Glottal Airflow and Glottal Area Waveform Characteristics of Flow Phonation in Untrained Vocally Healthy Adults

*Rita R. Patel, †Johan Sundberg, ‡Brian Gill, and §Filipa M.B. Lã, *‡*Bloomington, Indiana,* †*Stockholm, Sweden, and* §*Madrid, Spain*

Summary: Objective. To examine flow phonation characteristics with regard to vocal fold vibration and voice source properties in vocally healthy adults using multimodality voice measurements across various phonation types (breathy, neutral, flow, and pressed) and loudness conditions (typical, loud, and soft).

Participants and Methods. Vocal fold vibration, airflow, acoustic, and subglottal pressure was analyzed in 13 untrained voices (six female and seven male). Participants repeated the syllable / pæ:/ using breathy, neutral, flow, and pressed phonation during typical, loud, and soft loudness conditions. Glottal area (GA) waveforms were extracted from high-speed videoendoscopy; glottal flow was derived from inverse filtering the airflow or the audio signal; and subglottal pressure was measured as the intraoral pressure during /p/ occlusion.

Results. Changes in phonation type and loudness conditions resulted in systematic variations across the relative peak closing velocity derived from the GA waveform for both males and females. Amplitude quotient derived from the flow glottogram varied across phonation types for males.

Conclusion. Multimodality evaluation using the GA waveform and the inverse filtered waveforms revealed a complex pattern that varied as a function of phonation types and loudness conditions across males and females. Emerging findings from this study suggests that future large-scale studies should focus on spatial and temporal features of closing speed and closing duration for differentiating flow phonation from other phonation types in untrained adults with and without voice disorders.

Key Words: Flow phonation−High-speed videoendoscopy−Glottal area waveform−Inverse filtering.

INTRODUCTION

Phonation can be varied within wide limits with regard to both loudness and phonation type, ranging from breathy/hypofunctional to pressed/hyperfunctional. Traditionally, phonation types are characterized by variations in glottal flow (Figure 1) using the non-invasive technique called glottal inverse filtering. In glottal inverse filtering, the effects of the vocal-tract filter characteristics and the lip radiation are cancelled from the speech output to provide estimates of the glottal source characteristics during phonation. The resulting flow glottograms which shows the glottal volume velocity waveform provides information related to the type of phonation and other glottal source characteristics noninvasively. Several time-based parameters (eg, open quotient, speed quotient, closed quotient, pulse amplitude) and frequency-based parameters (eg, fundamental frequency, ratio of the first and second harmonics) can be derived from the flow glottogram to estimate the glottal excitation characteristics.[1] Breathy/hypofunctional phonation has a large amplitude of the flow oscillation and lacks vocal fold closure. Pressed/hyperfunctional phonation, by contrast, is characterized by a small amplitude of the flow oscillation, the minimum of which reaches zero. Neutral phonation, which is typically used in normal conversation, is characterized by larger peak-to-peak amplitude of the flow oscillation than pressed/hyperfunctional phonation and is produced with complete or almost complete vocal fold closure. Flow phonation has been defined as a phonation type produced with the largest peak-to-peak flow amplitude, where the minimum still reaches zero. The characteristic airflow for flow phonation is reduced compared to breathy phonation but higher compared to typical or neutral phonation.[2,3] In this sense, flow phonation can be regarded as a phonation type located between breathy and neutral along the breathy-pressed continuum.[2,3]

Phonation types are relevant both pedagogically and clinically. Breathy/hypofunctional phonation is inefficient, as air is expended without generating complete vocal fold closure. The opposite extreme of pressed/hyperfunctional phonation is produced with excessive muscular and physical effort/force. Habitual use of hyperfunctional phonation may lead to voice disorders.[4,5]

Several therapeutic approaches have been proposed for rehabilitation/habilitation of hyperfunctional phonation. One such approach used in voice therapy, aimed at reducing vibration dose, increased vocal fold adduction,[6] and excessive muscular effort[7,8] in patients with muscle tension dysphonia,[9] is called flow phonation. Flow phonation is associated with a higher ratio between output sound pressure level and input subglottal pressure compared to neutral and pressed phonations. Thus, flow phonation has been

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From the *Department of Speech, Language and Hearing Sciences, Indiana University, Bloomington, Indiana; †Division of Speech, Music, and Hearing, KTH Royal Institute of Technology, Stockholm, Sweden; ‡Voice Department, Indiana University, Bloomington, Indiana; and the §Department of Didactics, School Organization and Special Didactics, Faculty of Education, The National Distance Education University (UNED), Madrid, Spain.

Address correspondence and reprint requests to Rita R. Patel, Department of Speech, Language and Hearing Sciences, Indiana University, 200 South Jordan Avenue, Bloomington, IN 47405-7002. E-mail: patelrir@indiana.edu

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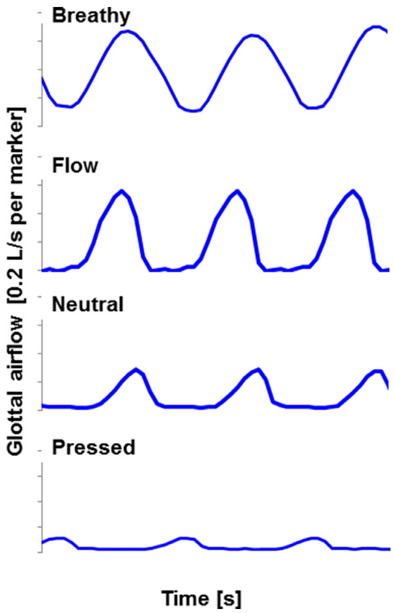

FIGURE 1. Typical examples of flow glottograms for the indicated phonation types of breathy, flow, neutral, and pressed.

regarded, in some sense, as optimal.[2] Voice production in flow phonation is known to feel effortless and efficient.[10] Flow phonation generates a strong voice source fundamental, indicating a touch glottal adduction.[2] Since the pulse amplitude from the flow glottograms (AC amplitude) is high in flow phonation, it implies good airflow with a clear, but not so long closed phase and a strong voice source fundamental.

Flow phonation should not be confused with another voice therapy approach called stretch-and-flow,[11,12] where the goal is to facilitate a balance between the respiratory, phonatory, and articulatory subsystems of voice production using a hierarchical approach of unvoiced to voice airflow stimuli. Furthermore, therapeutically, there is often confusion between breathy phonation and flow phonation. In studies on healthy male participants, breathy phonation has been found to be produced with low subglottal pressure and incomplete glottal closure causing a larger glottal airflow than flow phonation. The ratio between sound level and subglottal pressure is much lower in breathy phonation compared to both flow phonation and neutral phonation. Airflow in flow phonation is lower than in breathy phonation but higher than neutral phonation.[2,3,13,14] Thus, flow phonation and breathy phonation are associated with substantially different voice source properties.[2,3,13,14] It is important to note the possibility of using breathy phonation as a means to teach patients/students how to produce flow phonation, even though the goal is to produce flow phonation without a breathy voice quality.

The goal of voice treatment when using the flow phonation approach typically is to improve phonatory physiology by guiding the patient to combining high glottal airflow with complete glottal closure.[2,15] Treatment outcomes clinically are measured using laryngeal imaging, acoustic evaluation, aerodynamic evaluation, or measurement of patient self-perception of the impact of the voice disorder on their daily function.[16–18] The advantage of direct visualization of the vocal folds is that it can be used to provide feedback of the vocal fold contact during voice training. Inverse filtering, though useful for noninvasive evaluations of the glottal source characteristics, has not gained widespread clinical use, probably because it is time-consuming and has limitations in accurately estimating glottal source properties across all voice types. For example, high-pitch voices of females and children including the presence of nasalization makes estimating source characteristics unreliable with inverse filtering and thus limiting its clinical applicability across the range of voice conditions routinely encountered in the clinics.[1] Direct visualization of the vocal folds through methods of laryngeal imaging is the gold standard to evaluate the structure and the function of the source / vocal folds.[17,19] Stroboscopy is the gold-standard in laryngeal imaging, although limited for tracking cycle-to-cycle vocal fold vibrations in severely aperiodic voices.[20,21] The increased temporal resolution of high-speed videoendoscopy over stroboscopy has the advantage of capturing cycle-to-cycle variation in glottal area (GA) rather than an apparent motion.[20,22,23]

Most studies evaluating flow phonation have used inverse filtering.[2,3,14,15,24,25] Therefore, it is important to evaluate the relationship between airflow and the GA by simultaneously using inverse-filtering and high-speed videoendoscopy. It is well-established that the airflow pulse is asymmetrical[26,27] and skewed to the right while the GA waveform is more symmetrical.[28,29] Theoretically, this relationship has been investigated for normal and loud phonations.[30,31] Direct relationship between simultaneous airflow and GA has been examined in only a handful of studies. Hertegard, Gauffin, and Karlsson (1992)[32] examined the relationship between GA and flow in two males and three females (26–45 years) in chest register at frequencies around 175 Hz, 200 Hz, and 250 Hz for females and 175 Hz, 220 Hz, and 240 Hz for males in normal and breathy phonation using simultaneous inverse filtering, electroglottography, and videostroboscopy. The findings revealed that the flow glottogram volume velocity waveform, henceforth the flow glottogram, in males and females during complete closure had an offset of 20–30 mL/second for typical phonation. Furthermore, the authors found a small hump at the beginning of the closed phase in the flow glottograms at low pitch, which coincided with a large mucosal wave on videostroboscopy, revealing a clear vertical phase difference between the upper and lower margins. This vertical component was more pronounced in males compared to females but it was not observed for both genders during high pitch phonation. Similar piston movement was later confirmed by Hertegard and Gauffin (1995).[33] Piston movement during flow phonation was also confirmed by Granqvist et al (2003)[34] in a trained male and a trained female participant using simultaneous recordings of airflow, electroglottography, air pressure, acoustic signal, and high-speed videoendoscopy at 1900 frames/second.

Presently there are limited numbers of large group studies describing in quantitative terms the relationship between glottal airflow and vibratory parameters as derived from methods of simultaneous airflow, subglottal pressure, and laryngeal imaging during flow phonation. The present study extends the previous efforts by Granqvist et al (2003)[34] just mentioned and by Gauffin & Sundberg (1989)[2] and Sundberg (1995),[3] in which flow glottogram characteristics were quantified in male participants. In order to describe flow phonation in quantitative terms, the relationship between subglottal pressure, vibratory amplitude, and glottal flow during breathy, flow, neutral, and pressed phonation was examined using an ambitious experimental setup of simultaneous high-speed videoendoscopy, inverse filtering, subglottal pressure, electroglottography, and acoustic recordings in untrained adult male and female vocies. This study seeks to address the following two main questions:

1. Do the vibratory amplitude, the relative peak closing velocity (PCV), the flow pulse amplitude, and the maximum flow declination rate decrease systematically as a function of phonation modes - breathy, flow, neutral, and pressed - in adult males and females?
2. What is the relationship between total flow (mL/second) and GA (pixels) and its derivatives of (i) flow amplitude quotient versus area amplitude quotient, (ii) duration of flow decrease phase (ms) and duration of the area decrease phase (ms). Additionally the relationship between the relative PCV and the amplitude-to-length ratio (ALR), both derived from the GA waveform, was explored.

METHOD

Participants

Nineteen untrained young adults (18−45 years), ten females and nine males participated in the experiment. The lower age limit was established to conform to the NIH definition of an adult participant, while the upper age limit was established to reduce the confounding effects of voice changes due to senescence. Children were excluded from this initial study because the determinants for flow phonation may be different from those for adults and warrant a separate study. For inclusion in the study, the participants had negative histories of vocal pathology, no identifiable vocal fold pathology on stroboscopic screening, negative history of smoking, were able to produce different types of phonations (breathy, flow, neutral, and pressed), and had no more than up to 4 years of training in classical music. All were perceptually judged to have a normal voice (overall grade = 0) by a certified speech language pathologist (co-author RP) who has over 20 years of experience in using the Consensus Auditory Perceptual Evaluation of Voice scale for determining voice status and voice disorders.[35]

Participants were recruited from advertisements and fliers placed around the Indiana University Campus following approval by the Institutional Review Board. Two participants (one male & one female) were excluded as they were unable to produce the different types of phonations. Additionally, two participants (one male & one female) participated in the first half of the experiment without endoscopy and hence were excluded from further analysis. Data verification of expected average flow values across the various phonation types (Figure 2) revealed that two female participants did not perform as expected for breathy phonation. Their flow glottogram signal had minimum flow values at or near zero rather than well above zero flow and was therefore excluded. Data analysis was performed on the remaining seven males (M = 24.5 ± 2.07 years) and six females (M = 28.86 ± 5.11 years).

Data collection/instrumentation

Simultaneous high-speed videoendoscopy, airflow, subglottal pressure, electroglottography, and audio recordings were conducted for each participant during a series of the syllables /pæ:/ in typical (conversational), loud, and soft phonation for each of the phonation types of breathy, flow, neutral, and pressed. High-speed videoendoscopic recordings were captured at 2000 frames per second with the PentaxMedical model 9710 (Montvale, New Jersey). Simultaneous audio (omnidirectional electret microphone TCM110, V-JEFE), flow (Glottal Enterprises MSIF2), subglottal pressure (Glottal Enterprises PG100E), and

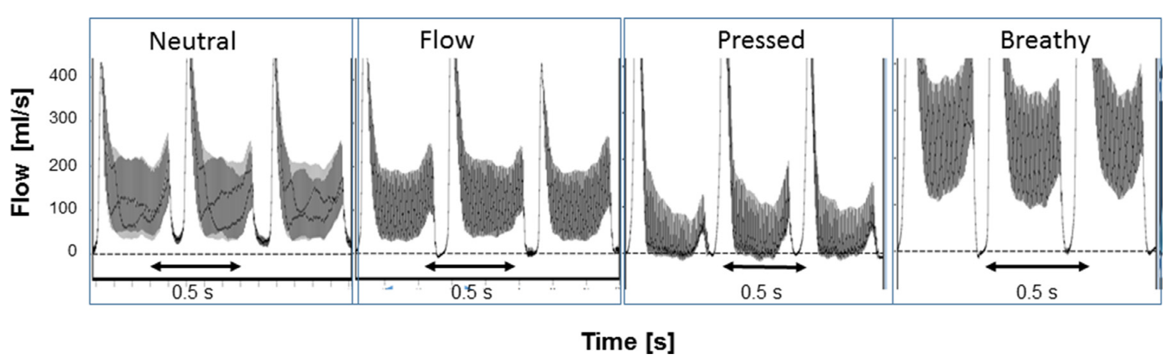

FIGURE 2. Example of the flow glottograms displayed during the recording produced by a male subject with each of the indicated phonation types.

electroglottographic (Glottal Enterprises EG2-PCX) recordings were captured at 44 kHz on separate tracks using the data acquisition system (National Instruments, Austin Texas, USB 6221) and recorded directly with the high-speed videoendoscopy. The data acquisition system (National Instruments, Austin Texas, USB 6221) has the capability to capture up to eight channels of simultaneous data with a combined sampling rate of 250 kHz and is driven by the clock-out signal from the high-speed video system, thus ensuring synchronization.[36–38] A xenon light source of 300 watts was used for the high-speed videoendoscopic recordings.

An omnidirectional head mounted microphone was placed at a mouth-to-microphone distance of 10–12 cm at a fixed angle of 45 degrees to the side of the mouth. The microphone was calibrated by recording a sustained phonation, the sound pressure level of which was measured at the recording microphone at 30 cm mouth-to-microphone distance by means of a sound level meter (RadioShack) with C-weighting and slow response.[17,39]

The airflow signal was captured from a Rothenberg flow mask connected to a Glottal Enterprises MSIF2 inverse filter unit. Each participant held the mask such that it fitted snuggly to the face. Calibration of the flow signal was conducted by means of the calibration unit provided by the manufacturer which drives 140 mL of air through the mask.

High-speed videoendoscopic recordings were captured using a standard digital flexible nasal fiberscope (Pentax FNL-10RP3) introduced through a custom hole in the flow mask without application of topical anesthetic to the nasal mucosa. The fiberscope was fitted tightly in the hole by means of a custom plug, thus preventing airflow leakage through the mask.

Subglottal pressure was recorded as the oral pressure during /p/ occlusion captured by means of a pressure transducer attached to a thin plastic tube. The tube was introduced into a hole in the flow mask and then into the corner of the participant's mouth. Subglottal pressure was captured using the Glottal Enterprises new PG100E system, which leaves a DC signal output proportional to the pressure. The transducer was calibrated by means of the unit provided by the manufacturer, which produces a pressure of 20 cm H_2O. The pressure signal was monitored on an oscilloscope during the recordings. The sound pressure level from the microphone is strongly influenced by the relationship between the strongest partial and its distance to the first formant and hence is not a reliable estimate of vocal loudness level.[40,41] In this study, subglottal pressure, which is a physiologically more relevant measure of vocal loudness compared to vocal sound pressure level,[42–44] was collected to verify the vocal loudness levels of typical, loud, and soft conditions. Since subglottal pressure was used to verify that the participants performed the task of loud, soft, and typical loudness, it was not included for statistical analyses. The experimental set-up is depicted in Figure 3.

Prior to recordings, participants were trained (co-authors BG & FL) to produce pressed, neutral, flow, and breathy phonation types at self-selected comfortable pitch and three loudness levels on /pæ:/ syllable sequences. During the recording the participants were seated in a comfortable exam chair in a double walled sound treated booth. The participants were provided with real-time visual feedback in terms of flow glottogram, obtained from the Glottal Enterprises MSIF1 inverse filter. While the participant sustained a loud /æ:/ vowel its two formant filters were tuned using a ripple-free closed phase as the criterion. The unit's output was displayed on an oscilloscope screen in front of the participant, adjusted to show a time window of about 5 seconds.

During the recordings the participant was asked to view the oscilloscope screen and to produce a flow glottogram signal that: (i) for Neutral phonation had a minimum as

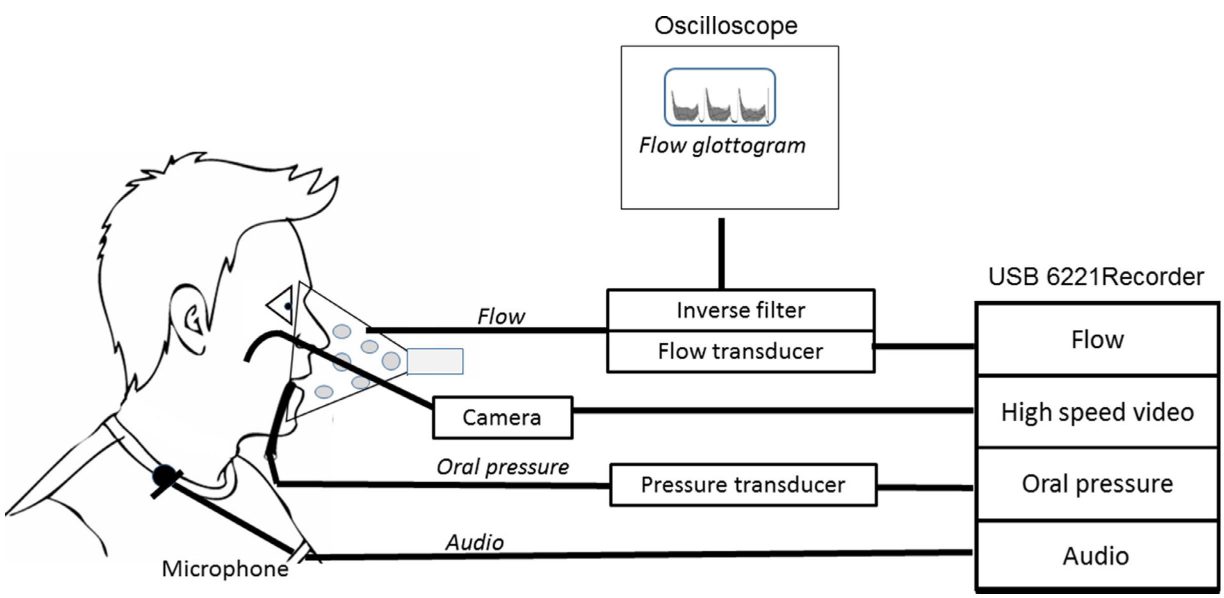

FIGURE 3. Schematic illustration of the experimental set-up.

close to zero flow as possible; (ii) for Flow phonation showed a large amplitude while keeping the minimum close to zero flow; (iii) for Pressed phonation had as low amplitude as possible; and (iv) for Breathy phonation showed a signal with a minimum well above zero flow. If the participants were able to produce three consecutive repetitions of /pæ:/ at the target flow levels, they were considered sufficiently trained for the experiment (Figure 2). The criterion of successful training based on the ability to produce three consecutive repetitions of /pæ:/ at the target flow levels was empirically determined since three consecutive repetitions of /pæ:/ are required for measurement of the subglottal pressure.[17,45] During the experiment, the experimenters (authors JS, FL, and BG) verified that the participants were maintaining the effect of training by visual inspection of the oscilloscope screen for target flow levels and auditory-perceptual judgments of the target production including the loudness level.

In each of the four phonation types, the participants produced in typical, loud, and soft voice a string of five /pæ:/ syllables in one breath at the rate of approximately 1.5−2 syllables per second.[46] Thus each syllable was approximately 0.5 seconds in duration. The experimenters confirmed whether the participants were truly producing typical versus soft versus loud phonation by simultaneous measurement of the subglottal pressure (Figure 3). Thus, each syllable was approximately 0.5 seconds in duration. The syllable / pæ:/ was chosen, as subglottal pressure can be captured from the oral pressure during the /p/ occlusion, and the vowel /ae/ is optimal for inverse filtering due to its high and widely separated first and second formants. In addition, it tends to be pronounced with complete occlusion of the velopharyngeal port.[47] In instances where it was impossible to visualize the free margins of the vocal folds during phonation the vowel /æ:/, the vowel /i/ was used instead. Problems to visualize the free margins of the vocal folds generally occurred for pressed phonation. In the current analyses only one data point with pressed phonation using the vowel /i:/ was included.

The following signals were simultaneously recorded on separate tracks of the data acquisition system: high-speed videoendoscopic, audio, electroglottograph, subglottal pressure, and airflow. Calibration signals for sound pressure level, subglottal pressure, and flow were recorded in a separate file each day.

Overall, each participant was recruited to produce a total of 12 conditions (four phonation types x three degrees of vocal loudness). The participants performed the various types of phonations in the neutral condition first, followed by loud, and then the soft condition. The participants performed all the conditions first without the endoscope and then with the endoscope in place. For the study only the data with the endoscope in place was further analyzed. Data collection was completed in about 2 hours for each participant. Only two participants (one male and one female) completed all phonation types across the three loudness conditions (Table 1). Producing target phonations at soft loudness level was challenging for the untrained participants in the study and hence soft loudness was the last condition recorded in the study. All participants first produced neutral, then flow, then pressed, and finally breathy phonation in typical loudness level, followed by loud and then soft loudness levels. Due to the level of difficulty of the task and the fatiguing nature of the experiment with the flow mask with simultaneous intraoral pressure tube and flexible nasendoscopy in place, 11 participants completed the target productions at only typical and loud conditions. All recordings were conducted at the Vocal Physiology and Imaging Laboratory at the Department of Speech, Language, and Hearing Sciences, Indiana University.

TABLE 1.
Summary table of number of tokens per condition and phonation type across male (M) female (F) participants

Phonation Type	Breathy		Flow		Neutral		Pressed	
	M	F	M	F	M	F	M	F
Condition								
Typical	7	4	6	5	5	6	6	4
Loud	3	2	3	2	3	4	2	2
Soft	1	0	1	1	1	1	0	0

Analysis

The steady-state of the vowel appearing in the middle three syllables was selected for analysis of vocal fold vibrations and inverse filtering. Segmentation and analysis of the high-speed recordings along with the acoustic signal was conducted using an automated endoscopic imaging analysis tool called the Glottis Analysis Tool.[48] GA waveforms were derived from the high-speed videoendoscopy data. The following parameters were derived for each of five subsequent cycles and averaged: GA, pixels, ALR, Relative CV, Speed quotient (SQ), GA index (GAI), Closing quotient (CQ), Maximum area declination rate (MADR), Amplitude quotient (AQ), Closing Duration (CD_{area} [ms]) and Stiffness index (SI) (Table 2).

The flow signal was analyzed using the Sopran software (Svante Granqvist, available at www.Tolvan.com). As a first step, the flow signal was calibrated in mL/s using the integral of the signal produced by 140 mL of air driven through the Rothenberg mask from a syringe, and multiplying the average of that signal with its duration in seconds. Average flow (mL/s) values were calculated from the calibrated flow signal.

Inverse filtering of the flow signal was performed after resampling the recordings to 16 kHz and specifying the microphone distance. The tuning of the formant filters, on average one per kHz, was made manually (co-author JS) using the “Inverse filter” module of the Sopran software. This module displays the flow glottogram and the voice source spectrum simultaneously in separate windows. For

TABLE 2.
Description of the dependent variables derived from high-speed videoendoscopy

High-Speed Videoendoscopy Parameters	Definition
Glottal area (GA)	Glottal area in pixels from the visible glottal contour
Amplitude-to-length ratio (ALR)	Ratio between changing glottal area and the glottal length
Relative peak closing velocity (PCV)	Maximum speed with which the area of the glottis would be changing during opening or closing of the glottis movement is approximated as a sine curve
Speed quotient (SQ)	Ratio of the opening and closing duration of a glottal cycle
Glottal area index (GAI)	Ratio between the minimum and maximum glottal opening
Closing quotient (CQ)	The portion of the time during a glottal cycle when the glottis is closing
Maximum area declination rate (MADR)	Maximum closing velocity
Amplitude quotient (AQ)	Maximum closing velocity normalized with the amplitude of the GAW
Closing duration (CD_{area} [ms])	Time in ms during which the vocal folds are closing
Stiffness index (SI)	Maximum speed with which the area of the glottis is changing during opening or closing normalized to the total varying glottal area

tuning the filters two criteria were used, a ripple-free closed phase and a source spectrum envelope as free from dips and peaks near the formants as possible. After completing the tuning of the inverse filters, the resulting flow glottograms were saved in a separate channel of the recording and the frequencies and bandwidths of the inverse filters were saved into a log file. Subsequently, the flow glottograms were analyzed using the Glottal flow parameter measurement module of the Sopran software. Three flow glottogram properties were manually marked, (i) the period, (ii) the closed phase, and (iii) the mean airflow during the quasi-closed phase. The following flow glottogram parameters were then automatically computed and recorded into the same log file, which was then exported to an excel file: Flow pulse amplitude (PA_{flow} mL/s), Maximum Flow Declination Rate ($MFDR_{flow}$ mL/s^2, Amplitude Quotient (AQ_{flow} ms), Closed Quotient (CQ_{flow}), Level difference between the first and second harmonics ($H1H2_{flow}$), Duration of Closing Phase (CD_{flow} (ms)), Speed Quotient (SQ_{flow}), and Glottal Resistance (GR_{flow}) (Figure 4). The definitions of parameters extracted from flow glottograms are given in Table 3.

Using the Sopran software, the subglottal pressure was measured as the plateau of the oral pressure signal during the /p/ occlusion for the middle of the five syllables.[17] A total of 69 tokens (Table 1) were subjected to statistical analysis for males and females across condition (typical, loud, and soft) and phonation types (breathy, flow, neutral, and pressed) after verification of expected flow values (Figure 2) from a total of 258 tokens collected from 13 participants.

As mentioned, the participants viewed the flow glottogram of their voice during the experimental recordings. The participants were instructed to produce a large pulse amplitude in flow and breathy phonation and small pulse amplitude in pressed phonation. For breathy phonation they were asked to produce a signal well above zero flow (Figure 2). Qualitative observation from Figure 5 reveals that the pulse amplitude was greatest in flow and breathy phonation and smallest in pressed phonation. The two middle panels show the corresponding mean values for subglottal pressure. On qualitative observation the subglottal pressure was generally higher in loud than in typical, and male participants used higher pressures than the female participants. The right panels show the corresponding averages of glottal resistance. As expected, they were lowest in breathy and highest in pressed on qualitative observation.

Statistical analysis

A two-way Analysis of Variance was used to statistically evaluate the effect of phonation type (breathy, flow, neutral, pressed) and condition (typical, loud, and soft) on the dependent variables derived from inverse filtering and high-speed videoendoscopy within males and females respectively. Simple effects tests using the least square method were conducted to test the interactions. For question 2, regarding the relationship between total flow and GA, Pearson's correlation coefficients were computed and evaluated for statistical significance using Analysis of Variance. Results were considered significant for $p \leq 0.5$. Statistical analysis was performed using SAS 9.4 (SAS Institute Inc., Cary, NC).

RESULTS

I. Changes in GA waveform and airflow parameters as a function of breathy, flow neutral, and pressed phonation types during typical loudness:
   (a) Male: The relative PCV, derived from the GA waveform, was the only parameter that systematically varied significantly across all combinations of

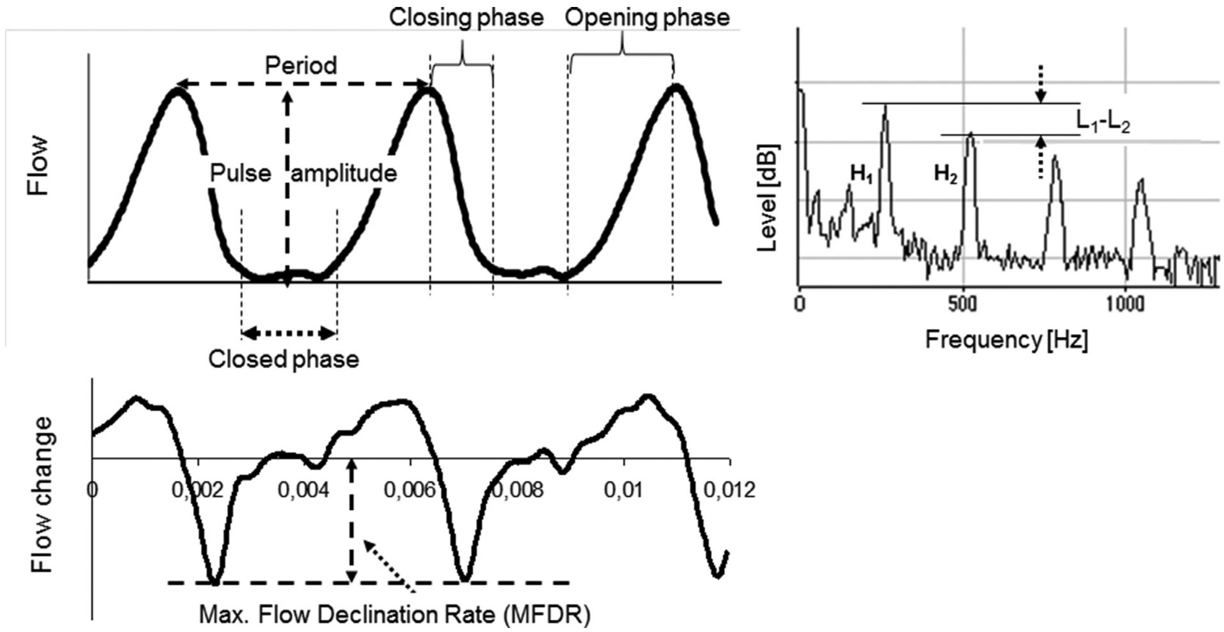

FIGURE 4. Measures of the flow glottogram, its derivative (upper and lower left graphs) and its spectrum (right panel).

TABLE 3.
Description of the dependent variables derived from the inverse filtered flow glottograms

Inverse Filtered Parameters	Definition
Flow pulse amplitude (PA_{flow} mL/s)	AC amplitude of the flow pulse
Maximum flow declination rate ($MFDR_{flow}$ (mL/s^2)	Negative peak amplitude of the derivative of the flow glottogram
Amplitude quotient (AQ_{flow})	Ratio between PA_{if} and $MFDR_{if}$ also referred to as 'T_d' by Fant (1995).[61]
Closed quotient (CQ_{flow})	The portion of the time during a glottal cycle when the glottis is closed or nearly closed according to the inverse filtered waveform
$H1H2_{flow}$	Level difference between first and second partial of the voice source spectrum
Duration of closing phase (CD_{flow} (ms))	Duration of the decreasing part of the flow pulse
Speed quotient (SQ_{flow})	Ratio between the durations of the increasing and decreasing part of the flow pulse
Glottal resistance (GR_{flow})	Ratio of subglottal pressure to glottal airflow

phonation types of breathy, flow, neutral, and pressed during typical loudness (F = 0.001 [3, 27], $p < 0.0001$) (Figure 6). The PCV was large for breathy, followed by neutral, flow, and pressed. GA (F = 4.23 [3, 27], $p = 0.014$) was significantly larger in breathy ($M = 473.93 \pm 286.52$) compared to the neutral ($M = 180.41 \pm 143.40$, t [27] = 2.90, $p = 0.007$), flow (M = 176.31 ± 92.26, t [27] = 3.09, $p = 0.005$), and pressed (M = 85.74 ± 78.23, t [27] = 4.03, $p < 0.001$) phonation types. AQ was significantly reduced in breathy (M = −3.74 ± 0.81) compared to the flow (M = −2.87 ± 0.45, t [27] = −2.87, $p = 0.008$), neutral (M = −2.82 ± 0.55, t [27] = −2.87, $p = 0.008$), and pressed (M = −2.48 ± 0.57, t [27] = −4.16, $p < 0.001$) phonation types (Table 4). As hypothesized the ALR was not statistically significant across phonation types (F = 0.10 [3, 27], $p = 0.96$).

The AQ_{flow} was significantly greater in breathy ($M = 1.26 \pm 0.29$) compared to the pressed ($M = 0.89 \pm 0.25$, t [27] = 3.67, $p = 0.013$), neutral ($M = 0.83 \pm 0.27$, t [27] = 2.76, $p = 0.010$), and flow ($M = 0.78 \pm 0.19$, t [27] = 3.67, $p = 0.001$) phonation types. The PA_{flow} (F = 3.00 [3, 27], $p = 0.05$) and $MFDR_{flow}$ (F = 2.44 [3, 27], $p = 0.86$) were not statistically significant across phonation types as hypothesized.

Female: The only parameter that was statistically significant across all combinations of phonation types during typical loudness was the relative PCV derived from the GA waveform (F = 0.001 [3, 21], $p < 0.0001$). The PCV was large for breathy,

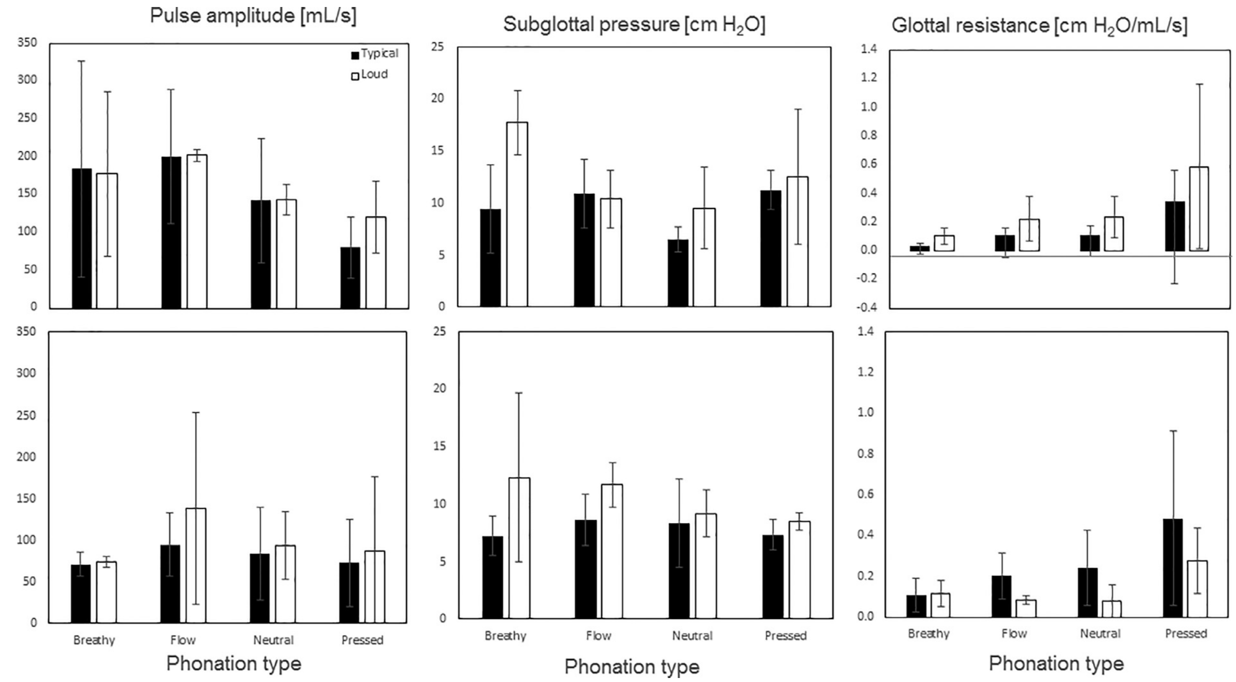

FIGURE 5. Mean and standard deviations of pulse amplitude, glottal resistance, and subglottal pressure for breathy, flow, neutral, and pressed phonation types during typical and loud voice produced by males(upper panels) and females (lower panels).

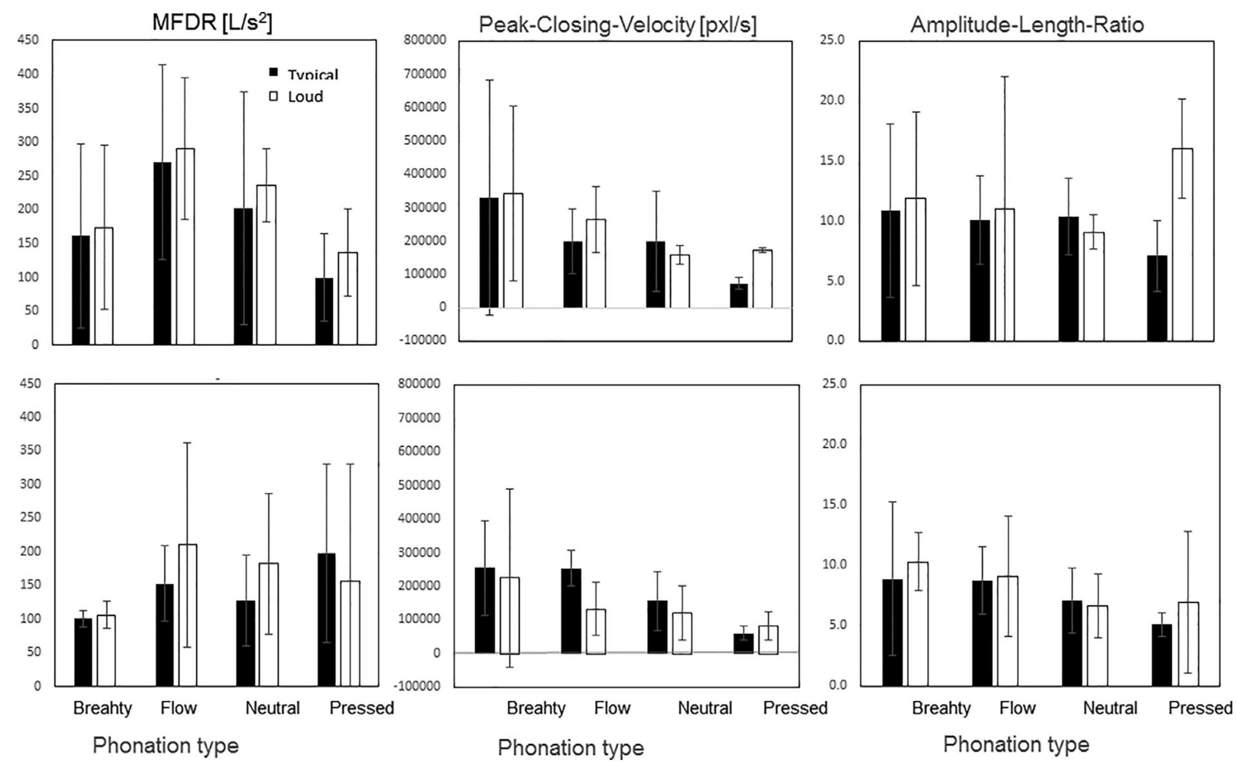

FIGURE 6. Mean and standard deviations of maximum flow declination rate derived from inverse filtering, and relative peak closing velocity, amplitude-to-length ratio from high-speed video for breathy, flow, neutral, and pressed phonation types during typical and loud voice produced by males (upper panels) and females (lower panels).

followed by flow, neutral, and pressed phonations (Table 5). The MADR was significantly increased in pressed (M = −37.09 ± 16.37) compared to the flow (M = −124.84 ± 45.53, p = 0.024) and breathy (M = −128.73 ± 86.84, p = 0.025) phonation types. The GA (F = 2.93 [3, 21], p = 0.05) was significantly increased in breathy (M = 241.76 ± 119.87) compared to the neutral (M = 107.09 ± 69.86,

TABLE 4.
Mean and standard deviations of the dependent variables for males across typical loudness

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
Typical	Breathy	Closed quotient$_{flow}$	7	0.29	0.12	0.17	0.51
		Speed quotient$_{flow}$	7	1.28	0.33	0.92	1.76
		H1H2$_{flow}$	7	15.36	3.87	8	20.1
		Flow pulse amplitude$_{flow}$ (mL/s)	7	170.75	135.71	80	464
		Maximum flow declination rate$_{flow}$ (mL/s^2)	7	146395.57	129746.64	58833	424250
		Amplitude quotient$_{flow}$	7	1.26	0.29	0.80	1.62
		Duration closing phase$_{flow}$ (ms)	7	2.32	0.61	1.52	3.22
		Glottal resistance$_{flow}$	7	0.04	0.02	0.02	0.06
		Glottal area	7	473.93	286.52	49.41	890.39
		Peak closing velocity	7	309042.13	326452.24	60543.62	1019928.53
		Speed quotient	7	1.75	0.62	1.27	3.07
		Glottal area index	7	0.83	0.30	0.59	1.32
		Amplitude-length-ratio	7	10.31	6.81	6.81	25.69
		Closing quotient	7	0.36	0.07	0.25	0.44
		Maximum area declination rate	7	−190.37	185.17	−584.00	−52.20
		Amplitude quotient	7	−3.74	0.81	−4.85	−2.33
		Stiffness index	7	0.32	0.06	0.25	0.43
		Closing duration$_{area}$ (ms)	7	2.71	0.73	1.50	3.60
	Flow	Closed quotient$_{flow}$	6	0.38	0.14	0.25	0.59
		Speed quotient$_{flow}$	6	1.85	0.42	1.37	2.54
		H1H2$_{flow}$	6	9.64	3.99	4.7	15.2
		Flow pulse amplitude$_{flow}$ (mL/s)	6	200.58	88.61	113	370
		Maximum flow declination rate$_{flow}$ (mL/s^2)	6	270708.33	144164.02	247710	558340
		Amplitude quotient$_{flow}$	6	0.78	0.19	0.46	0.97
		Duration closing phase$_{flow}$ (ms)	6	1.57	0.24	1.22	1.87
		Glottal resistance$_{flow}$	6	0.11	0.05	0.07	1
		Glottal area	6	176.31	92.26	77.97	347.64
		Peak closing velocity	6	200315.19	96002.75	140586.27	394956.89
		Speed quotient	6	1.89	0.51	1.30	2.67
		Glottal area index	6	1.31	0.83	0.83	2.99
		Amplitude-length-ratio	6	10.14	3.69	6.86	16.25
		Closing quotient	6	0.30	0.10	0.15	0.44
		Maximum area declination rate	6	−159.23	49.81	−255.00	−108.70
		Amplitude quotient	6	−2.87	0.45	−3.41	−2.32
		Stiffness index	6	0.37	0.07	0.31	0.49
		Closing duration$_{area}$ (ms)	6	2.23	0.83	1.20	3.40
	Neutral	Closed quotient$_{flow}$	5	0.43	0.13	0.28	0.56
		Speed quotient$_{flow}$	5	1.77	0.26	1.52	2.13
		H1H2$_{flow}$	5	9.45	3.53	5.2	13
		Flow pulse amplitude$_{flow}$ (mL/s)	5	142.81	82.09	93	288
		Maximum flow declination rate$_{flow}$ (mL/s^2)	5	201367.6	172512.9	98668	507240
		Amplitude quotient$_{flow}$	5	0.83	0.27	0.57	1.21
		Duration closing phase$_{flow}$ (ms)	5	1.68	0.28	1.36	2
		Glottal resistance$_{flow}$	5	0.11	0.07	0.05	0.19
		Glottal area	5	180.41	143.40	47.03	379.11
		Peak closing velocity	5	200450.85	150595.29	49825.25	443605.77
		Speed quotient	5	2.26	1.12	1.34	4.13
		Glottal area index	5	1.07	0.22	0.92	1.46
		Amplitude-length-ratio	5	10.44	3.20	7.25	14.93
		Closing quotient	5	0.32	0.12	0.14	0.44
		Maximum area declination rate	5	−162.40	82.44	−273.80	−54.80
		Amplitude quotient	5	−2.82	0.55	−3.56	−2.23
		Stiffness index	5	0.38	0.06	0.31	0.45
		Closing duration$_{area}$ (ms)	5	2.60	1.03	1.10	3.78
	Pressed	Closed quotient$_{flow}$	6	0.54	0.12	0.40	0.70
		Speed quotient$_{flow}$	6	1.25	0.52	0.64	2.07
		H1H2$_{flow}$	6	6.67	2.15	4.1	9.6
		Flow pulse amplitude$_{flow}$ (mL/s)	6	80.65	40.27	38	148
		Maximum flow declination rate$_{flow}$ (mL/s^2)	6	99549.83	64915.65	141100	83388
		Amplitude quotient$_{flow}$	6	0.89	0.25	0.56	1.20
		Duration closing phase$_{flow}$ (ms)	6	1.68	0.63	0.90	2.72

(*Continued*)

TABLE 4. (*Continued*)

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
		Glottal resistance$_{flow}$	5	0.35	0.22	0.24	0.72
		Glottal area	6	85.74	78.23	20.18	232.27
		Peak closing velocity	6	73350.57	17243.26	52227.48	98428.87
		Speed quotient	5	2.19	0.46	1.53	2.73
		Glottal area index	6	2.03	1.60	0.43	4.80
		Amplitude-length-ratio	6	7.11	2.96	2.53	11.13
		Closing quotient	6	0.21	0.11	0.08	0.31
		Maximum area declination rate	6	−75.07	18.10	−105.30	−51.60
		Amplitude quotient	6	−2.48	0.57	−3.52	−2.01
		Stiffness index	6	0.43	0.08	0.30	0.50
		Closing duration$_{area}$ (ms)	6	1.63	0.88	0.50	2.50

TABLE 5.
Mean and standard deviations of the dependent variables for females across typical loudness

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
Typical	Breathy	Closed quotient$_{flow}$	4	0.28	0.06	0.22	0.37
		Speed quotient$_{flow}$	4	1.02	0.45	0.52	1.47
		H1H2$_{flow}$	4	19.76	3.9	17.9	24
		Flow pulse amplitude$_{flow}$ (mL/s)	4	71.0	14.2	55	87
		Maximum flow declination rate$_{flow}$ (mL/s^2)	4	100850	12593	91224	112190
		Amplitude quotient$_{flow}$	4	0.71	0.12	0.59	0.84
		Duration closing phase$_{flow}$ (ms)	4	1.31	0.21	1.11	1.59
		Glottal resistance$_{flow}$	4	0.11	0.08	0.03	0.23
		Glottal area	4	241.76	119.87	128.33	409.65
		Peak closing velocity	4	256696.42	141434.33	79944.56	424723.38
		Speed quotient	3	1.69	0.20	1.47	1.83
		Glottal area index	4	0.70	0.35	0.28	1.00
		Amplitude-length-ratio	4	8.89	6.38	1.91	17.03
		Closing quotient	4	0.36	0.04	0.30	0.41
		Maximum area declination rate	4	−128.73	86.84	−242.50	−31.40
		Amplitude quotient	4	−2.41	0.28	−2.66	−2.04
		Stiffness index	4	0.45	0.05	0.38	0.50
		Closing duration$_{area}$ (ms)	4	1.30	0.18	1.03	1.39
	Flow	Closed quotient$_{flow}$	5	0.24	0.04	0.22	0.30
		Speed quotient$_{flow}$	5	1.70	0.21	1.46	1.90
		H1H2$_{flow}$	5	19.93	5.02	13.9	26.4
		Flow pulse amplitude$_{flow}$ (mL/s)	5	94.4	38.0	55	132
		Maximum flow declination rate$_{flow}$ (mL/s^2)	5	152963	59636.63	78060	206030
		Amplitude quotient$_{flow}$	5	0.63	0.06	0.59	0.71
		Duration closing phase$_{flow}$ (ms)	5	1.11	0.16	0.90	1.29
		Glottal resistance$_{flow}$	5	0.27	0.18	0.10	0.53
		Glottal area	5	147.78	38.17	94.81	188.93
		Peak closing velocity	5	242709.97	53924.28	191367.87	334509.80
		Speed quotient	5	1.75	0.38	1.15	2.07
		Glottal area index	5	0.97	0.07	0.84	1.03
		Amplitude-length-ratio	5	8.39	2.59	4.88	11.44
		Closing quotient	5	0.38	0.06	0.33	0.47
		Maximum area declination rate	5	−124.84	45.53	−203.90	−86.20
		Amplitude quotient	5	−2.40	0.15	−2.51	−2.15
		Stiffness index	5	0.43	0.03	0.40	0.47
		Closing duration$_{area}$ (ms)	5	1.41	0.17	1.29	1.60
	Neutral	Closed quotient$_{flow}$	6	0.30	0.09	0.22	0.43
		Speed quotient$_{flow}$	6	1.42	0.37	1.01	1.98
		H1H2$_{flow}$	6	17.43	7.31	11.5	31.2
		Flow pulse amplitude$_{flow}$ (mL/s)	6	83.6	56.1	31	19.6
		Maximum flow declination rate$_{flow}$ (mL/s^2)	6	1277335.9	70807.14	44822	249770
		Amplitude quotient$_{flow}$	6	0.65	0.15	0.36	0.70
		Duration closing phase$_{flow}$ (ms)	6	1.18	0.12	1.05	1.37
		Glottal resistance$_{flow}$	6	0.19	0.15	0.07	0.45
		Glottal area	6	107.09	69.86	40.18	199.79
		Peak closing velocity	6	153484.30	94551.70	63819.49	317772.10
		Speed quotient	5	1.83	0.70	1.28	3.00

(*Continued*)

TABLE 5. (*Continued*)

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
		Glottal area index	6	1.01	0.38	0.29	1.39
		Amplitude-length-ratio	6	7.13	2.94	2.84	11.01
		Closing quotient	6	0.30	0.07	0.20	0.41
		Maximum area declination rate	6	−79.72	46.32	−160.60	−22.28
		Amplitude quotient	6	−4.72	5.88	−16.70	−2.02
		Stiffness index	6	0.45	0.04	0.41	0.50
		Closing duration$_{area}$ (ms)	6	1.20	0.36	0.69	1.62
	Pressed	Closed quotient$_{flow}$	4	0.51	0.13	0.37	0.66
		Speed quotient$_{flow}$	4	1.27	0.64	0.50	2.05
		H1H2$_{flow}$	4	6.14	1.89	4.8	8.9
		Flow pulse amplitude$_{flow}$ (mL/s)	4	72.92	52.48	12	140
		Maximum flow declination rate$_{flow}$ (mL/s^2)	4	197717.75	132378.85	23151	345060
		Amplitude quotient$_{flow}$	4	0.43	0.21	0.21	0.67
		Duration closing phase$_{flow}$ (ms)	4	0.99	0.22	0.06	0.13
		Glottal resistance$_{flow}$	4	0.48	0.43	0.08	1.09
		Glottal area	4	79.70	60.33	18.94	161.78
		Peak closing velocity	4	62812.94	19663.94	38376.62	83473.95
		Speed quotient	3	2.03	0.94	1.08	2.96
		Glottal area index	4	1.20	1.16	0.54	2.93
		Amplitude-length-ratio	4	5.11	0.96	4.45	6.54
		Closing quotient	4	0.31	0.16	0.10	0.49
		Maximum area declination rate	4	−37.09	16.37	−54.80	−19.00
		Amplitude quotient	4	−2.67	0.51	−3.22	−2.00
		Stiffness index	4	0.43	0.07	0.35	0.50
		Closing duration$_{area}$ (ms)	4	1.45	0.71	0.40	1.88

t [21] = 2.94, p = 0.008) and pressed (M = 79.90 ± 60.33, t [21] = 3.24, p = 0.004) phonation types. The ALR was not statistically significant across phonation types as hypothesized (F = 1.23 [3, 21], p = 0.32).

The AQ$_{flow}$ (F = 5.26 [3, 21], p = 0.007) was significantly greater in breathy (M = 0.71 ± 0.12) compared to the flow (M = 0.63 ± 0.06, t [21] = 2.11, p = 0.047) phonation type. The CQ$_{flow}$ (F = 3.20 [3, 21], p = 0.044) was significantly greater in pressed (M = 0.51 ± 0.13) compared to neutral (M = 0.30 ± 0.09, t [21] = −3.38, p = 0.003), breathy (M = 0.28 ± 0.06, t [21] = −3.83, p < 0.001), and flow (M = 0.24 ± 0.04, t [21] = −3.23, p = 0.004) phonation types. As hypothesized the PA$_{flow}$ (F = 0.83 [3, 21], p = 0.49) and MFDR$_{flow}$ (F = 0.08 [3, 21], p = 0.90) were not statistically significant across phonation types.

II. Changes in GA waveform and airflow parameters as a function of breathy, flow neutral, and pressed phonation types during loud condition:

(a) Male: The only parameter that was statistically significant across all combinations of phonation types during loud phonation was the relative PCV derived from the GA waveform (F = 0.001 [3, 27], p < 0.0001) . For the loud condition the PCV was large for breathy, followed by flow, pressed, and neutral phonations. The CD$_{flow}$ was significantly greater in breathy (M = 2.01 ± 0.43) compared to the flow (M = 1.93 ± 0.27, t [27] = 2.60, p = 0.015), pressed (M = 1.76 ± 0.58, t [27] = 2.32, p = 0.028), and neutral (M = 1.70 ± 0.42, t [27] = 2.60, p = 0.015), phonation types (Table 6).

(b) Female: The only parameter that was statistically significant across all combinations of phonation types during loud phonation was the relative PCV derived from the GA waveform (F = 0.001 [3, 21], p < 0.0001). The PCV was large for breathy followed by flow, neutral, and pressed phonations. The AQ$_{flow}$ (F = 5.26 [3, 21], p = 0.007) was significantly greater in pressed (M = 0.64 ± 0.15) compared to flow (M = 0.62 ± 0.10, t [21] = −3.38, p = 0.007), and neutral (M = 0.56 ± 0.16, t [21] = −3.71, p = 0.001) and lower compared to breathy (M = 0.71 ± 0.14, t [21] = −2.38, p = 0.027) phonation types. The CD$_{flow}$ (F = 3.62 [3, 21], p = 0.030) was significantly greater in pressed (M = 1.17 ± 0.43) compared to the flow (M = 1.14 ± 0.03, t [21] = −2.93, p = 0.008), breathy (M = 1.06 ± 0.02, t [21] = −3.15, p = 0.005), and neutral (M = 1.03 ± 0.10, t [21] = −4.08, p < 0.001) phonation types. The GR$_{flow}$ (F = 4.53 [3, 21], p = 0.013) was significantly greater in pressed (M = 0.59 ± 0.58) compared to the neutral (M = 0.24 ± 0.14, t [21] = −2.46, p = 0.023), flow (M = 0.22 ± 0.16, t [21] = −2.83, p = 0.01), and breathy (M = 0.10 ± 0.06, t [21] = −3.11, p = 0.005) phonation types. The SQ$_{flow}$ (F = 2.91 [4, 21], p = 0.046] was significantly greater in neutral (M = 1.35 ± 0.29, t [21] = −3.03, p = 0.006) compared to pressed (M = 1.20 ± 0.42, t [21] = 3.66, p = 0.002), and breathy (M = 0.80 ± 0.34, t [21] = −2.48, p = 0.022), phonation types and lower compared to flow (M = 1.42 ± 0.26, t [21] = −3.03, p = 0.006) (Table 7).

TABLE 6.
Mean and standard deviations of the dependent variables for males across loud condition

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
Loud	Breathy	Closed quotient$_{flow}$	3	031	0.03	0.28	0.34
		Speed quotient$_{flow}$	3	1.35	0.26	1.16	1.64
		H1H2$_{flow}$	3	14.60	2.67	11.7	16.9
		Flow pulse amplitude$_{flow}$ (mL/s)	3	178.19	108.68	64	280
		Maximum flow declination rate$_{flow}$ (mL/s^2)	3	173529.33	121508.90	47198	289560
		Amplitude quotient$_{flow}$	3	1.12	0.20	0.97	1.35
		Duration closing phase$_{flow}$ (ms)	3	2.01	0.43	1.69	2.5
		Glottal resistance$_{flow}$	3	0.12	0.07	0.04	0.17
		Glottal area	3	398.50	267.08	165.97	690.21
		Peak closing velocity	3	343514.20	262653.84	58949.73	576649.80
		Speed quotient	3	1.82	0.56	1.33	2.43
		Glottal area index	3	0.96	0.47	0.60	1.49
		Amplitude-length-ratio	3	11.89	7.21	4.20	18.48
		Closing quotient	3	0.34	0.12	0.20	0.44
		Maximum area declination rate	3	−214.20	145.84	−303.30	−45.90
		Amplitude quotient	3	−3.23	0.20	−3.35	−3.01
		Stiffness index	3	0.35	0.05	0.30	0.40
		Closing duration$_{area}$ (ms)	3	2.29	0.84	1.40	3.08
	Flow	Closed quotient$_{flow}$	3	0.34	0.08	0.28	0.43
		Speed quotient$_{flow}$	3	1.37	0.31	1.02	1.63
		H1H2$_{flow}$	3	11.17	1.24	10	12.5
		Flow pulse amplitude$_{flow}$ (mL/s)	3	203.03	7.78	194	206
		Maximum flow declination rate$_{flow}$ (mL/s^2)	3	290326.67	104239.13	217860	409790
		Amplitude quotient$_{flow}$	3	0.76	0.25	0.47	0.96
		Duration closing phase$_{flow}$ (ms)	3	1.93	0.27	1.69	2.23
		Glottal resistance$_{flow}$	3	0.08	0.02	0.07	0.11
		Glottal area	3	222.00	82.63	149.44	311.94
		Peak closing velocity	3	265175.95	98031.62	152053.08	325288.56
		Speed quotient	3	2.17	0.08	2.07	2.22
		Glottal area index	3	1.15	0.31	0.92	1.50
		Amplitude-length-ratio	3	11.01	3.25	8.92	14.76
		Closing quotient	3	0.29	0.06	0.22	0.33
		Maximum area declination rate	3	−211.53	47.01	−240.70	−157.30
		Amplitude quotient	3	−2.66	0.20	−2.88	−2.48
		Stiffness index	3	0.38	0.02	0.36	0.40
		Closing duration$_{area}$ (ms)	3	1.96	0.21	1.79	2.20
	Neutral	Closed quotient$_{flow}$	3	0.38	0.11	0.27	0.50
		Speed quotient$_{flow}$	3	1.63	0.10	1.56	1.75
		H1H2$_{flow}$	3	10.59	1.57	9.6	12.4
		Flow pulse amplitude$_{flow}$ (mL/s)	3	143.75	20.17	123	164
		Maximum flow declination rate$_{flow}$ (mL/s^2)	3	235866.67	54415.84	191410	296550
		Amplitude quotient$_{flow}$	3	0.64	0.19	0.42	0.75
		Duration closing phase$_{flow}$ (ms)	3	1.70	0.42	1.23	2.03
		Glottal resistance$_{flow}$	3	0.08	0.08	0.07	0.16
		Glottal area	3	145.13	26.88	116.24	169.40
		Peak closing velocity	3	157838.52	28402.13	128426.46	185109.54
		Speed quotient	3	2.02	0.15	1.87	2.16
		Glottal area index	3	1.02	0.16	0.90	1.20
		Amplitude-length-ratio	3	9.11	1.41	8.13	10.73
		Closing quotient	3	0.32	0.03	0.28	0.35
		Maximum area declination rate	3	−135.23	16.22	−150.20	−118.00
		Amplitude quotient	3	−2.68	0.24	−2.85	−2.41
		Stiffness index	3	0.38	0.03	0.35	0.42
		Closing duration$_{area}$ (ms)	3	2.29	0.20	2.10	2.49
	Pressed	Closed quotient$_{flow}$	2	0.38	0.17	0.25	0.50
		Speed quotient$_{flow}$	2	1.44	0.10	1.37	1.50
		H1H2$_{flow}$	2	10.16	1.75	8.9	11.4
		Flow pulse amplitude$_{flow}$ (mL/s)	2	121.58	47.71	88	155
		Maximum flow declination rate$_{flow}$ (mL/s^2)	2	136808.5	64433.691	91247	182370
		Amplitude quotient$_{flow}$	2	0.91	0.08	0.85	0.96
		Duration closing phase$_{flow}$ (ms)	2	1.76	0.58	1.36	2.17

(*Continued*)

TABLE 6. (*Continued*)

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
		Glottal resistance$_{flow}$	2	0.08	0.16	0.16	0.39
		Glottal area	2	127.04	55.80	87.59	166.50
		Peak closing velocity	2	173207.86	8445.06	167236.30	179179.41
		Speed quotient	2	1.39	0.16	1.28	1.50
		Glottal area index	2	1.89	0.81	1.31	2.46
		Amplitude-length-ratio	2	16.03	4.11	13.13	18.94
		Closing quotient	2	0.25	0.12	0.17	0.34
		Maximum area declination rate	2	−145.80	8.49	−151.80	−139.80
		Amplitude 1uotient	2	−2.55	0.03	−2.57	−2.53
		Stiffness index	2	0.43	0.03	0.41	0.45
		Closing duration$_{area}$ (ms)	2	1.70	0.85	1.10	2.30

TABLE 7.
Mean and standard deviations of the dependent variables for females across loud condition

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
Loud	Breathy	Closed quotient$_{flow}$	2	0.33	0.08	0.28	0.39
		Speed quotient$_{flow}$	2	0.80	0.34	0.56	1.04
		H1H2$_{flow}$	2	13.99	4.97	10.5	17.5
		Flow pulse amplitude$_{flow}$ (mL/s)	2	73.99	0.06	73.95	74
		Maximum flow declination rate$_{flow}$	2	106064.5	20174.46	91799	120330
		Amplitude quotient$_{flow}$	2	0.71	0.14	0.62	0.81
		Duration closing phase$_{flow}$ (ms)	2	1.06	0.02	0.87	1.08
		Glottal resistance$_{flow}$	2	0.10	0.06	0.06	0.15
		Glottal area	2	111.83	115.33	30.28	193.38
		Peak closing velocity	2	226795.95	264664.82	39649.66	413942.23
		Speed quotient	2	4.42	4.60	1.17	7.67
		Glottal area index	2	1.16	0.17	1.03	1.28
		Amplitude-length-ratio	2	10.34	2.41	8.63	12.04
		Closing quotient	2	0.26	0.16	0.15	0.37
		Maximum area declination rate	2	−102.98	86.59	−164.20	−41.75
		Amplitude quotient	2	−2.30	0.37	−2.56	−2.04
		Stiffness index	2	0.48	0.02	0.47	0.49
		Closing duration$_{area}$ (ms)	2	1.09	0.14	0.99	1.19
	Flow	Closed quotient$_{flow}$	2	0.32	0.12	0.23	0.40
		Speed quotient$_{flow}$	2	1.42	0.26	1.24	1.61
		H1H2$_{flow}$	2	17.86	10.54	10.4	25.3
		Flow pulse amplitude$_{flow}$ (mL/s)	2	137.97	115.61	56	220
		Maximum flow declination rate$_{flow}$	2	210545	152289.59	102860	318230
		Amplitude quotient$_{flow}$	2	0.62	0.10	0.55	0.69
		Duration closing phase$_{flow}$	2	1.14	0.03	1.14	1.16
		Glottal resistance$_{flow}$	2	0.22	0.16	0.11	0.33
		Glottal area	2	61.21	40.93	32.27	90.16
		Peak closing velocity	2	134382.37	78423.23	78928.78	189835.97
		Speed quotient	2	1.70	0.57	1.30	2.10
		Glottal area index	2	1.77	0.47	1.44	2.10
		Amplitude-length-ratio	2	9.13	5.00	5.59	12.66
		Closing quotient	2	0.22	0.02	0.21	0.24
		Maximum area declination rate	2	−78.55	53.39	−116.30	−40.80
		Amplitude quotient	2	−2.27	0.34	−2.51	−2.02
		Stiffness index	2	0.47	0.04	0.44	0.50
		Closing duration$_{area}$ (ms)	2	0.89	0.15	0.79	1.00
	Neutral	Closed quotient$_{flow}$	4	0.37	0.18	0.19	0.56
		Speed quotient$_{flow}$	4	1.35	0.29	0.92	1.52

(*Continued*)

TABLE 7. (*Continued*)

Condition	Phonation	Variable	N	Mean	Std Dev	Minimum	Maximum
		$H1H2_{flow}$	4	14.99	7.13	6.6	21.9
		Flow pulse $amplitude_{flow}$ (mL/s)	4	93.25	40.75	46	144
		Maximum flow declination $rate_{flow}$	4	182087.5	104910.42	78620	289460
		Amplitude $quotient_{flow}$	4	0.56	0.16	0.39	0.78
		Duration closing $phase_{flow}$	4	1.03	0.10	0.92	1.14
		Glottal $resistance_{flow}$	4	0.24	0.14	0.12	0.44
		Glottal area	4	51.67	41.22	20.67	111.32
		Peak closing velocity	4	122583.53	79693.15	54458.08	230572.95
		Speed quotient	4	2.13	0.93	1.50	3.50
		Glottal area index	4	1.88	0.73	1.19	2.88
		Amplitude-length-ratio	4	6.63	2.65	3.58	10.03
		Closing quotient	4	0.21	0.09	0.14	0.33
		Maximum area declination rate	4	−75.10	45.97	−140.40	−42.80
		Amplitude quotient	4	−2.02	0.02	−2.05	−2.01
		Stiffness index	4	0.50	0.00	0.50	0.50
		Closing $duration_{area}$ (ms)	4	0.85	0.31	0.60	1.29
	Pressed	Closed $quotient_{flow}$	2	0.50	0.05	0.46	0.51
		Speed $quotient_{flow}$	2	1.20	0.42	0.91	1.50
		$H1H2_{flow}$	2	7.02	0.71	6.5	7.5
		Flow pulse $amplitude_{flow}$ (mL/s)	2	87.52	88.64	25	150
		Maximum flow declination $rate_{flow}$	2	156200	173962.41	33190	279210
		Amplitude $quotient_{flow}$	2	0.64	0.15	0.54	0.75
		Duration closing $phase_{flow}$	2	1.17	0.43	1.05	1.47
		Glottal $resistance_{flow}$	2	0.59	0.58	0.18	0.99
		Glottal area	2	43.70	32.63	20.62	66.77
		Peak closing velocity	2	84421.58	43071.28	53965.58	114877.57
		Speed quotient	2	4.22	2.10	2.73	5.70
		Glottal area index	2	1.22	0.01	1.21	1.23
		Amplitude-length-ratio	2	6.96	5.90	2.79	11.13
		Closing quotient	2	0.19	0.07	0.14	0.24
		Maximum area declination rate	2	−62.70	40.87	−91.60	−33.80
		Amplitude quotient	2	−2.06	0.07	−2.11	−2.01
		Stiffness index	2	0.49	0.02	0.48	0.50
		Closing $duration_{area}$ (ms)	2	0.84	0.21	0.69	0.99

III. Changes in GA waveform and airflow parameters as a function of breathy, flow neutral, and pressed phonation types during soft condition:
   (a) Male: The only parameter that was statistically significant across all combinations of phonation types during soft loudness was the relative PCV derived from the GA waveform (F = 0.001 [3, 27], $p < 0.0001$). For soft condition the PCV was largest for flow phonation followed by breathy, and neutral phonations (Table 8). The PA_{flow} (F = 3.00 [3, 27], $p = 0.048$) was significantly greater in flow phonation (212 mL/s) compared to neutral (89 mL/s, t [27] = 2.15, $p = 0.041$).
   (b) Female: The only parameter that was statistically significant across all combinations of phonation types during soft loudness was the relative PCV derived from the GA waveform between flow and neutral (F = 0.001 [3, 21], $p < 0.0001$) (Table 9).
IV. Relationship between GA and flow:

An important aspect of the results and our second study question is to what extent the High-Speed Videoendoscopy (HSV) and the flow data agree. There is a significant positive relationship between the amplitude quotient from inverse filtering and HSV, r (41) = 0.65, $p < 0.001$ (Figure 7).

There was also a statistically significant positive relationship between the HSV closing phase and the flow glottogram closing phase r (41) = 0.76, $p < 0.001$ and between the entire GA and the total glottal flow r (41) = 0.47, $p = 0.001$. In most cases the duration of glottal closing on HSV is longer than the duration of glottal flow decrease (Figure 8). The Figure 9 shows the relationship between GA and total glottal flow. A contributing factor to the low value of the determination coefficient is that the flow to area relationship must depend on both subglottal pressure and phonation type; a given subglottal pressure will produce a greater flow through a wide than through a narrow GA. In addition, female adults have shorter vocal

TABLE 8.
Mean and standard deviations of the dependent variables for males across soft loudness

Condition	Phonation	Variable	N	Mean
Soft	Breathy	Closed quotient$_{flow}$	1	0.21
		Speed quotient$_{flow}$	1	1.56
		H1H2$_{flow}$	1	19.9
		Flow pulse amplitude$_{flow}$ (mL/s)	1	106
		Maximum flow declination rate$_{flow}$ (mL/s^2)	1	79219
		Amplitude quotient$_{flow}$	1	1.34
		Duration closing phase$_{flow}$ (ms)	1	2.04
		Glottal resistance$_{flow}$	1	0.04
		Glottal area	1	591.80
		Peak closing velocity	1	341287.44
		Speed quotient	1	1.90
		Glottal area index	1	0.74
		Amplitude-length-ratio	1	11.38
		Closing quotient	1	0.35
		Maximum area declination rate	1	–211.50
		Amplitude quotient	1	–3.39
		Stiffness index	1	0.30
		Closing duration$_{area}$ (ms)	1	2.30
	Flow	Closed quotient$_{flow}$	1	0.22
		Speed quotient$_{flow}$	1	1.72
		H1H2$_{flow}$	1	19.6
		Flow pulse amplitude$_{flow}$ (mL/s)	1	212
		Maximum flow declination rate$_{flow}$ (mL/s^2)	1	148610
		Amplitude quotient$_{flow}$	1	1.43
		Duration closing phase$_{flow}$	1	1.96
		Glottal resistance$_{flow}$	1	0.08
		Glottal area	1	462.48
		Peak closing velocity	1	424190.96
		Speed quotient	1	1.13
		Glottal area index	1	0.90
		Amplitude-length-ratio	1	13.47
		Closing quotient	1	0.47
		Maximum area declination rate	1	–226.30
		Amplitude quotient	1	–4.06
		Stiffness index	1	0.29
		Closing duration$_{area}$ (ms)	1	3.20
	Neutral	Closed quotient$_{flow}$	1	0.26
		Speed quotient$_{flow}$	1	1.72
		H1H2$_{flow}$	1	14.5
		Flow pulse amplitude$_{flow}$ (mL/s)	1	89
		Maximum flow declination rate$_{flow}$ (mL/s^2)	1	81757
		Amplitude quotient$_{flow}$	1	1.09
		Duration closing phase$_{flow}$ (ms)	1	1.87
		Glottal resistance$_{flow}$	1	0.08
		Glottal area	1	292.31
		Peak closing velocity	1	319310.10
		Speed quotient	1	1.29
		Glottal area index	1	1.05
		Amplitude-length-ratio	1	13.67
		Closing quotient	1	0.42
		Maximum area declination rate	1	–193.90
		Amplitude quotient	1	–3.62
		Stiffness index	1	0.28
		Closing duration$_{area}$ (ms)	1	2.90

TABLE 9.
Mean and standard deviations of the dependent variables for females across soft loudness

Condition	Phonation	Variable	N	Mean
Soft	Flow	Closed quotient$_{flow}$	1	0.42
		Speed quotient$_{flow}$	1	1.71
		H1H2$_{flow}$	1	13.0
		Flow pulse amplitude$_{flow}$ (mL/s)	1	214
		Maximum flow declination rate$_{flow}$ (mL/s^2)	1	278970
		Amplitude quotient$_{flow}$	1	0.77
		Duration closing phase$_{flow}$ (ms)	1	1.05
		Glottal resistance$_{flow}$	1	0.06
		Glottal area	1	78.86
		Peak closing velocity	1	169269.01
		Speed quotient	1	1.40
		Glottal area index	1	2.10
		Amplitude-length-ratio	1	10.84
		Closing quotient	1	0.20
		Maximum area declination rate	1	–115.60
		Amplitude quotient	1	–2.34
		Stiffness index	1	0.44
		Closing duration$_{area}$ (ms)	1	1.00
	Neutral	Closed quotient$_{flow}$	1	0.23
		Speed quotient$_{flow}$	1	1.57
		H1H2$_{flow}$	1	16.4
		Flow pulse amplitude$_{flow}$ (mL/s)	1	193
		Maximum flow declination rate$_{flow}$ (mL/s^2)	1	196440
		Amplitude quotient$_{flow}$	1	0.98
		Duration closing phase$_{flow}$ (ms)	1	1.51
		Glottal resistance$_{flow}$	1	0.05
		Glottal area	1	27.30
		Peak closing velocity	1	72199.51
		Speed quotient	0	
		Glottal area index	1	3.05
		Amplitude-length-ratio	1	7.72
		Closing quotient	1	0.04
		Maximum area declination rate	1	–58.50
		Amplitude quotient	1	–2.00
		Stiffness index	1	0.50
		Closing duration$_{area}$ (ms)	1	0.19

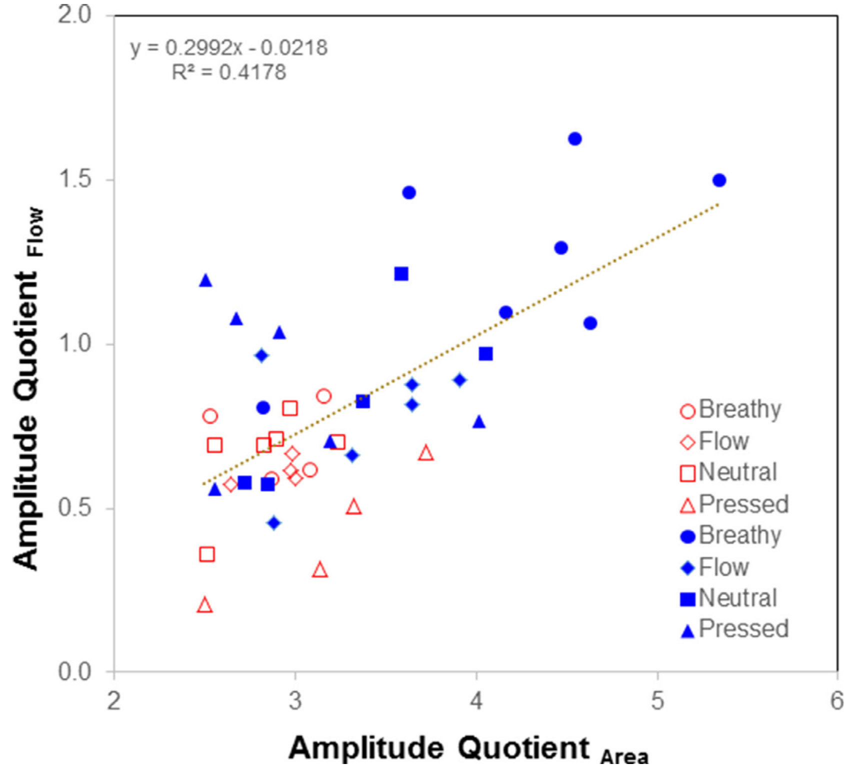

FIGURE 7. Amplitude quotient derived from the high-speed video data (x-axis) as a function of the associated values derived from the flow glottogram (y-axis), produced in the four phonation types for typical vocal loudness. Open and filled symbols refer to female and male participants, respectively respectively. The dashed line and the equation refer to the trendline across all participants and phonation types.

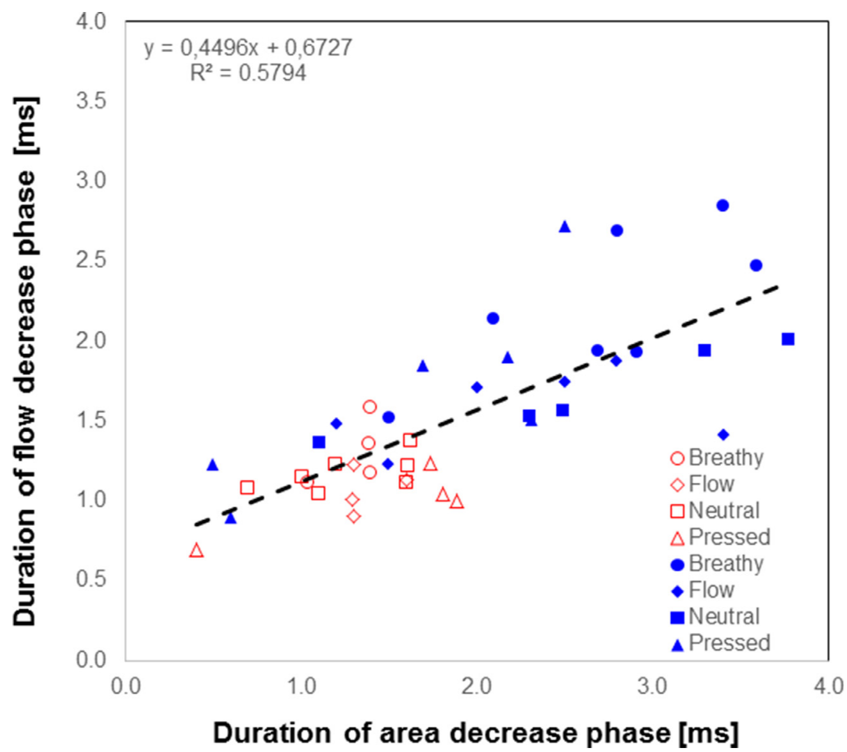

FIGURE 8. Duration of the closing phase (ms) from the high-speed video data (x-axis) as function of the duration of the closing phase derived (ms) from the flow glottograms (y-axis) produced in the four phonation types for typical vocal loudness. Open and filled symbols refer to female and male participants respectively. The dashed line and the equation refer to the trendline across all participants and phonation types.

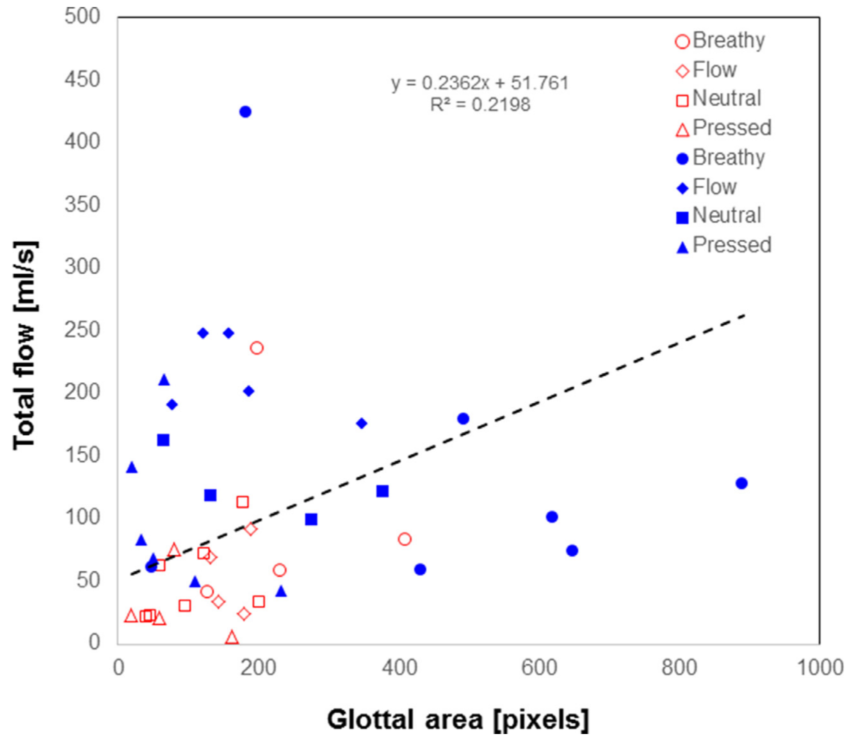

FIGURE 9. Glottal area in pixels (x-axis) from the high-speed video data as a function of the total flow from the flow glottograms (mL/s) (y-axis) produced in the four phonation types for typical vocal loudness. Open and filled symbols refer to female and male participants respectively. The dashed line and the equation refer to the trendline across all participants and phonation types.

folds than male adults. This should be the reason why the female subjects showed lower flow and area values than the male subjects. There was a statistically significant positive relationship between the relative PCV and the ALR r (41) = 0.84, $p < 0.001$, both derived from HSV (Figure 10).

DISCUSSION

The goal of this study was to quantify the most salient source characteristics of flow phonation in males and females. A comprehensive set of source measurements were evaluated from simultaneous high-speed video endoscopy, inverse filtering, subglottal pressure, acoustic recordings, and electroglottography. In this study, analysis of electroglottography was not conducted as the main goal was to evaluate source characteristics from direct examination of the vocal folds against flow glottogram characteristics of flow phonation. Young, vocally healthy adult males and females performed a series of the syllables /pæ:/ in typical (conversational), loud, and soft phonation in each of the phonation types breathy, flow, neutral, and pressed.

Source characteristics of flow phonation from high-speed videoendoscopy

Systematic changes in shape of the GA waveform during various phonation types resulted in changes in the relative PCV derived from high-speed videoendoscopy for both male and female participants across typical, loud, and soft phonations. For females, as expected, the relative PCV systematically decreased from breathy to flow to neutral and pressed phonation types for typical and loud condtions (Figure 6). The PCV also decreased from flow to neutral phonation during the soft condition as expected. Systematic changes in PCV suggest that the GA is changing quickly during the closing phase for breathy compared to pressed phonations.

Contrary to the female participants, the PCV was large for breathy, followed by neutral, flow, and pressed phonation for typical loudness for male participants. For the loud condition, the relative PCV was large for breathy followed by flow, pressed, and neutral. The difference between neutral and flow in the typical condition (Table 4) and between pressed and neutral in the loud condition was small (Table 6). Further empirical studies are required to examine whether or not the trend of the PCV observed in this study across phonation types holds true with a larger number of male participants. For the soft condition, the PCV was large for flow followed by breathy and neutral phonation types. Prior studies have investigated variations in relative PCV to analyze changes during modal, low, and high pitch conditions, and soft, medium, and loud vocal loudness conditions using stroboscopy.[49] Using high-speed videoendoscopy Patel et al (2015)[50] investigated normalized mid-membranous closing velocity to evaluate changes in speed of vocal fold closure during typical phonation across healthy male,

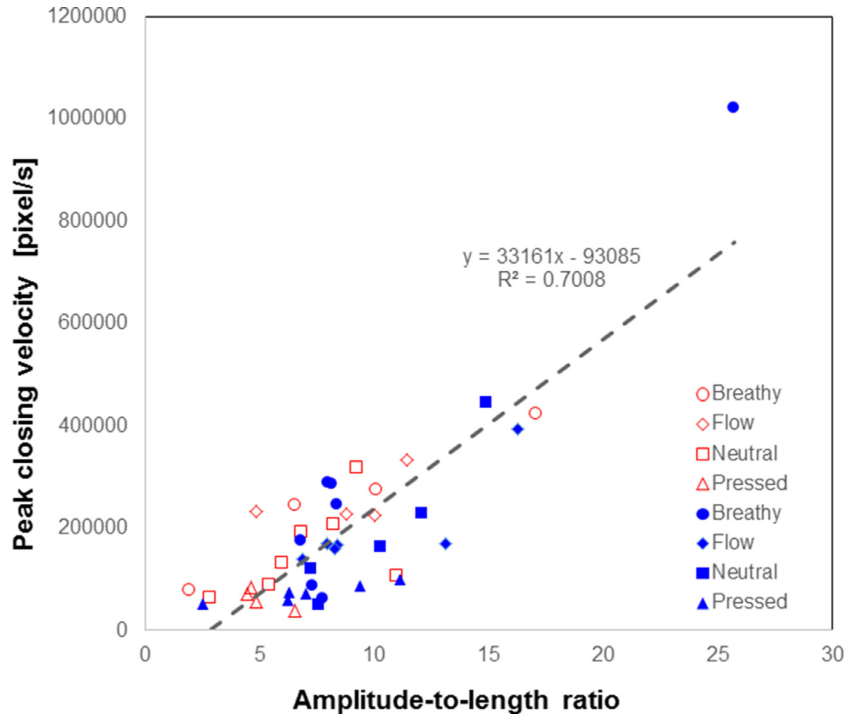

FIGURE 10. Amplitude-to-length ratio (x-axis) as a function of relative peak closing velocity (pixels/s) (y-axis) produced in the phonation modes represented by symbols at typical degree of vocal loudness. Open and filled symbols refer to female and male participants respectively. The dashed line and the equation refer to the trendline calculated across all participants and phonation types.

females, and children.[50] Children had the highest normalized closing velocity followed by males, and females. In the current study overall the relative PCV was smaller for females compared to males; however, this was not subjected to statistical analysis. Normalized closing velocity has also been used to evaluate the changes in vibratory characteristics due to impact stress in vocal nodules.[37,51] Findings of this study suggest that the relative PCV derived from the GA waveform was useful for distinguishing the various phonation types of breathy, flow, neutral, and pressed; however, there appears to be gender differences and a complex relationship in how the relative PCV is varied across vocal loudness conditions during breathy, flow, neutral, and pressed phonation types for males. According to previous studies, this could be caused by the vertical phase difference between the upper and lower margins of the vocal folds,[28,32,33] where the convergence angle is widest for breathy voice and smallest for pressed voice.

Contrary to our expectation, statistical difference was not observed across changes in vibratory amplitude (ampltiude-to-length ratio) across phonation types in males or females for various vocal loudness levels. The vibratory amplitude however, systematically reduced from breathy to flow to neutral and pressed in females for typical and loud vocal loudness levels, although it was not statistically significant. For the soft condition, the amplitude was larger for flow phonation compared to neutral. For male participants, changes in phonation type resulted in expected changes across typical phonation; however, the relative vibratory amplitude was marginally larger for neutral (10.44) than flow phonation (10.14). Contrary to our hypothesis, the loud condition resulted in the largest vibratory amplitude for pressed, followed by breathy, flow, and neutral phonations in males. For the soft condition, vibratory amplitude was large for neutral (13.67), followed by flow (13.47), and breathy phonation (11.38) in males. There appears to be a gender difference in how amplitude is varied across various loudness conditions for breathy, flow, neutral, and pressed phonations. Figure 10 shows an overview of the data in terms of a scatter plot of PCV as a function of the ALR. As expected, the velocity increases with increasing ALR. It can also be noted that for the male participants, pressed and neutral phonation tended to produce lower velocity values than flow and breathy phonation compared to females.

Unexpectantly, the amplitude quotient, which reflects the length of the glottal closing phase was largest for breathy, followed by flow, neutral, and pressed phonation during typical loudness; however, statistical difference was observed only between breathy and the other phonation types in males. Statistical difference was not observed in amplitude quotient across females. Findings suggest that male participants not only vary closing speed but also vary the duration of the closing phase to achieve target changes in the GA waveform for breathy, flow, neutral, and pressed phonation. Females on the other hand, predominantly vary closing speed as a function of phonation types.

Source characteristics of flow phonation from flow glottogram

The second question that we wanted to answer with the present study was what the relationship is between parameters derived from the glottal airflow and the GA waveform. Contrary to our hypothesis flow pulse amplitude and the maximum flow declination rate did not achieve statistical significance, but varied with phonation type as expected. The flow pulse amplitude was consistently large for flow phonation followed by neutral, pressed, and breathy phonation types for typical and loud sound level for both females and males, however, this was not statistically significant possibly because being underpowered. For the males' typical and loud conditions, MFDR was large for flow, followed by the neutral, breathy and pressed phonation types, whereas for the females' typical sound level condition, the MFDR was highest in pressed followed by flow, neutral, and breathy phonations. Flow phonation at soft loudness levels resulted in larger flow pulse amplitudes and maximum flow declination rate compared to neutral phonation.

Several studies have investigated the effects of varying subglottal pressure on the voice source flow waveform in untrained adult males and adult females,[45,52,53] however there are few studies investigating variations in flow glottograms across phonation types in females. Södersten et al (1995)[54] recorded videofiberstroboscopy, glottal airflow and EGG in healthy middle-aged women during soft, middle and loud phonation and had expert listeners rate voice samples along visual analogue scales representing breathiness, hypofunction, and hyperfunction. A correlation of approximately 0.5 between pulse amplitude and subglottal pressure in voices perceived as breathy and hypofunctional was reported by Södersten et al (1995),[55] while for voices perceived as hyperfunctional the correlation was -0.52.

For male participants, the flow pulse amplitude was consistently larger for flow, followed by breathy, neutral, and pressed phonation types across both typical and loud vocal loudness levels. This is in accordance with findings from one male particpant in Sundberg (1995)[3] and 6 males participants in Gauffin & Sundberg (1989)[2]. However, this difference failed to reach statistical significance in the present study. For the soft vocal loudness condition, the flow pulse amplitude was large for flow phonation followed by breathy and neutral phonation types. The maximum flow declination rate was large for flow phonation across typical, loud, and soft vocal loudness levels and smallest for pressed phonation across typical and loud vocal loudness levels. Overall, it appears that the flow pulse amplitude was a bit small for flow phonation in females and large for males, whereas the maximum area declination rate was large for flow phonation in females and males during typical condition.

The statistical analysis revealed very few significant flow glottogram differences between the phonation modes. For example, the inverse filtered closed quotient was statistically larger for pressed compared to breathy, flow, and neutral phonation during typical loudness only in females, but not in males. This was surprising, as earlier studies have observed that the closed quotient as well as several other flow glottogram parameters differed systematically between phonation types. Prior studies have shown MFDR, Q_{Closed}, H1H2 and NAQ to have significant correlations with expert listeners' ratings of degree of phonatory pressedness.[2,13,14] The lack of statistical significance in the present investigation could be due to the challenges posed by the extended duration of the recordings and the complex experimental setup, which required participants to produce the various phonation types with a flow mask, intraoral tube, and a flexible endoscopy. In addition, the participants were untrained and not used to consistently shifting between phonation types. Other studies investigating the relationship between airflow and phonation types typically were performed with trained participants and without the endoscope in place.[2,34,56]

The speed quotient from the flow glottogram was statistically larger for flow compared to breathy, neutral, and pressed phonations during loud sound level in females suggesting a skewing of the glottal volume velocity waveform to the right. In males, the speed quotient was larger in flow compared to breathy, neutral, and pressed phonation types during typical sound level, again suggesting that the duration of the opening phase was longer compared to the closing phase for neutral phonation. This assymmetry between the rising and falling parts of the flow glottogram can be explained by the nonlinear source-filter interaction.[30,31]

Similar to high-speed videoendoscopy, the amplitude quotient from inverse filtering was significantly greater for breathy compared to flow, neutral, and pressed phonation types in male and female participants, suggesting that the length of the closing phase is longer. This finding is similar to the findings reported by Alku & Vilkman (1996)[57] in four males and females and Alku et al (2002)[58] in five speakers with inverse filtering.

The glottal resistance was significantly larger for pressed compared to neutral, breathy, and flow phonation in males during typical sound level. This is in accordance with results from previous investigations on individuals with various vocal pathologies by Yanagihara (1970)[59] and from exiosed canine laryngeal expirements by Alipour et al (1997).[60]

Relationship between flow and area

The amplitude quotient, which is a measure related to the degree of glottal abduction,[1,61,62] decreased more slowly in the GA than the flow (Figure 7). The difference between the area-based and the flow-based versions is that the former includes the glottal leakage. As expected, the females produced lower values compared to the males. Also, as anticipated, the GA during the closing phase decreased more slowly than the flow in both males and females (Figure 8). Thus, the flow glottogram was more skewed to the right than the area waveform. This is in good agreement with the theory of source-filter interaction[31,63,64] and is similar to the findings in one male and one trained female in Granqvist et al (2003)[34] and Alku et al (2019)[62] on 10 speakers for the vowel /i/. At the beginning of the glottal opening, a small airflow is produced for a given GA, however, at the end of the open phase due to the inertia and the non-linear source-filter interaction, a large airflow is produced for a given glottal opening.[31,65–67] The data reveal that the changes in phonation type are mainly due to the changes in the closing phase in the glottal volume velocity waveform and the GA. During closing, the GA decrease is slower than the flow decrease in both males and females (Figure 8).

CONCLUSION

This study provides insights into the relationship between the GA and flow glottograms across various phonation types of breathy, flow, neutral, and pressed. Emerging findings from this study suggest that the pulse amplitude is not the determining factor for flow phonation in the untrained participants in this study. The closing speed and duration of the closing, conversely, were robust in differentiating the phonation types. The flow pulse amplitude however, is useful for visual feedback purposes in vocal training. The study findings futher suggest the use of PCV from the GA waveform and amplitude quotient from both the GA waveform and flow glottograms has the potential for monitoring changes in treatment targeting flow phonation. Untrained male participants in this study not only varied closing speed but also varied the duration of the closing phase to achieve target changes in the GA waveform for breathy, flow, neutral, and pressed phonation. Females on the other hand, predominantly vary closing speed as a function of phonation types. Findings from this study could lead to the development of empirically based quantitative treatment targets for training flow phonation in adults with voice disorders and assessment of treatment outcomes by providing the most salient objective measures of flow phonation in individuals with voice disorders. Having only two participants with complete data set is a limitation of the study. Future studies should consider scheduling the experiment for two days to facilitate complete data acquisition.

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