocal intensity changes to loud or soft, the NSV_{Mag}–P'_{sg} relationship also changes. The impact of this change is small and not consistent across all participants, with five of 12 participants exhibiting a strong relationship regardless of intensity ($r > .85$). Thus, more work is needed to (a) determine if those changes across vocal intensities persist in individuals with voice disorders and (b) evaluate which additional parameters (e.g., airflow) could be incorporated into an NSV-based ambulatory monitoring device to improve algorithm accuracy. Due to the recent development of the IBIF technique, it appears that specific airflow parameters can be extracted accurately from the NSV signal, making it a promising parameter for future investigation.

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