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External Laryngeal Oscillation and Aerodynamic Measures of Voice Onset: A Translational Study

Erik McLeod Christensen

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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Christopher Dromey
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ABSTRACT

External Laryngeal Oscillation and Aerodynamic Measures of
Voice Onset: A Translational Study

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Department of Communication Disorders, BYU
Master of Science

The purpose of this study was to examine external laryngeal oscillation and its potential effects on phonation threshold pressure (PTP; cm H_2O) and phonation threshold flow (PTF; L/sec). Measures of PTP and PTF have inherent limitations due to the nonlinear nature of phonation, influencing their clinical and experimental utility. This is true particularly for tracking relatively small changes in voice function because variability in the measure itself can be larger than that resulting from voice change. Elevated PTP and PTF are associated with a variety of voice disorders and correlate with self-reported vocal effort and fatigue. Prior studies involving silicone and excised animal larynges have demonstrated PTP reduction in response to external oscillation. In an extension of this work, this thesis examined external laryngeal oscillation and aerodynamic voice measures in two experiments including a translational benchtop to human approach. Experiment 1 used a within-subjects counterbalanced design to examine PTF in 12 porcine larynges. Larynges were fitted with a custom oscillation device and 30 phonation trials were conducted for each larynx, 15 with external oscillation and 15 without. Although summary statistics indicated that PTF was lower with external oscillation, differences were not significant. Experiment 2 applied a within-subjects counterbalanced design to examine PTP in four healthy adult females and one healthy adult male. Individuals produced repeated syllable strings of /pi/ productions at comfortable pitch with and without external oscillation using an electrolarynx and the second and third syllables were averaged. Descriptive analysis indicated that PTP was lowered for female participants but not the male participant. Taken together, the results of these studies offer preliminary evidence that external oscillation influences voice onset aerodynamic measures. The effects of external oscillation seem to be more evident in PTP. These findings have important clinical and research applications for PTP measurement and the potential positive influence on voice function. These preliminary results indicate the need for further research in this area.

Keywords: phonation threshold pressure, phonation threshold flow, benchtop model, excised larynx, laryngeal oscillation

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Introduction

The voice, as the primary means of communication for most people, is an integral part of human experience. Voice is intimately connected to identity and self-expression (Crow et al., 2021; Nathanson, 2017; S. Patel et al., 2011). Approximately 30% of people will experience a voice disorder at some point in their life (Roy et al., 2005). These disorders and resultant life disruptions can cause financial, emotional, and physical distress (Chong et al., 2022; Falanga et al., 2020; Gartling et al., 2021; Naunheim et al., 2020; Wilson et al., 2002). In order to address this widespread need, the American Speech-Language-Hearing Association has designated voice disorders as a core clinical practice area for speech-language pathologists (American Speech-Language-Hearing Association, n.d.). The present study aims to contribute to this effort. This introduction will review mechanisms, measures, and models of voice.

Voicing Process and Phonation Onset

To produce voice, a complex coordination of respiration (i.e., the power), vocal fold vibration (i.e., the source), and resonance (i.e., the filter) must occur. Voicing is typically initiated when the vocal folds adduct, subglottal pressure increases, and the vocal folds are set in a weakly-damped, self-sustained vibration governed by aerodynamic, acoustic, and myoelastic forces (Švec et al., 2021). Through this process, subglottal pressure is transduced into vocal fold vibration as energy is transferred from the airstream to the vocal fold tissues (Thomson et al., 2005). The vibrating vocal folds in turn modulate airflow through the glottis, producing pressure waves that are then filtered by supraglottic structures—including those in the laryngeal vestibule, pharynx, and oral cavity—to produce what is perceived as a person's voice.

The initiation of voicing, or phonation onset, was defined by Berry et al. (1996) as "an initialization of self-sustained vocal fold oscillations from a state of rest." Much is still unknown about the precise mechanisms of phonation onset, but by this definition it involves a change from a resting to a vibratory state. In order to trigger this change, a perturbation is required. One possible source of this perturbation is described by DeJonckere and Lebacq (2021). They examined the aerodynamic conditions present at vocal fold vibration onset (soft onset, i.e., vocal folds not in full medial contact). Using photoglottography, electroglottography, high-speed video, and flow measurements, they found that vocal fold vibration onset immediately follows the development of glottic airflow turbulence for a soft onset. Hence, turbulence in the airstream may provide the perturbation necessary to initiate vocal fold vibration.

Titze (1988) emphasized the importance of negative damping for phonation onset and energy transfer to the vocal folds. Negative damping can be provided by the convergent-divergent glottal configurations of the mucosal wave (i.e., vertical phase difference) and by the inertive reactance of the vocal tract. In addition to negative damping, Zhang (2016) summarized a different mechanism for phonation onset: eigenmode synchronization. An eigenmode is a normal mode or pattern of vibration. For example, the eigenmodes of a guitar string would include vibrating as a whole, in halves, in thirds, and so on. Vocal fold vibration can similarly be deconstructed into a series of eigenmodes. In this model, the synchronization of two or more eigenmodes of vocal fold vibration is the event that allows for energy transfer to the vocal folds to begin (Zhang, 2011; Zhang et al., 2007). For more information on eigenmodes and resonance properties of the vocal folds, the work of Berry and Titze (1996), and Švec et al. (2000) is recommended.

Regardless of the exact mechanisms of phonation onset, it is clear that the process is intricately balanced and can be disrupted by even small changes in the tissue or positioning of the vocal folds (Chan & Titze, 2006; Tao et al., 2011; Tokuda & Shimamura, 2017). Common changes that can lead to impaired phonation onset include tissue dehydration (Fujiki et al., 2017; Tanner et al., 2016), vocal fold asymmetry (Lucero et al., 2020), vocal fold paresis/paralysis (Jen et al., 2021), and excessive or imbalanced muscle tension (Zheng et al., 2012). These are the core elements of various structural, neurological, and behavioral voice disorders. Detrimental effects of impaired phonation onset may be most overt in connected speech, which is characterized by constant alternation between voiced and unvoiced speech segments (Gartner-Schmidt et al., 2015). Phonation onset and offset occur for each of these alternations. Impaired or delayed phonation onset can therefore significantly impair functional communication as the coordination for voice onset timing is precise and a delay of even hundredths of a second can disrupt the intended production.

Onset Measures: PTP and PTF

Since phonation onset is a critical part of voicing, it is important to be able to quantify and track it in individuals with voice disorders. One way to objectively measure phonation onset is by collecting aerodynamic data. Specific aerodynamic measures for phonation onset include, among others, subglottal pressure and flow at the moment the vocal folds begin to vibrate, i.e., phonation threshold pressure (PTP) and phonation threshold flow (PTF). PTP is defined as the minimum pressure needed to initiate vocal fold vibration (Titze, 1992), while PTF is correspondingly defined as the minimum air flow needed to initiate vocal fold vibration (Jiang & Tao, 2007). PTP and PTF both tend to be elevated for individuals with voice disorders (Jen et al., 2021; Zhuang et al., 2009). Elevated PTP and PTF values also correlate with increased vocal effort (Chang & Karnell, 2004; Enflo et al., 2013; McHenry et al., 2013; McKenna et al., 2019; Rosenthal et al., 2014), vocal fatigue (Xue et al., 2019), and perceptual ratings of breathiness (Fujiki & Thibeault, 2021).

While PTP and PTF may be useful clinical indicators of problems with phonation onset, PTP is not measured directly in clinical settings due to the invasive nature of such measurements, most commonly involving tracheal puncture (Plant et al., 2004). To circumvent this issue, PTP is typically estimated using bilabial plosives alternated with vowels following the work of Smitheran and Hixon (1981). PTF is collected from the oral flow signal based on the assumption that oral flow is roughly equal to glottal flow. In addition to the impracticality of direct measurement for PTP, there are other issues with PTP and PTF data collection. Voice onset, by definition, starts with vocal folds that are not vibrating transitioning to vocal folds that are vibrating. The process is nonlinear (Tokuda et al., 2008), indicating that PTP and PTF both have some inherent instability. This is in part due to the multitude of factors that influence PTP and PTF, including glottal configuration, tissue viscosity, and tissue stiffness (Titze, 1988). PTP has also been shown to plateau at large asymmetries of the vocal folds such as those caused by polyps and cysts, indicating that it may not be a useful measure for certain disorder types and more severe voice disorders (Lucero et al., 2020).

Other studies of aerodynamic measurement accuracy have shown that PTP and PTF collection in human subjects can also be affected by examiner training; participant instruction and prior voice training; cognitive, muscular, and tissue fatigue; and learning effects (Dastolfo, 2011). In one review paper, the authors identified and described several potential pitfalls that might occur during the quantification of voice onset and PTP (Plexico et al., 2011). They listed factors including vowel selection, syllable rate, number of syllable repetitions, occlusion of the nares, and environmental variables as potential sources of variability in PTP measurement. Follow-up studies investigating the influence of syllable-train length, performance end effects, and vowel selection yielded useful information on the relative influence of each of these parameters on PTP (Faver et al., 2012; Plexico & Sandage, 2012). Pitch also has a significant effect on PTP (Solomon et al., 2007). Other factors that can affect PTP and PTF in humans include auditory feedback (Morgan et al., 2004) and the presence of the flow mask (Orr & Cranen, 2005). Ideally, these factors should all be accounted for to increase confidence in phonation onset measure acquisition. Mechanical airflow interruption methods have been used as an alternative to labial interruption in an attempt to increase reliability and consistency (Lamb et al., 2020), yet many of the same issues remain.

In addition to data collection procedures, data analysis must be carefully considered when acquiring PTP and PTF. Sundarrajan et al. (2015) investigated potential sources of bias in PTP and PTF analysis and interpretation. After having two trained researchers analyze identical data sets with different labels (one presented as "blinded" and the other as "unblinded"), they found that intrarater reliability was high regardless of blinding. However, interrater reliability was relatively low, indicating that differences between raters could have a significant impact on PTP analysis.

It is currently recommended that aerodynamic data, including pressure and flow, be collected as part of a comprehensive voice evaluation (R. R. Patel et al., 2018). Due to the issues of instability summarized in this section, a minimum of nine measures for each elicited voice condition (e.g., softest voice possible) is recommended. This is not always clinically practical due to time constraints, billing requirements, and concerns for patient experience. Therefore, if these measures could be stabilized, it could potentially make PTP and PTF acquisition more efficient and increase confidence in the accuracy and reliability of the data.

External Oscillation and Voice

One way to potentially stabilize or reduce voice onset measures is by applying external oscillation to the larynx. As discussed earlier, phonation onset involves a state change from stationary vocal folds to vibrating vocal folds. As the vocal folds adduct, the mucosa disrupts the airstream from the lungs and begins to vibrate to produce sound. Even in very controlled voicing contexts such as those used in PTP and PTF measurement, each onset will be slightly different in how the vocal folds begin to interact with the airstream. By definition, voice onset is characterized by air pressure and flow perturbation. Because of this, it has been suggested that the introduction of an external oscillation might act as a catalyst for phonation onset and thereby reduce the air pressure and flow observed at the onset of voicing (Jackson & Thomson, 2021).

Several studies have examined external oscillation effects on laryngeal function. These studies have primarily looked at external laryngeal oscillation (ELO) as part of a therapeutic intervention, either for recovery from a vocally demanding task or as part of a regular therapeutic exercise regimen. Both whole body vibration and ELO appear to have benefits for recovery from vocal fatigue when applied after prolonged voice use, based on improvements of self-ratings of fatigue and highest sung pitch (Yiu et al., 2021). Anderson et al. (2018) found that 10-15 minutes of ELO led to more predictable changes in acoustic measures collected post-intervention than a placebo condition. Nascimento et al. (2021) and Barsties v. Latoszek (2020) investigated longer-term effects of external laryngeal oscillation as a component of a therapeutic voice program, with promising results reflected in acoustic and perceptual data. Mulheren and Ludlow (2017) ran a particularly innovative study in which they worked with Passy Muir, Inc. to develop a novel device worn on the neck that applied ELO. They then examined the effects of ELO on fundamental frequency (F_0), swallowing frequency, and cortical activation during swallowing.

While swallowing was the primary focus of their study, they found that ELO applied to the thyroid cartilage significantly reduced F_0 as analyzed from 8-second sustained vowel samples. Despite these recent studies, the extant literature does not include direct examination of the effects of ELO on aerodynamic measures of phonation onset in humans.

Jackson and Thomson (2021) found that onset measures were reduced and stabilized by applying external oscillation to a silicone vocal fold model. The theoretical basis for these findings is that the mechanical energy introduced into the system by the external oscillation is directly transferred to the larynx so that the vocal folds are already somewhat in motion before voicing begins. Modeling literature would suggest that this transfer of energy could act as a catalyst for phonation onset at lower thresholds. However, this technique has not been applied beyond silicone studies, and given the many factors that differ between silicone, ex vivo, and in vivo models of phonation, translational research is needed to further investigate the potential effects of ELO on phonation onset.

A logical bridge between silicone model findings and human subjects research is the ex vivo benchtop model of phonation using excised larynges. Leonardo DaVinci conducted the first known studies of ex vivo phonation by observing that human cadavers could phonate when air was blown through the larynx (Luo et al., 2020). In the modern day, Jiang and Titze (1993) investigated ex vivo phonation with an excised dog hemilarynx on a benchtop apparatus to determine if vocal fold vibration could be adequately modeled using this setup. Measures obtained were sufficiently similar to those obtained from human subjects to warrant further use of ex vivo benchtop phonation models in voice research.

Since Jiang and Titze's seminal hemilarynx work (1993), excised larynx models have been used to study various voice conditions using a variety of animal models, including cows, dogs, sheep, rabbits, and pigs (Alipour & Jaiswal, 2008). These studies employed a now widely used ex vivo benchtop setup that involves mounting larynges on a benchtop apparatus in order to passively elicit vocal fold vibration. Typical setup for excised larynx studies includes humidification, insulation of subglottal tubing to damp reverberation, coupling of the trachea to the subglottal tubing, and micropositioning of the laryngeal tissues into a configuration conducive to phonation. Subglottal pressure is then gradually increased using compressed air until phonation is initiated. In this context, PTP and PTF are defined as the observed pressure and airflow at the onset of phonation, respectively. Benchtop studies have also been conducted with excised human larynges (Alipour et al., 2013; Mau et al., 2011), but animal models are advantageous due to the challenges of procuring human larynges. Porcine models in particular are often used because there are many anatomical, histological, and physiological similarities between humans and pigs (Swindle et al., 2012), including their larynges (Mason, 2015). These similarities include arytenoid cartilage structure (Gao et al., 2019), vocal fold geometry (Stevens et al., 2016), oscillatory characteristics and frequency range (Alipour et al., 2013), and vocal fold stiffness (Jiang et al., 2001). For more information on the history and development of excised larynx benchtop research, see recent reviews by Garcia and Herbst (2018) and Luo et al. (2020).

Returning to the discussion of ELO and phonation onset, Jones (2022) used an ex vivo porcine model to examine the effect of ELO on PTP and found significant reductions (i.e., improvements) but no greater stability of the measure. In other excised model studies, PTF measures have been theorized to be more stable and reliable than PTP measures (Jiang & Tao, 2007). The next logical step is to examine the effects of ELO on PTF in excised larynges to determine if ELO might improve voice function. It is also vital to begin studying the immediate effects of ELO on PTF in human subjects due to the variety of factors that are different in phonation onset measurement with humans compared to ex vivo larynges. To these ends, this investigation involves two experiments. The first examines PTF in excised porcine larynges with an external oscillation device and is a companion experiment to Jones (2022) that examined PTP in the same context. The second experiment examines PTP pilot data in human subjects, also using an external oscillation device. For the porcine experiment, a novel oscillatory device was developed (Jones, 2022). For the human experiment, an electrolarynx (Griffin Laboratories TruTone™ Electrolarynx K101, Atos Medical Inc., New Berlin, WI) was used to apply external oscillation. The electrolarynx is a commercially available oscillatory device that is typically used as a sound source for alaryngeal speech. However, in this experiment it was used with healthy subjects as a source of external oscillation.

Statement of the Problem

PTP and PTF remain the most frequently used aerodynamic measures of voice function. These onset measures provide critical information on the overall efficiency of the phonatory system and offer a general assessment of vocal effort. Unfortunately, onset measures are known to be inherently variable, in part due to the nature of voice onset and the introduction of a perturbation into the airstream. Jackson and Thomson (2021) recently demonstrated reduction of PTP in a silicone model with application of an external oscillation. Critical next steps include examining the potential effects of ELO on phonation onset measures in an ex vivo animal model and extending those results in humans. In a companion study to this project, Jones (2022) studied the effects of a custom external oscillation device on PTP in a group of benchtop-mounted porcine larynges. From the same excised larynx specimens, the present investigation examined PTF with and without supplying ELO using a custom device. Further, this investigation examined the potential application of this technique to PTP measurement in humans.

Research Hypotheses

This study will address the following research hypotheses:

1. ELO reduces PTF in ex vivo porcine phonation.
2. ELO reduces PTP in human phonation.

Method

This master's thesis was based on a large-scale five-year project funded by the National Institute on Deafness and Other Communication Disorders of the National Institutes of Health (2R01DC00961606A1). That project addresses airway narrowing below the level of the vocal folds and its effects on voice function. Two of the main outcome variables for that project involve aerodynamic measurement of pressure and flow. Therefore, this project was undertaken to explore how to optimize the acquisition of these variables in benchtop animal models and in humans. All procedures for this study were completed in compliance with the research activities office at Brigham Young University (BYU), including Institutional Animal Care and Use Committee standards and approval by the Institutional Review Board (approval #2020-504).

Experimental Design

This thesis consisted of two projects, including a modeling experiment and a pilot human translational experiment. Experiment 1 involved 12 excised porcine larynges using a within-subjects experimental design. The independent variable was the application of an external oscillatory device including two levels, specifically with and without the device. The dependent variable for Experiment 1 was PTF. In a parallel study involving the same animal larynges, PTP was examined (Jones, 2022). Experiment 2 involved a pilot investigation in human subjects, again employing a within-subjects experimental design. The independent variable was the application of ELO using an electrolarynx; the dependent variable was PTP. The order of device application was counterbalanced for both experiments.

Experiment 1

Larynges were procured from Circle V Meats in Spanish Fork, Utah. All larynges were obtained from pigs following sacrifice at the butcher shop on the same day of sacrifice. Larynges were then grossly dissected in the Taylor Building Annex at Brigham Young University. Gross dissection included removal of extralaryngeal tissue and inspection for structural integrity. Dissected larynges were placed in one-gallon Ziploc™ bags filled with 0.9% isotonic saline. Following gross dissection, larynges were immediately taken to the BYU Chemlab where they were flash-frozen by submerging the bags in liquid nitrogen for approximately seven minutes. After this was complete, the frozen larynges were transported back to the Taylor Building Annex and stored in the on-site freezer at approximately -80 degrees Celsius.

On data collection days, the frozen larynges were removed from the freezer and thawed by immersing the Ziploc™ bags in a sink filled with lukewarm water for approximately two to three hours. Once thawed, the larynges underwent fine dissection in preparation for mounting and data collection. Fine dissection included removal of the false folds and all other soft tissue directly superior to the true vocal folds; the superior-medial portion of the epiglottis; and a superior section of the thyroid cartilage so that the micropositioner prongs could be properly inserted into the arytenoid cartilages. Fine dissection was accomplished using surgical-grade stainless steel #10, #11, and #15 scalpels; hemostats; scissors; and X-Acto® knives. Measurements were also taken of various dimensions of each larynx before and after fine dissection (for a table of these measurements see Jones, 2022). After fine dissection was completed, each larynx was mounted on a benchtop apparatus (Jiang & Titze, 1993) using previously established methodology (e.g., Hoggan, 2020; Jones, 2022; Pang, 2021). For each larynx, the trachea was attached to the subglottal tubing via hose clamps and the vocal folds were adducted using micropositioners. Subglottal airflow was supplied from a compressed air tank filled with medical grade dry air (<1% relative humidity). Hydration of the tissue was maintained by spraying the larynges with a fine mist of isotonic saline every three to four phonation trials. Airflow was increased until phonation was initiated and sustained. Phonation was elicited 15 times for each of two conditions: with a custom external oscillation device, developed in Dr. Thomson's mechanical engineering laboratory (Jones, 2022), and without the device. The acoustic signal was acquired using a Shure SM-48 microphone positioned 6 inches from the vocal folds. An in-line respiratory airflow head was used for PTF data. Signal acquisition was accomplished using PowerLab™ hardware and LabChart™ software, version 8 (AD Instruments, Colorado Springs, CO).

Data analysis of the aerodynamic variables was accomplished in using a custom Matlab™ (The MathWorks Inc, 2019) program developed by Dr. Christopher Dromey, with subsequent acoustic analysis with Praat™ software, version 6.0.49 (Boersma & Weenink, 2020). Phonation onset was identified and segmented with LabChart™ software for exportation as a .txt file. These files were imported into the Matlab™ application and the flow during a 10-ms window surrounding the first identifiable quasiperiodic acoustic waveform was averaged to obtain PTF. For more information on materials and data acquisition for Experiment 1, see the methods and appendices of the recent study by Jones (2022).

Experiment 2

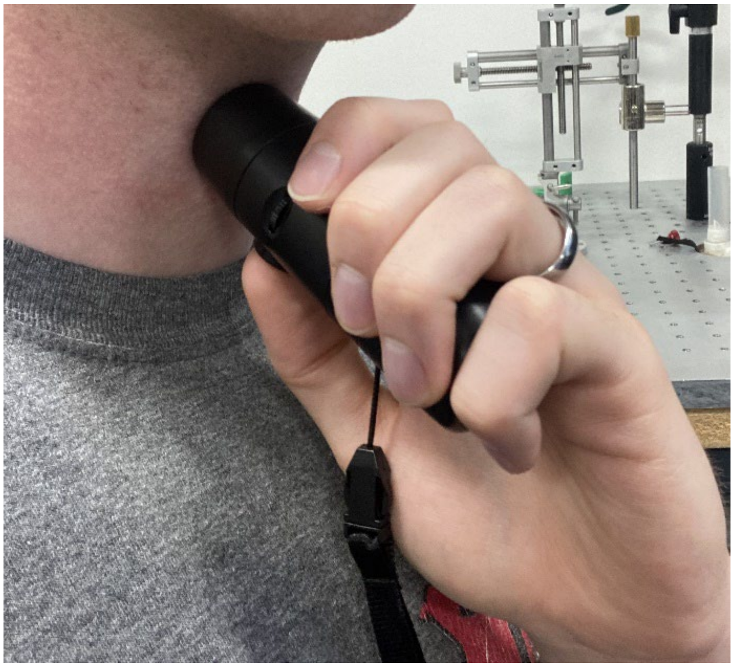
Participants for this pilot experiment were a convenience sample of individuals working in the BYU voice lab. They included four females and one male between the ages of 19 and 46.

Inclusion criteria included self-report of no voice disorders within the last two years, no history of smoking, and generally good vocal health. Additionally, all participants were judged by the examiner to be free from dysphonia based on auditory perception during brief conversation prior to data collection.

Following established methodology for acquiring PTP (Smitheran & Hixon, 1981; Tanner et al., 2016), participants were instructed on how to produce phonation threshold syllable strings of /pi/ at a comfortable modal pitch. The data collection procedure was explained to the point of verbal understanding and adequate signal acquisition (i.e., adequate lip closure and production of pressure peaks). Participants were permitted a limited number of practice trials prior to signal acquisition. For the external oscillation trials, an electrolarynx (Griffin Laboratories TruTone™ Electrolarynx K101, Atos Medical Inc., New Berlin, WI) was placed on the thyroid cartilage just superior to the cricothyroid membrane by the participant after instruction from the examiner. Figure 1 shows how the electrolarynx was placed by the participant.

Figure 1

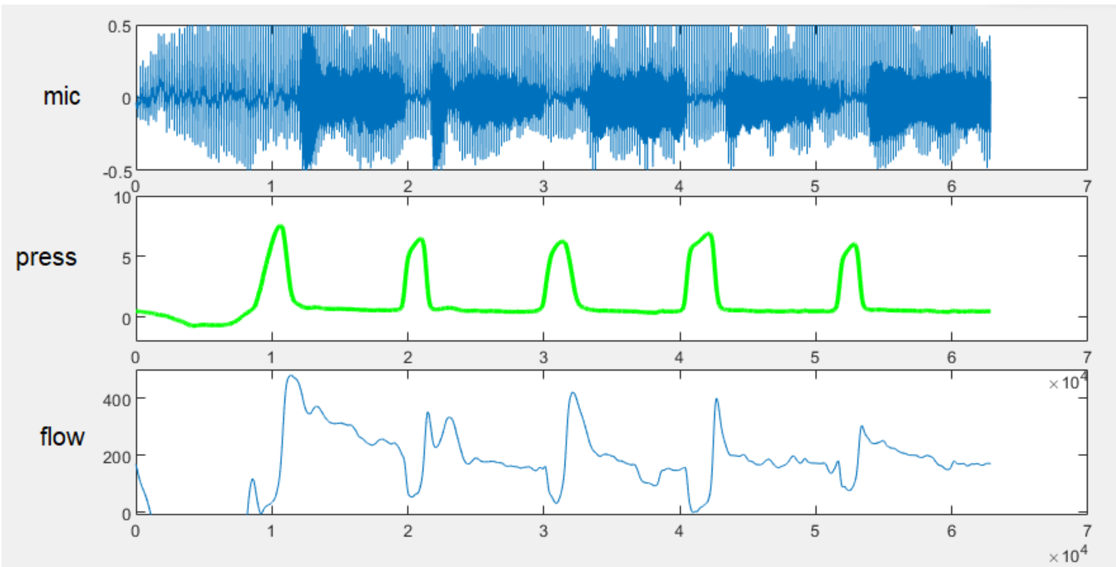
Electrolarynx Placement



Fifteen five-syllable string phonation trials were obtained both with and without application of the external oscillation device. These were administered in a counterbalanced manner in sets of five trials: one set with device, one set without (or vice versa), alternating until three sets were completed for each condition. Pitch (comfortable) and syllable rate (90 syllables per second) were established and prompted repeatedly throughout data collection using iPhone® applications: *Piano* (Impala Studios, 2022) for pitch and *Metronome* (ONYX Apps, 2020) for syllable rate. Aerodynamic data were acquired using a Rothenberg mask (Glottal Enterprises, Syracuse, NY) and the AD Instruments system described above. Similar to Experiment 1, syllable string segments were exported as .txt files. Using previously established methodology (Plexico et al., 2011), PTP was determined by averaging the second and third pressure peaks of the central syllable string for each set; this conservative approach was used in an effort to avoid initial training and performance end effects. Inclusion criteria included relatively clear and consistent pressure peaks across the syllable string and no noted anomalies in the audio signal. Figure 2 shows one of the syllable strings as an example.

Figure 2

Five-Syllable String for Analysis



Statistical Analysis

For both experiments, descriptive statistics and data normality were examined. A paired samples *t*-test was used to determine significant differences between external oscillation presence or absence conditions. The alpha level for each experiment was .05. For Experiment 1, interjudge and intrajudge reliability were calculated for 15% repeated segmentation during which the examiner identified phonation onset from the acoustic signal. For Experiment 2, interjudge and intrajudge reliability were calculated for repeated analysis of 20% of the data set. For Experiment 1, the interjudge Pearson correlation was 0.99 and the intrajudge correlation was 0.99. For Experiment 2, the interjudge Pearson correlation was 0.99 and the intrajudge correlation was 0.99.

Results

Experiment 1

Average PTF for the 12 larynges with the external oscillation device on was 0.21 L/sec (SD = 0.11; range = 0.06 to 0.39). When the device was not running, average PTF was 0.28 L/sec (SD = 0.23; range = 0.07 to 0.89). Paired-samples *t*-tests were performed for PTF with and without the external oscillation device. No statistically significant differences were observed for PTF between the two conditions, $t\ (df = 11) = 1.236$, $p = 0.242$. Table 1 lists PTF measurements under each experimental condition for each pig larynx. Figure 3 shows boxplots of PTF values for both experimental conditions; note the presence of an outlier in the non-ELO condition.

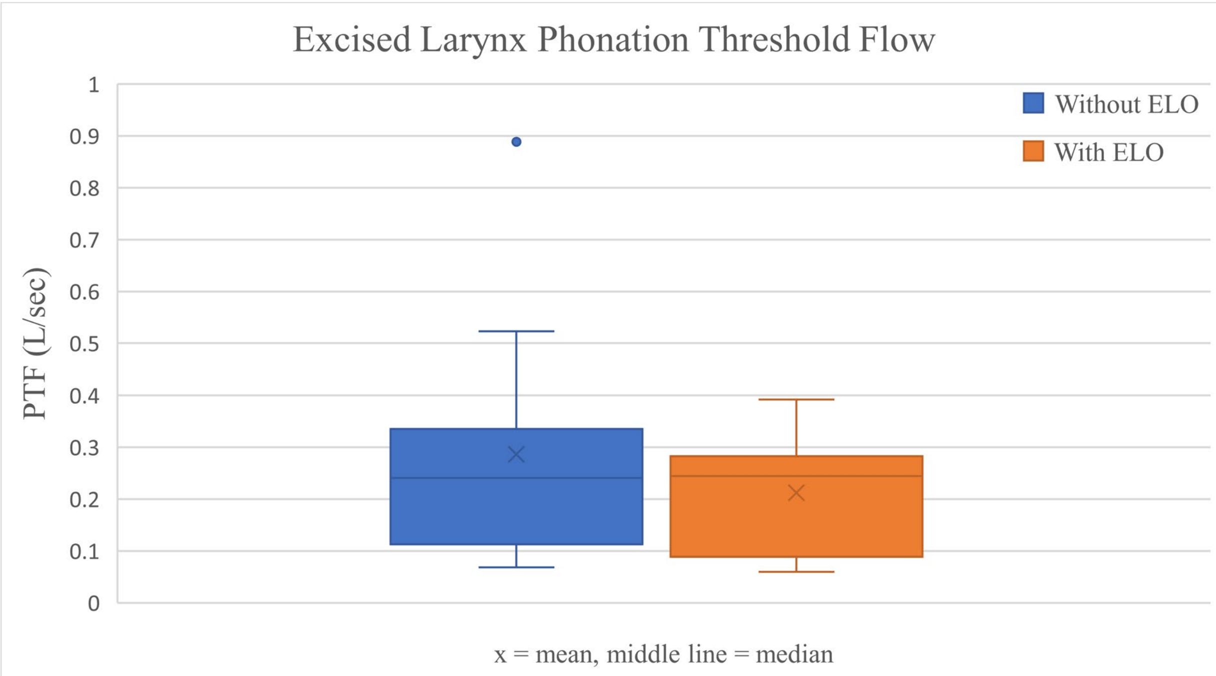
Table 1

Mean PTF Measurements for Each Excised Larynx

Pig #	PTF without ELO (L/sec) (SD)	PTF with ELO (L/sec) (SD)	Order (Device applied for 1st 15 trials or 2nd 15 trials)
1	0.198 (SD = 0.018)	0.266 (SD = 0.030)	Device 2nd
2	0.167 (SD = 0.023)	0.062 (SD = 0.004)	Device 2nd
3	0.889 (SD = 0.293)	0.175 (SD = 0.119)	Device 2nd
4	0.068 (SD = 0.008)	0.060 (SD = 0.008)	Device 1st
5	0.523 (SD = 0.049)	0.392 (SD = 0.069)	Device 1st
6	0.094 (SD = 0.006)	0.101 (SD = 0.005)	Device 1st
7	0.306 (SD = 0.008)	0.255 (SD = 0.014)	Device 2nd
8	0.095 (SD = 0.011)	0.085 (SD = 0.008)	Device 1st
9	0.345 (SD = 0.053)	0.363 (SD = 0.018)	Device 2nd
10	0.261 (SD = 0.012)	0.288 (SD = 0.022)	Device 1st
11	0.275 (SD = 0.006)	0.268 (SD = 0.006)	Device 1st
12	0.220 (SD = 0.010)	0.234 (SD = 0.016)	Device 2nd

Figure 3

Boxplots of PTF Measures for Both Experimental Conditions



Experiment 2

One participant was excluded after two reviewers concluded that the signal was not reliable enough to analyze, likely due to trouble with the face mask—the participant had to switch to a smaller mask during training and the fit was still not optimal. Mean PTP for the other four participants with ELO was 4.80 cmH_2O (median = 4.51; SD = 1.04; range = 3.76 to 7.45). For the same participants in the control condition, average PTP was 5.38 cmH_2O (median = 5.34; SD = 1.21; range = 3.31 to 7.32). Paired-samples *t*-tests were performed for PTP with and without the external oscillation device. No significant differences were observed for PTP between the two conditions, $t\ (df = 3) = 1.21$, $p = 0.31$. Table 2 lists PTP measurements for each trial analyzed. Figure 4 shows mean PTP values for each individual under both conditions. Participants 1 through 3 were female; Participant 4 was male.

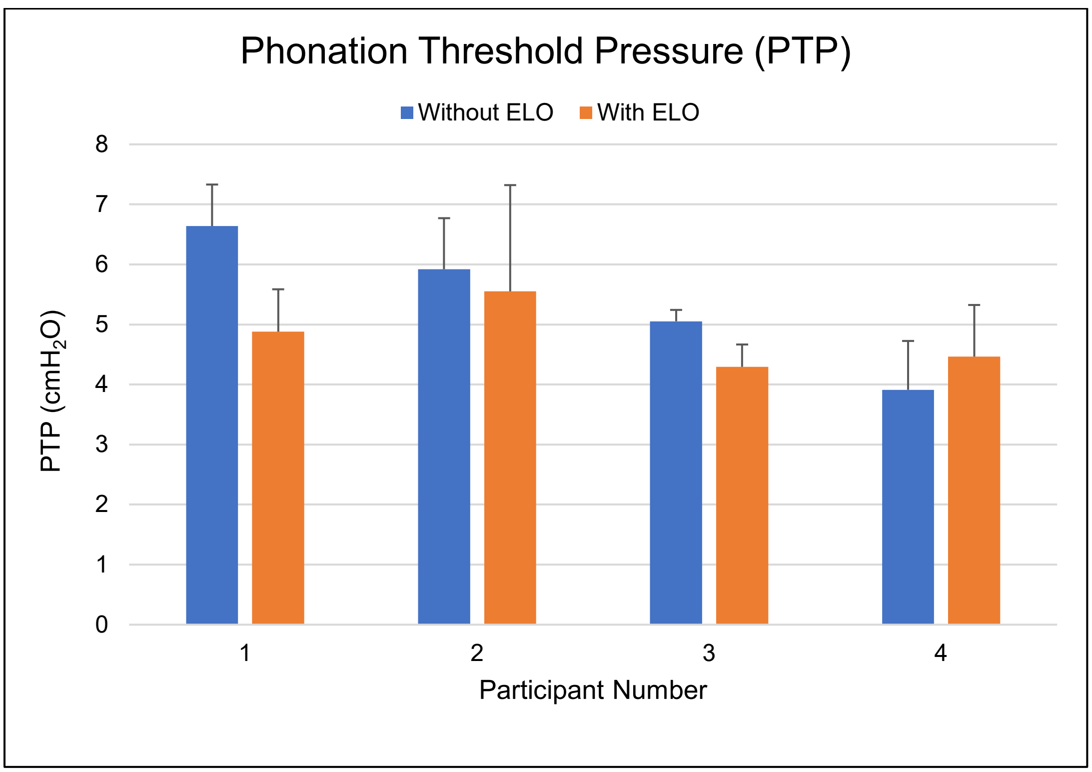
Table 2

Mean PTP Measurements for Each Participant

Participant #	Pitch Elicited for Phonation	PTP Without External Oscillatory Device Applied (cmH_2O)	PTF With External Oscillatory Device Applied (cmH_2O)	Order (Device 1st = ABABAB, Device 2nd = BABABA)
1	E4	6.64	4.88	Device 1st
2	B3	5.92	5.55	Device 2nd
3	A3	5.05	4.29	Device 1st
4	C3	3.91	4.46	Device 2nd

Figure 4

Mean PTP for Both Experimental Conditions by Participant (error bars = SD)



Discussion

Findings

The purpose of this study was to examine the effects of ELO on voice onset, quantified using aerodynamic measures, in benchtop and human phonation. PTF was examined using an ex vivo porcine model of phonation; PTP was examined in human subjects. Based on theories of phonation onset and previous findings in silicone models (Jackson & Thomson, 2021) and a companion excised larynx study (Jones, 2022), we hypothesized that ELO would lower onset measures in both experiments. In Experiment 1, we found that ELO applied by a custom device (Jones, 2022) in an ex vivo porcine model had no significant effect on mean PTF compared to the control condition. In Experiment 2, we found that ELO applied by an electrolarynx in human subjects had no statistically significant effect on PTP across subjects but did result in PTP reduction in all female participants. Further discussion of the research questions in the context of the results of each experiment is provided below.

Experiment 1: Does ELO Reduce PTF in Ex Vivo Porcine Phonation?

While there was no significant difference in mean PTF between the two conditions, there is some concern for type II error since there was a difference in the descriptive statistics: mean PTF across larynges was 0.28 L/sec without the device and 0.21 L/sec with the device. On the other hand, it is possible that ELO has a greater influence on PTP (see Jones, 2022) than on PTF. PTP is more sensitive to changes in tissue damping, while PTF is more sensitive to changes in posterior glottal closure (Zhuang et al., 2013). Theoretically, it seems more likely that ELO would affect tissue damping than posterior glottal closure, particularly in an excised larynx model where the posterior glottal closure is largely determined by the micropositioners. Descriptive statistics also showed that external oscillation may stabilize PTF measures: the SD for the device condition was .11 (mean = 0.21 L/sec) while the SD for the control condition was .22 (mean = 0.28 L/sec). However, these differences should be interpreted with caution given the small sample size and the presence of an outlier in the control condition data. Taken together with the results of Jones' companion study (2022), these results show that ELO has an apparent influence on phonation onset in an ex vivo porcine model, with reduction of PTP and potential reduction and stabilization of PTF.

Experiment 2: Does ELO Reduce PTP In Normal Human Phonation?

As noted above, we found no statistically significant within-subjects difference in mean PTP between the two experimental conditions. Descriptively, three of the four participants included in analysis had lower PTP with ELO while one had lower PTP without ELO. Despite these mixed results, it is clear that ELO influenced PTP in these subjects. Potential confounding factors that may have contributed to these mixed results are addressed in the following sections.

Synthesis and Interpretation of Findings

This study was the logical next step in looking at the effects of ELO on aerodynamic measures of phonation onset, following previous work with silicone vocal fold models. Phonation onset is the process by which vocal folds transition from a state of rest to a state of quasiperiodic, self-sustained vibration. ELO may serve as a catalyst for this transition and lower or stabilize aerodynamic measures of phonation onset. In a silicone model, the effects of external oscillation can be viewed primarily from a mechanical perspective. Jackson and Thomson (2021) subjected a pair of silicone vocal folds to external oscillation of varying frequencies and amplitudes. They found that the frequency of the external oscillation was strongly and inversely correlated with PTP ($r^2 = 0.843$), while amplitude had a much weaker inverse correlation with PTP ($r^2 = 0.135$). Simply put, PTP tended to decrease as the input frequency increased.

Jones (2022) showed that similar mechanical effects of ELO (i.e., lower PTP) may also apply in an ex vivo model of phonation and found that ELO of approximately 100 Hz lowered PTP by about 1 cmH_2O on average. In Experiment 1 of the present study, the SD for PTF was lower in the ELO condition, indicating that ELO may have stabilized PTF measures. Stability of PTP and PTF measures is important because the variability can sometimes be greater than the effect size; it has also been suggested that differences as small as 0.5 cmH_2O for PTP can be clinically meaningful (Tanner et al., 2007). Excised larynx studies like these offer a closer approximation of in vivo phonation than silicone models. However, they cannot account for dynamic physiological factors—such as sensory feedback systems and fine-tuned muscle tension adjustments—that are present in human phonation and that may be affected by ELO. It is therefore necessary to consider the myriad possible effects of ELO on human phonation beyond its direct mechanical impact.

Vibration as applied to the human body has been studied in various ways. There is a substantial corpus of literature on the effects of whole body vibration, wherein the subject typically stands on a vibrating platform. Some studies have also examined the effects of localized or focal vibration, where an oscillation device is placed directly on the target area. Both vibration types have been used in studies of the effects of external oscillation on voice (Yiu et al., 2021), although localized oscillation of the larynx is more common (Anderson et al., 2018; Barsties v. Latoszek, 2020; Mulheren & Ludlow, 2017; Nascimento et al., 2021).

It has been shown that vibration can affect both sensory and motor neurons by stimulating mechanoreceptors (Souron et al., 2017), thereby altering sensation and inducing a tonic vibration reflex (TVR). The TVR involves stiffening of skeletal muscle to resist vibration-induced tissue deformation and displacement (Rittweger, 2020). The TVR has been shown to vary in relation to the frequency of the oscillation stimulus, the muscle being stimulated, and the initial level of muscle contraction prior to oscillation input. It appears that the TVR tends to increase with frequency increases up to approximately 100 Hz (Martin & Park, 1997). It should be noted, however, that these studies were primarily conducted on limb muscles and that the results may not translate to laryngeal musculature (Johnson & Sandage, 2021).

While there no known studies of TVR in the intrinsic or extrinsic muscles of the larynx, Loucks et al. (2005) found a short-latency stretch reflex in the sternothyroid muscle in response to mechanical displacement of the thyroid cartilage. They also found that mechanical displacement of the thyroid cartilage resulted in F_0 shifts that could not be explained by laryngeal muscle reflexes, implicating the role of passive tissue rebound and possibly the auditory pitch-shift reflex. Changes in phonation in response to ELO, such as the F_0 shifts found by Mulheren and Ludlow (2017), may be due to direct effects of the stimulus or reflexive responses. Further exploration of the physiological effects of ELO applied before, during, and after phonation may yield insights into laryngeal function and coordination with implications for voice training and therapy. Finally, it should be noted that excessive vibration can have damaging effects on tissue (Rittweger, 2020; Titze & Hunter, 2015). What constitutes "excessive" may vary, but is influenced by duration, frequency, and amplitude of vibration exposure. This should be taken into account for future experiments and therapeutic applications involving the use of ELO.

Given its pervasive effects and interactions, ELO frequency merits a final summary. Frequency was the dominant variable affecting PTP in a silicone model (Jackson & Thomson, 2021). In humans, ELO frequency can have variable effects on different parameters that may affect phonation onset. For instance, TVR (Martin & Park, 1997), vibration transmissibility (Rittweger, 2020, p. 75), and vocal fold resonance (Švec et al., 2000) are all variably responsive to frequency. During phonation, F_0 may either destructively or constructively interfere with ELO. This is suggested by the lowering of F_0 in response to ELO found by Mulheren and Ludlow (2017), which was much more pronounced for the female subjects than for the male subjects. This could also explain why the lone male participant in Experiment 2 of the present study responded differently to the ELO stimulus, with an increase in PTP instead of the decrease seen in the three female participants. These factors should all be considered when deciding on the ELO frequency. This discussion also highlights the importance of examining the effects of a range of frequencies to better understand these complex interactions.

Limitations

It is important to consider the limitations of this study across both experiments. In Experiment 1, despite an acceptable number of data points being collected from each larynx, the total number of larynges (12) was relatively small. Also, this experiment used an ex vivo porcine model of phonation, which does not translate directly to in vivo human phonation. In Experiment 2, participants were a small convenience sample composed of members of the research lab. It was apparent from reviewing the data that one participant had difficulty maintaining a seal around the mask. As a result, this participant's data were excluded. A larger study including a more diverse sample of speakers is an important next step in determining the extent to which ELO might influence human phonation.

Another limitation of note was the variable frequency, placement, and contact pressure of the electrolarynx used to apply ELO. While we attempted to control these factors by verbally encouraging the participants to apply consistent pressure to the electrolarynx and standardizing the placement, this was not objectively monitored beyond visual inspection. It should also be acknowledged that the participants were all healthy individuals with no apparent voice pathology or reported voice problems. As such, these findings may not translate directly to individuals with voice disorders. Despite these limitations, the results of these two experiments show promise for this line of research and lay the groundwork for future studies to build on.

Implications for Future Research

Experiment 1, together with the work of Jones (2022), is the first, to our knowledge, to examine the effects of ELO on aerodynamic measures of phonation onset in an ex vivo animal model. Further studies with greater statistical power are needed to determine if the results are reproducible and to reduce the possibility of type II error. This study also involved the development and use of a novel external oscillation device, which may be optimized for greater control of amplitude and frequency in future studies. Frequency of external oscillation appears to have a greater effect than amplitude on PTP in a silicone model (Jackson & Thomson, 2021). It would therefore be beneficial to examine this potential relationship in an ex vivo porcine model by varying amplitude and frequency of the external oscillation and perhaps examining relationships and possible resonance between the external oscillation frequency and the F_0 of phonation. It could also be fruitful to explore different methods of oscillation transmission beyond the device arm and strap that were used in this experiment, as proximity of the oscillation source to the larynx could also influence outcomes. An automated benchtop setup could expedite all of these explorations by providing more efficient data collection and analysis (Birk et al., 2017).

Experiment 2 is the first known exploration of the immediate effects of ELO on PTP in humans. As with Experiment 1, it would be useful to examine a range of input frequencies and amplitudes for future studies of ELO in human phonation. To accomplish this, a device similar to that used by Mulheren and Ludlow (2017) could be ideal, given that it allows for greater control of placement, pressure, frequency, and duration of oscillatory input. As mentioned previously, a larger and more diverse sample would offer greater power for drawing conclusions and making generalizations. It is also important to begin studying ELO as applied to individuals with a range of voice disorders to examine how the effects may differ.

Implications for Practitioners

In addition to areas for further research, there are intriguing clinical possibilities with ELO applied during phonation onset. ELO may have a stabilizing effect on phonation onset measures, as was found for PTP in a silicone model (Jackson & Thomson, 2021) and reflected in the lower variance of PTF values in the excised larynx portion of this study. As mentioned previously, stabilizing PTP and PTF measures could strengthen their clinical use in diagnosis and progress tracking for individuals with voice disorders. Another practical application of this research could be in the context of voice therapy. A speech-language pathologist or other voice professional might be able to use an ELO device to help an individual train gentle voice onset, an approach often used for people with excessive laryngeal muscle tension. In this scenario, the device could be used to facilitate easy voicing and then gradually faded out. Another potential use could be as an adjunct to direct therapy. For example, an individual might be able to wear a small, quiet oscillation device on their neck and turn it on as needed throughout the day to reduce their vocal effort while speaking.

These theoretical applications are based on previous work that has found correlations between PTP and vocal effort/fatigue, and between PTF and ease of phonation. Higher PTP is also correlated with higher dB levels and maximum flow declination rates, which can be indicators of vocal load. Therefore, lowering PTP and PTF could lead to corresponding decreases in vocal effort or load. While these possible applications should not be implemented solely based on this study due to the limitations discussed above, they certainly merit continued exploration.

Conclusion

Vocal fold vibration is powered by energy transfer from the glottal airstream to the vocal fold tissues and involves the vocal folds changing states from rest to quasiperiodic, self-sustained oscillation. This state change is also called phonation onset. Factors such as glottal width, vocal fold thickness, glottal angle, muscle tension, and tissue viscosity affect phonation onset. Various mechanisms have been described for how phonation onset may be triggered, but all involve some sort of perturbation. ELO may provide that perturbation externally and lower or stabilize pressure and flow thresholds for phonation onset, as has been found in preliminary silicone vocal fold model results.

Measures of pressure and flow thresholds for phonation onset (i.e., PTP and PTF), are frequently used as part of a comprehensive clinical evaluation of vocal function. PTP and PTF are also difficult to reliably measure clinically for many reasons. Stabilizing PTP and PTF could increase their reliability and clinical utility. Lowering PTP and PTF could reduce perception of vocal fatigue and enhance vocal control.

In this study, we found that phonation onset, as measured by PTF in excised porcine larynges and PTP in human subjects in this study, was affected by ELO. In Experiment 1, mean PTF for the excised pig larynges was lower in the ELO condition than in the control condition. In Experiment 2, mean PTP was lower for three of four subjects in the ELO condition than in the control condition. While the results are preliminary and not statistically significant, they align with prior work (Jackson & Thomson, 2021; Jones, 2022) and form the basis for further exploration of the effects of ELO on aerodynamic measures of phonation onset in humans.

References

Alipour, F., Finnegan, E. M., & Jaiswal, S. (2013). Phonatory characteristics of the excised human larynx in comparison to other species. *Journal of Voice*, *27*(4), 441–447. https://doi.org/10.1016/j.jvoice.2013.03.013

Alipour, F., & Jaiswal, S. (2008). Phonatory characteristics of excised pig, sheep, and cow larynges. *The Journal of the Acoustical Society of America*, *123*(6), 4572–4581. https://doi.org/10.1121/1.2908289

American Speech-Language-Hearing Association. (n.d.). *Voice disorders.* https://www.asha.org/practice-portal/clinical-topics/voice-disorders/

Anderson, J., DeLuca, M., Haines, M., & Merrick, G. (2018). Immediate effects of external vibration vs placebo on vocal function therapy in singers. *JAMA Otolaryngology–Head & Neck Surgery*, *144*(3), 187-193. https://doi.org/10.1001/jamaoto.2017.2679

Barsties v. Latoszek, B. (2020). Treatment effectiveness of Novafon local vibration voice therapy for dysphonia treatment. *Journal of Voice*, *34*(1), 160.e7-160.e14. https://doi.org/10.1016/j.jvoice.2018.05.009

Berry, D. A., Herzel, H., Titze, I. R., & Story, B. H. (1996). Bifurcations in excised larynx experiments. *Journal of Voice, 10*(2), 129-138. https://doi.org/10.1016/S0892-1997(96)80039-7

Berry, D. A., & Titze, I. R. (1996). Normal modes in a continuum model of vocal fold tissues. *The Journal of the Acoustical Society of America, 100*(5), 3345-3354. https://doi.org/10.1121/1.416975

Birk, V., Döllinger, M., Sutor, A., Berry, D. A., Gedeon, D., Traxdorf, M., Wendler, O., Bohr, C., & Kniesburges, S. (2017). Automated setup for *ex vivo* larynx experiments. *The*

Journal of the Acoustical Society of America, 141(3), 1349-1359. https://doi.org/10.1121/1.4976085

Chan, R. W., & Titze, I. R. (2006). Dependence of phonation threshold pressure on vocal tract acoustics and vocal fold tissue mechanics. *The Journal of the Acoustical Society of America*, *119*(4), 2351–2362. https://doi.org/10.1121/1.2173516

Chang, A., & Karnell, M. P. (2004). Perceived phonatory effort and phonation threshold pressure across a prolonged voice loading task: A study of vocal fatigue. *Journal of Voice*, *18*(4), 454–466. https://doi.org/10.1016/j.jvoice.2004.01.004

Chong, H. J., Choi, J. H., & Lee, S. S. (2022). Does the perception of own voice affect our behavior? *Journal of Voice*. Advance online publication. https://doi.org/10.1016/j.jvoice.2022.02.003

Crow, K. M., Van Mersbergen, M., & Payne, A. E. (2021). Vocal congruence: The voice and the self measured by interoceptive awareness. *Journal of Voice*, *35*(2), 324.e15-324.e28. https://doi.org/10.1016/j.jvoice.2019.08.027

Dastolfo, C. (2011). *Effects of repetition on phonation threshold pressure task performance* [Master's thesis, University of Pittsburgh]. D-Scholarship@Pitt. http://d-scholarship.pitt.edu/7466/

DeJonckere, P., & Lebacq, J. (2021). Intraglottal aerodynamics at vocal fold vibration onset. *Journal of Voice*, *35*(1), 156.e23–156.e32. https://doi.org/10.1016/j.jvoice.2019.08.002

Enflo, L., Sundberg, J., & McAllister, A. (2013). Collision and phonation threshold pressures before and after loud, prolonged vocalization in trained and untrained voices. *Journal of Voice*, *27*(5), 527–530. https://doi.org/10.1016/j.jvoice.2013.03.008

Falanga, C., Costa, G., Volpe, U., Saracino, D., Lechien, J. R., Estomba, C. M. C., Tripodi, M., Cammaroto, G., Angelillo, N., Nacci, A., & Barillari, M. R. (2020). Psychological distress in a sample of adult Italian patients affected by vocal nodules and muscle-tension dysphonia: Preliminary results. *Journal of Voice*. Advance online publication. https://doi.org/10.1016/j.jvoice.2020.12.011

Faver, K. Y., Plexico, L. W., & Sandage, M. J. (2012). Influence of syllable train length and performance end effects on estimation of phonation threshold pressure. *Journal of Voice*, *26*(1), 18–23. https://doi.org/10.1016/j.jvoice.2010.10.021

Fujiki, R. B., Chapleau, A., Sundarrajan, A., McKenna, V., & Sivasankar, M. P. (2017). The interaction of surface hydration and vocal loading on voice measures. *Journal of Voice*, *31*(2), 211–217. https://doi.org/10.1016/j.jvoice.2016.07.005

Fujiki, R. B., & Thibeault, S. L. (2021). Examining relationships between GRBAS ratings and acoustic, aerodynamic and patient-reported voice measures in adults with voice disorders. *Journal of Voice*. Advance online publication. https://doi.org/10.1016/j.jvoice.2021.02.007

Gao, N., Cui, X., Sun, G., Zhang, G., Zhou, G., & Zhao, X. (2019). Comparative anatomy of pig arytenoid cartilage and human arytenoid cartilage. *Journal of Voice*, *33*(5), 620–626. https://doi.org/10.1016/j.jvoice.2018.02.015

Garcia, M., & Herbst, C. T. (2018). Excised larynx experimentation: History, current developments, and prospects for bioacoustic research. *Anthropological Science*, *126*(1), 9–17. https://doi.org/10.1537/ase.171216

Gartling, G. J., Van Mersbergen, M., Crow, K., Lewandowski, A., Smith, L. J., & Gartner-Schmidt, J. L. (2021). The patient experience: The relationship between vocal handicap, congruency, perceived present control, and mood across four voice disorders. *Journal of Voice*. Advance online publication. https://doi.org/10.1016/j.jvoice.2021.08.007

Gartner-Schmidt, J. L., Hirai, R., Dastolfo, C., Rosen, C. A., Yu, L., & Gillespie, A. I. (2015). Phonatory aerodynamics in connected speech. *The Laryngoscope*, *125*(12), 2764–2771. https://doi.org/10.1002/lary.25458

Hoggan, M. C. (2020). *Aerodynamic measurement stability during rabbit versus pig benchtop phonation* [Master's thesis, Brigham Young University]. BYU ScholarsArchive. https://scholarsarchive.byu.edu/etd/8412

Impala Studios. (2022). *Piano* (Version 2.0.1) [Mobile App]. Apple App Store. https://apps.apple.com/us/app/piano/id1126477246

Jackson, A. & Thomson, S. (2021). *The effects of external vibrations on the onset pressure of a pair of synthetic vocal folds* [Unpublished manuscript]. Department of Mechanical Engineering, Brigham Young University.

Jen, J. H., Chan, R. W., Wu, C., & Wang, C. (2021). Phonation threshold pressure/flow for reflecting glottal closure in unilateral vocal fold paralysis. *The Laryngoscope*, *131*(5), E1598-E1604. https://doi.org/10.1002/lary.29274

Jiang, J. J., Raviv, J. R., & Hanson, D. G. (2001). Comparison of the phonation-related structures among pig, dog, white-tailed deer, and human larynges. *Annals of Otology, Rhinology, & Laryngology*, *110*(12), 1120–1125. https://doi.org/10.1177/000348940111001207

Jiang, J. J., & Tao, C. (2007). The minimum glottal airflow to initiate vocal fold oscillation. *The Journal of the Acoustical Society of America*, *121*(5), 2873–2881. https://doi.org/10.1121/1.2710961

Jiang, J. J., & Titze, I. R. (1993). A methodological study of hemilaryngeal phonation. *The Laryngoscope, 103*(8), 872-882. https://doi.org/10.1288/00005537-199308000-00008

Johnson, A. M., & Sandage, M. J. (2021). Exercise science and the vocalist. *Journal of Voice*, *35*(4), 668–677. https://doi.org/10.1016/j.jvoice.2021.06.029

Jones, B. T. (2022). *Effects of an external oscillation device on phonation threshold pressure* [Master's thesis, Brigham Young University]. BYU ScholarsArchive. https://scholarsarchive.byu.edu/etd/9567

Lamb, J. R., Schultz, S. A., Scholp, A. J., Wendel, E. R., & Jiang, J. J. (2020). Retest reliability for complete airway interruption systems of aerodynamic measurement. *Journal of Voice*, *36*(1), 27–33. https://doi.org/10.1016/j.jvoice.2020.02.024

Loucks, T. M. J., Poletto, C. J., Saxon, K. G., & Ludlow, C. L. (2005). Laryngeal muscle responses to mechanical displacement of the thyroid cartilage in humans. *Journal of Applied Physiology, 99*(3), 922-930. https://doi.org/10.1152/japplphysiol.00402.2004

Lucero, J. C., Pelorson, X., & Van Hirtum, A. (2020). Phonation threshold pressure at large asymmetries of the vocal folds. *Biomedical Signal Processing and Control, 62*, Article 102105. https://doi.org/10.1016/j.bspc.2020.102105

Luo, R., Kong, W., Wei, X., Lamb, J., & Jiang, J. J. (2020). Development of excised larynx. *Journal of Voice*, *34*(1), 38–43. https://doi.org/10.1016/j.jvoice.2018.07.023

Martin, B. J., & Park, H. S. (1997). Analysis of the tonic vibration reflex: Influence of vibration variables on motor unit synchronization and fatigue. *European Journal of Applied Physiology and Occupational Physiology*, *75*(6), 504–511. https://doi.org/10.1007/s004210050196

Mason, N. L. (2015). *The anatomy of porcine and human larynges: Structural analysis and high resolution magnetic resonance imaging of the recurrent laryngeal nerve* [Doctoral dissertation, Brigham Young University]. BYU ScholarsArchive. https://scholarsarchive.byu.edu/etd/5783/

Mau, T., Muhlestein, J., Callahan, S., Weinheimer, K.T., & Chan, R.W. (2011). Phonation threshold pressure and flow in excised human larynges. *The Laryngoscope*, *121*(8), 1743–1751. https://doi.org/10.1002/lary.21880

McHenry, M., Evans, J., & Powitzky, E. (2013). Singers' phonation threshold pressure and ratings of self-perceived effort on vocal tasks. *Journal of Voice*, *27*(3), 295–298. https://doi.org/10.1016/j.jvoice.2012.12.013

McKenna, V. S., Diaz-Cadiz, M. E., Shembel, A. C., Enos, N. M., & Stepp, C. E. (2019). The relationship between physiological mechanisms and the self-perception of vocal effort. *Journal of Speech, Language, and Hearing Research: JSLHR*, *62*(4), 815–834. https://doi.org/10.1044/2018_JSLHR-S-18-0205

Morgan, M. D., Triana, M. A., & Milroy, T. J. (2004). The effect of auditory feedback on phonation threshold pressure measurement. *Journal of Voice*, *18*(1), 46–55. https://doi.org/10.1016/S0892-1997(03)00069-9

Mulheren, R. W., & Ludlow, C. L. (2017). Vibration over the larynx increases swallowing and cortical activation for swallowing. *Journal of Neurophysiology*, *118*(3), 1698–1708. https://doi.org/10.1152/jn.00244.2017

Nascimento, A., Korn, G. P., Sacaloski, M., & Azevedo, R. R. (2021). Effects of mechanical vibration stimulation of the larynx on voice production. *Journal of Voice*. https://doi.org/10.1016/j.jvoice.2020.12.024

Nathanson, E. (2017). Native voice, self-concept, and the moral case for personalized voice technology. *Disability and Rehabilitation, 39*(1), 73-81. https://doi.org/10.3109/09638288.2016.1139193

Naunheim, M. R., Goldberg, L., Dai, J. B., Rubinstein, B. J., & Courey, M. S. (2020). Measuring the impact of dysphonia on quality of life using health state preferences. *The Laryngoscope*, *130*(4), E177–E182. https://doi.org/10.1002/lary.28148

ONYX Apps. (2020). *Metronome* (Version 3.3.5) [Mobile App]. Apple App Store. https://apps.apple.com/us/app/metronome-%CF%9F/id416443133

Orr, R., & Cranen, B. (2005). The effect of the flow mask on phonation. *BMC Neuroscience*, 1000-1004. https://www.isca-speech.org/archive/pdfs/maveba_2005/orr05_maveba.pdf

Pang, C. L. (2021). *Effects of inhaled combination corticosteroid drugs on aerodynamic measures of phonation and visual-perceptual measures of vocal fold and arytenoid tissue in excised rabbit larynges* [Master's thesis, Brigham Young University]. BYU ScholarsArchive. https://scholarsarchive.byu.edu/etd/8934

Patel, R. R., Awan, S. N., Barkmeier-Kraemer, J., Courey, M., Deliyski, D., Eadie, T., Paul, D., Švec, J. G., & Hillman, R. (2018). Recommended protocols for instrumental assessment of voice: American speech-language-hearing association expert panel to develop a protocol for instrumental assessment of vocal function. *American Journal of Speech-Language Pathology*, *27*(3), 887–905. https://doi.org/10.1044/2018_AJSLP-17-0009

Patel, S., Scherer, K. R., Björkner, E., & Sundberg, J. (2011). Mapping emotions into acoustic space: The role of voice production. *Biological Psychology*, *87*(1), 93–98. https://doi.org/10.1016/j.biopsycho.2011.02.010

Plant, R. L., Freed, G. L., & Plant, R. E. (2004). Direct measurement of onset and offset phonation threshold pressure in normal subjects. *The Journal of the Acoustical Society of America*, *116*(6), 3640–3646. https://doi.org/10.1121/1.1812309

Plexico, L. W., & Sandage, M. J. (2012). Influence of vowel selection on determination of phonation threshold pressure. *Journal of Voice*, *26*(5), 673.e7-673.e12. https://doi.org/10.1016/j.jvoice.2011.12.005

Plexico, L. W., Sandage, M. J., & Faver, K. Y. (2011). Assessment of phonation threshold pressure: A critical review and clinical implications. *American Journal of Speech-Language Pathology*, *20*(4), 348–366. https://doi.org/10.1044/1058-0360(2011/10-0066)

Rittweger, J. (2020). *Manual of vibration exercise and vibration therapy*. Springer Nature. https://doi.org/10.1007/978-3-030-43985-9

Rosenthal, A. L., Lowell, S. Y., & Colton, R. H. (2014). Aerodynamic and acoustic features of vocal effort. *Journal of Voice*, *28*(2), 144–153. https://doi.org/10.1016/j.jvoice.2013.09.007

Roy, N., Merrill, R. M., Gray, S. D., & Smith, E. M. (2005). Voice disorders in the general population: Prevalence, risk factors, and occupational impact. *The Laryngoscope*, *115*(11), 1988–1995. https://doi.org/10.1097/01.mlg.0000179174.32345.41

Smitheran, J. R., & Hixon, T. J. (1981). A clinical method for estimating laryngeal airway resistance during vowel production. *Journal of Speech and Hearing Disorders*, *46*(2), 138-146. https://doi.org/10.1044/jshd.4602.138

Solomon, N. P., Ramanathan, P., & Makashay, M. J. (2007). Phonation threshold pressure across the pitch range: Preliminary test of a model. *Journal of Voice*, *21*(5), 541–550. https://doi.org/10.1016/j.jvoice.2006.04.002

Souron, R., Besson, T., Millet, G. Y., & Lapole, T. (2017). Acute and chronic neuromuscular adaptations to local vibration training. *European Journal of Applied Physiology*, *117*(10), 1939–1964. https://doi.org/10.1007/s00421-017-3688-8

Stevens, K. A., Thomson, S. L., Jetté, M. E., & Thibeault, S. L. (2016). Quantification of porcine vocal fold geometry. *Journal of Voice*, *30*(4), 416–426. https://doi.org/10.1016/j.jvoice.2015.06.009

Sundarrajan, A., Erickson-Levendoski, E., & Sivasankar, M. P. (2015). A preliminary investigation of potential biases in phonation threshold pressure analysis. *Journal of Voice*, *29*(1), 22–25. https://doi.org/10.1016/j.jvoice.2014.07.001

Švec, J. G., Horáček, J., Šram, F., & Veselý, J. (2000). Resonance properties of the vocal folds: In vivo laryngoscopic investigation of the externally excited laryngeal vibrations. *The Journal of the Acoustical Society of America*, *108*(4), 1397–1407. https://doi.org/10.1121/1.1289205

Švec, J., Schutte, H., Chen, J., & Titze, I. (2021). Integrative insights into the myoelastic-aerodynamic theory and acoustics of phonation. Scientific tribute to Donald G. Miller. *Journal of Voice*. Advance online publication. https://doi.org/10.1016/j.jvoice.2021.01.023

Swindle, M. M., Makin, A., Herron, A. J., Clubb, F. J., & Frazier, K. S. (2012). Swine as models in biomedical research and toxicology testing. *Veterinary Pathology*, *49*(2), 344–356. https://doi.org/10.1177/0300985811402846

Tanner, K., Fujiki, R. B., Dromey, C., Merrill, R. M., Robb, W., Kendall, K. A., Hopkin, J. A., Channell, R. W., & Sivasankar, M. P. (2016). Laryngeal desiccation challenge and nebulized isotonic saline in healthy male singers and nonsingers: Effects on acoustic, aerodynamic, and self-perceived effort and dryness measures. *Journal of Voice, 30*(6), 670-676. https://doi.org/10.1016/j.jvoice.2015.08.016

Tanner, K., Roy, N., Merrill, R. M., & Elstad, M. (2007). The effects of three nebulized osmotic agents in the dry larynx. *Journal of Speech, Language, and Hearing Research*, *50*(3), 635-646. https://doi.org/10.1044/1092-4388(2007/045)

Tao, C., Regner, M. F., Zhang, Y., & Jiang, J. J. (2011). Experimental and theoretical investigations of phonation threshold pressure as a function of vocal fold elongation. *Acta Acustica United with Acustica*, *97*(4), 669–677. https://doi.org/10.3813/AAA.918446

Thomson, S. L., Mongeau, L., & Frankel, S. H. (2005). Aerodynamic transfer of energy to the vocal folds. *The Journal of the Acoustical Society of America*, *118*(3), 1689–1700. https://doi.org/10.1121/1.2000787

Titze, I. R. (1988). The physics of small-amplitude oscillation of the vocal folds. *The Journal of the Acoustical Society of America*, *83*(4), 1536–1552. https://doi.org/10.1121/1.395910

Titze, I. R. (1992). Phonation threshold pressure: A missing link in glottal aerodynamics. *The Journal of the Acoustical Society of America*, *91*(5), Article 2926. https://doi.org/10.1121/1.402928

Titze, I. R., & Hunter, E. J. (2015). Comparison of vocal vibration-dose measures for potential-damage risk criteria. *Journal of Speech, Language, and Hearing Research: JSLHR*, *58*(5), 1425–1439. https://doi.org/10.1044/2015_JSLHR-S-13-0128

Tokuda, I. T., Horáček, J., Švec, J. G., & Herzel, H. (2008). Bifurcations and chaos in register transitions of excised larynx experiments. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *18*(1), Article 013102. https://doi.org/10.1063/1.2825295

Tokuda, I. T., & Shimamura, R. (2017). Effect of level difference between left and right vocal folds on phonation: Physical experiment and theoretical study. *The Journal of the Acoustical Society of America*, *142*(2), 482–492. https://doi.org/10.1121/1.4996105

Wilson, J. A., Deary, I. J., Millar, A., & Mackenzie, K. (2002). The quality of life impact of dysphonia. *Clinical Otolaryngology & Allied Sciences*, *27*(3), 179–182. https://doi.org/10.1046/j.1365-2273.2002.00559.x

Xue, C., Kang, J., Hedberg, C., Zhang, Y., & Jiang, J. J. (2019). Dynamically monitoring vocal fatigue and recovery using aerodynamic, acoustic, and subjective self-rating measurements. *Journal of Voice*, *33*(5), 809.e11-809.e18. https://doi.org/10.1016/j.jvoice.2018.03.014

Yiu, E. M. L., Liu, C. C. Y., Chan, C. Y. P., Barrett, E., & Lu, D. (2021). Vibrational therapies for vocal fatigue. *Journal of Voice*, *35*(1), 29–39. https://doi.org/10.1016/j.jvoice.2019.07.009

Zhang, Z. (2011). On the difference between negative damping and eigenmode synchronization as two phonation onset mechanisms. *The Journal of the Acoustical Society of America*, *129*(4), 2163–2167. https://doi.org/10.1121/1.3543989

Zhang, Z. (2016). Mechanics of human voice production and control. *The Journal of the Acoustical Society of America, 140*(4), 2614-2635. https://doi.org/10.1121/1.4964509

Zhang, Z., Neubauer, J., & Berry, D. A. (2007). Physical mechanisms of phonation onset: A linear stability analysis of an aeroelastic continuum model of phonation. *The Journal of the Acoustical Society of America*, *122*(4), 2279–2295. https://doi.org/10.1121/1.2773949

Zheng, Y. Q., Zhang, B. R., Su, W. Y., Gong, J., Yuan, M. Q., Ding, Y. L., & Rao, S. Q. (2012). Laryngeal aerodynamic analysis in assisting with the diagnosis of muscle tension dysphonia. *Journal of Voice*, *26*(2), 177–181. https://doi.org/10.1016/j.jvoice.2010.12.001

Zhuang, P., Sprecher, A. J., Hoffman, M. R., Zhang, Y., Fourakis, M., Jiang, J. J., & Wei, C. S. (2009). Phonation threshold flow measurements in normal and pathological phonation. *The Laryngoscope*, *119*(4), 811–815. https://doi.org/10.1002/lary.20165

Zhuang, P., Swinarska, J. T., Robieux, C. F., Hoffman, M. R., Lin, S., & Jiang, J. J. (2013). Measurement of phonation threshold power in normal and disordered voice production. *The Annals of Otology, Rhinology, and Laryngology*, *122*(9), 555–560. https://doi.org/10.1177/000348941312200904

APPENDIX

Annotated Bibliography

Alipour. F., Finnegan, E. M., & Jaiswal, S. (2013). Phonatory characteristics of the excised human larynx in comparison to other species. *Journal of Voice*, *27*(4), 441–447. https://doi.org/10.1016/j.jvoice.2013.03.013

Purpose of the study: To examine the phonation dynamics of excised human larynges, and to compare the results to the phonation dynamics of excised larynges from other animals collected during previous studies.

Method: The excised larynges were taken from six human subjects between 70 and 89 years old. They were then dissected down to the level of the vocal folds and mounted on a benchtop phonation apparatus. Each larynx then underwent aerodynamic testing to determine range of phonation at different pressure and flow values, including phonation threshold pressure.

Results: Pressure, flow, fundamental frequency, and sound pressure level were all recorded. The human larynges had average fundamental frequency and phonation threshold pressure, most similar to canine larynges. However, the pitch range was most similar to porcine larynges, and significantly greater than other species.

Conclusions: Excised human larynx data was largely comparable to previous similar studies. Average phonation frequency was most similar between human and canine excised larynges. The similar range of oscillation frequencies between excised human and porcine larynges is likely related to the physiological similarities of their structural makeup (similar distributions of collagen and elastin).

Relevance to the current work: This study supports the use of excised pig larynges in studies due to the physiological similarities between human and porcine vocal fold composition.

Anderson, J., DeLuca, M., Haines, M.-E., & Merrick, G. (2018). Immediate effects of external vibration vs placebo on vocal function therapy in singers. *JAMA Otolaryngology–Head & Neck Surgery*, *144*(3), 187-193. https://doi.org/10.1001/jamaoto.2017.2679

Purpose of the study: To examine the effects of external vibration on treatment outcomes for singers,

Method: Twenty-seven subjects were randomly assigned to either a treatment group, receiving external vibration therapy, or a control group, receiving a placebo with a similar device. Acoustic data and self-reports of vocal effort were recorded while the participants performed various vocal tasks before and then again after treatment.

Results: There were no meaningful differences between the treatment group and the placebo group, but both groups showed significant improvements in acoustic and self-measures of voice quality.

Conclusions: External vibration therapy may not benefit voice production more than a placebo; however, similar studies should be conducted with more participants and different vocal tasks.

Relevance to the current work: It is important to understand the potential effects of applying an external vibration source to the larynx beyond its possible effect of lowering or stabilizing PTP and PTF.

Awan, S. N., Novaleski, C. K., & Yingling, J. R. (2013). Test-retest reliability for aerodynamic measures of voice. *Journal of Voice*, *27*(6), 674–684. https://doi.org/10.1016/j.jvoice.2013.07.002

Purpose of the study: To investigate the stability of aerodynamic voice measures within individuals across multiple data collection points.

Method: Thirty females and 30 males between 18 and 31 years old with normal voices were recruited for the study. Aerodynamic data (including maximum phonation time, expiratory volume, airflow, and air pressure) were collected on two days about a week apart, and then analyzed for variability within subjects between the two days.

Results: No significant differences were found between the two data points at test and retest for any of the measures used. However, significant intersubject variability makes using these measures difficult for differentiating between normal and disordered voice.

Conclusions: It is important to be able to differentiate between normal variation in repeated measures compared to changes that reflect actual therapeutic effects. There is also sufficient variability within subjects to warrant caution in the application of these measures to monitor progress in therapy.

Relevance to the current work: This study supports the need for increased stability of aerodynamic measures to increase their clinical utility.

Barsties v. Latoszek, B. (2020). Treatment effectiveness of Novafon local vibration voice therapy for dysphonia treatment. *Journal of Voice*, *34*(1), 160.e7-160.e14. https://doi.org/10.1016/j.jvoice.2018.05.009

Purpose of the study: To determine the effects of a vibration treatment compared to a control group on voice outcomes for dysphonic individuals.

Method: Thirty-two participants who were at least 18 years old and had a laryngeal pathology were recruited for the study. Of those 32, 22 were able to complete the program (10 had to discontinue for different reasons, including illness). These 22 participants were randomly assigned to a treatment group (n=11), which received vibration therapy in conjunction with voice exercises and a control group (n=11), which received the voice exercises with no vibration. No significant differences were found between the groups prior to treatment. The voice exercises used included SOVT exercises, humming, and exercises for resonance. Voice outcome measures included acoustic (spectrogram analysis and voice range profile), self-report (VHI), AVQI and DSI, and aerodynamic measurements (phonation quotient).

Results: The treatment group showed significant improvements in almost all outcome measures, and most measures reached normal values. The control group showed significant improvements in VHI, spectrogram analysis, and DSI, and only VHI reached normal values. Significant differences were found between the groups for spectrogram analysis and AVQI scores.

Conclusions: Vibration therapy combined with voice exercises had better outcomes than voice exercises alone for measures of voice quality. Phonation quotient did not significantly change in either group pre- to post-treatment. Vibration therapy could be a good option for people with voice disorders.

Relevance to the current work: It is important to know the effects that vibration might have on voice outcomes. In this study the lone aerodynamic measure used, phonation quotient, was not changed by the treatment.

Dastolfo, C. (2011). *Effects of repetition on phonation threshold pressure task performance* [Master's thesis, University of Pittsburgh]. D-Scholarship@Pitt. http://d-scholarship.pitt.edu/7466/

Purpose of the study: To examine the effects of task repetition on phonation threshold pressure output.

Method: Participants included 19 females between the ages of 19 and 27 who reported no prior history of voice problems. Vocal range was elicited using a keyboard and an 80^{th}-percentile pitch was then calculated for use during PTP elicitation. PTP estimation was collected using a mask with an oral pressure tube. Five-syllable strings (pi-pi-pi-pi-pi) were repeated five times per practice block, and each subject did five practice blocks per data collection day for a total of 125 syllable repetitions per session. PTP was then calculated by averaging the peak pressure values of the second, third, and fourth syllables of the five-syllable strings.

Results: Learning effects were clearly demonstrated for PTP tasks, with improvement (i.e., decrease in pressure) being noted between initial and best practice blocks on both days of data collection.

Conclusions: PTP values should be interpreted cautiously when saturation or training is not feasible. Practice effects, including warm-up, learning, and fatigue, should be accounted for when using PTP in research or clinically.

Relevance to the current work: This study demonstrates the importance of alternating between trials with and without the device to try to mitigate the effect that practice might have when comparing the two conditions.

DeJonckere, P., & Lebacq, J. (2021). Intraglottal aerodynamics at vocal fold vibration onset. *Journal of Voice*, *35*(1), 156.e23–156.e32. https://doi.org/10.1016/j.jvoice.2019.08.002

Purpose of the study: To investigate the potential role of developing turbulence in the glottal airstream as a mechanism for initiating vocal fold vibration.

Method: Photoglottography was used to measure glottal area. Glottal flow was obtained by placement of a Rothenberg mask and inverse filtering of the signal. Estimates of subglottic pressure (including PTP) were collected through the mask using short flow interruptions. Electroglottography data and audio signal were recorded concurrently as well. All data were collected from a single subject who was an occupational voice user in good health who was used to controlling different aspects of voice. Reynolds numbers were proposed to capture the transition from laminar flow to turbulent flow in the glottal airstream.

Results: Changes in flow and photoglottography occurred a few cycles prior to changes in electroglottography. The mean Reynolds number for the 72 recordings used was approximately 3000. Moderate positive correlation (R = 0.56) was found between glottal area and airflow at oscillation onset.

Conclusions: The Reynolds numbers found in this study were in line with theoretical expectations, providing support for the idea that a change from laminar to turbulent flow may act as the trigger to start vocal fold vibration. Calculations also indicated that subglottal pressure and negative Bernoulli force were nearly equal at phonation onset.

Relevance to the current work: This *in vivo* study provides important theoretical context for mechanisms of phonation onset and the role that an external oscillation device could play in changing onset conditions.

Enflo, L., Sundberg, J., & McAllister, A. (2013). Collision and phonation threshold pressures before and after loud, prolonged vocalization in trained and untrained voices. *Journal of Voice*, *27*(5), 527–530. https://doi.org/10.1016/j.jvoice.2013.03.008

Purpose of the study: To examine the effects of a vocal loading task on phonation threshold pressure (PTP) and collision threshold pressure (CTP) in people with healthy voices.

Method: Eight men and two women volunteered for the study, five of whom were singers and five of whom were non-singers. They all performed a vocal loading task of repeating a string of vowels for 20 minutes while maintaining an intensity of 80 dB or greater. Recordings were made before and after the vocal loading exercise, and PTP and CTP were also collected before and after. EGG data was used to determine CTP data while data from a pressure transducer mask was used for both CTP and PTP.

Results: All five non-singers reported fatigue after the vocal loading task, while only one of the five singers reported fatigue. Similarly, PTP and CTP were significantly elevated for the non-singers after the vocal loading task, while they were not significantly affected for the singers.

Conclusions: CTP and PTP could be useful objective correlates of vocal effort. Trained voice users are more likely to be able to withstand vocal loading tasks.

Relevance to the current work: This study supports the use of objective aerodynamic measures (PTP and CTP) as part of voice assessment.

Faver, K. Y., Plexico, L. W., & Sandage, M. J. (2012). Influence of syllable train length and performance end effects on estimation of phonation threshold pressure. *Journal of Voice*, *26*(1), 18–23. https://doi.org/10.1016/j.jvoice.2010.10.021

Purpose of the study: To examine the effects of syllable train length (and which syllables are analyzed) on PTP measurements using oral stop pressure as an approximation.

Method: Participants were 16 healthy females between 20 and 36 years old with no history of voice problems or other potential confounding factors (pregnancy, smoking, asthma, etc.). Controlled variables included syllable train length (either 5 or 7 syllables) and pitch level (low, middle, and high). Pitch levels were determined by eliciting the pitch range of the participants' modal phonation and then finding the 10^{th}, 20^{th}, and 80^{th} percentiles, respectively. Hydration and menstrual cycle stage were also ensured by collecting urine samples. The dependent variable was PTP. Upon data collection, two subjects were discharged from the study due to pitch-matching difficulties, while the data from four more participants did not meet inclusion criteria; therefore, the results include the data from only 10 of the original 16 participants.

Results: PTP varied significantly by pitch, with the high pitch condition resulting in elevated PTP. Syllable train length and syllable position did not have statistically significant effects on PTP measurements at low and modal pitch levels, but initial syllables had significantly lower PTP for the high pitch condition.

Conclusions: Syllable trains of five repetitions should be clinically useful in measuring PTP. PTP collection and analysis procedures should be standardized to ensure clinical relevance.

Relevance to the current work: Syllable train length is important to consider in relation to the human-subjects portion of the study when collecting PTP, and syllable trains of five repetitions should be used for standardization.

Fujiki, R. B., & Thibeault, S. L. (2021). Examining relationships between GRBAS ratings and acoustic, aerodynamic, and patient-reported voice measures in adults with voice disorders. *Journal of Voice*. https://doi.org/10.1016/j.jvoice.2021.02.007

Purpose of the study: To explore the relationship of various voice measures to each other for dysphonic individuals.

Method: Data from 508 dysphonic individuals were analyzed, including GRBAS ratings, vocal range, HNR, MPT, DSI, PTP, and VHI.

Results: GRBAS scores of breathiness were significantly correlated with PTP, but r values were low. GRBAS ratings also correlated with other measures, but r values were similarly low.

Conclusions: This study supports the use of a variety of voice outcome measures to capture a complete picture of the individual's voice, and also validates individual measures due to the significance of correlations.

Relevance to the current work: It is important to know that there is clinical validity in the current use of PTP and other objective voice measures, but also to note that correlations are low and could potentially be increased if the measure becomes more stable.

Hoffman, M. R., Scholp, A. J., Hedberg, C. D., Lamb, J. R., Braden, M. N., McMurray, J. S., & Jiang, J. J. (2018). Measurement reliability of phonation threshold pressure in pediatric subjects. *The Laryngoscope*, *129*(7), 1520-1526. https://doi.org/10.1002/lary.27418

Purpose of the study: To examine the reliability of PTP measurement in the pediatric population.

Method: Participants included 9 males and 13 females between the ages of four and 17 years old with no history of voice problems, who were rated within normal limits using the CAPE-V. PTP was collected using two methods: 1) mechanical airflow interruption with a mouthpiece, and 2) labial interruption with a mask. Both methods were conducted under two conditions: 10 trials at comfortable loudness, and 10 trials at softest loudness. This resulted in a total of 40 trials for each participant. For both conditions, PTP was calculated by averaging the five repetitions for each trial.

Results: PTP was higher in the labial interruption condition compared to the mechanical interruption conditions. PTP variability was not significantly different between conditions and was relatively low in both.

Conclusions: PTP can be reliably measured in the pediatric population and may offer useful clinical information.

Relevance to the current work: PTP measurement methods may affect reliability of the data, which is important to consider with human subjects.

Jen, J. H., Chan, R. W., Wu, C., & Wang, C. (2021). Phonation threshold pressure/flow for reflecting glottal closure in unilateral vocal fold paralysis. *The Laryngoscope*, *131*(5), E1598-E1604. https://doi.org/10.1002/lary.29274

Purpose of the study: To explore the extent to which PTP and PTF may capture the degree of glottal closure for patients with UVFP.

Method: Participants were divided in two groups. The first group had 13 participants with unilateral adductor vocal fold paralysis or paresis (UAVFP) with onset within the last 6 months. These participants also had no other vocal problems, no vocal training, and no history of treatment that might have confounded results. The second group (a control group) had 21 participants with no history of voice problems and normal GRBAS ratings. Control participants were matched with UAVFP subjects by age and gender. Videostroboscopic exams were completed for all participants and glottal gap was measured by two judges and blinded to subject identity when measuring images. Flow and pressure measurements were collected at comfortable pitch. PTF was obtained by having subjects sustain /a/ with decreasing intensity until phonation ceased. PTP was obtained using five-syllable strings of /pa/ repeated as softly as possible without whispering, taking the average of the middle three peaks.

Results: PTF was significantly higher in the paresis group compared to the control group. PTF was also elevated for the paralysis group but did not reach statistical significance. PTP was significantly higher for both the paresis and paralysis groups compared to the control group.

Conclusions: PTP may be more effective at differentiating those with UAVFP and those without than PTF, based on effect size and area under the curve for ROC analysis. However, PTF more closely correlated with normalized glottal gap area and thus could be better for capturing the magnitude of incomplete closure. Limitations of the study included small sample size and large variability in the data.

Relevance to the current work: PTP and PTF may be useful clinical measures for differentiating and documenting the extent of incomplete glottal closure for people with UAVFP.

Mau, T., Muhlestein, J., Callahan, S., Weinheimer, K. T., & Chan, R. W. (2011). Phonation threshold pressure and flow in excised human larynges. *The Laryngoscope*, *121*(8), 1743–1751. https://doi.org/10.1002/lary.21880

Purpose of the study: To obtain PTP and PTF measurement in excised human larynges under various conditions (different glottal widths, different glottal areas, and males vs. females) for the purposes of comparison to measurements from excised canine larynges and measurements from live humans.

Method: Larynges were obtained from nine human subjects between the ages of 62 and 92, five males and four females, with no history of smoking and no apparent vocal fold pathologies. The larynges were dissected down to the level of the true vocal folds and mounted to a benchtop apparatus. Shims were used to simulate five different glottal widths. PTF and PTP were collected during five phonation trials for each of the five glottal widths for each larynx.

Results: PTF was significantly higher for males than females, while PTP was not significantly different between the two groups. For any given glottal width, there was significant variation between larynges for both PTP and PTF. PTP values were comparable to in vivo human data, while PTF values were significantly higher for the excised larynges than previous in vivo human data. Offset measurements of PTP and PTF were found to be lower and more stable than the corresponding onset measurements, indicating hysteresis.

Conclusions: PTP and PTF at offset may be more clinically valuable due to their greater stability. Excised human larynx models indicate a wide range of PTP and PTF values across individuals, indicating that these measures may not have useful normative values for comparison across individuals.

Relevance to the current work: This study helps to connect the excised pig larynx data and the human data in our work by providing a connecting link with excised human larynges.

Morgan, M. D., Triana, M. A., & Milroy, T. J. (2004). The effect of auditory feedback on phonation threshold pressure measurement. *Journal of Voice*, *18*(1), 46–55. https://doi.org/10.1016/s0892-1997(03)00069-9

Purpose of the study: To examine whether auditory feedback impacts the measurement of phonation threshold pressure.

Method: Fourteen healthy females between the ages of 20 and 30, who were blind to the study purpose and who had no formal voice training, were recruited for the study. Habitual pitch (as measured by a counting and descriptive task) was used to determine the pitch for PTP data collection. Rate was controlled using a metronome. Participants were also trained on how to produce threshold phonation (between a whisper and normal talking volume). Data were collected in three different conditions: mask, no mask, and mask with enhanced auditory feedback.

Results: As auditory feedback increased across the three conditions, PTP tended to decrease. However, the difference may not be clinically significant.

Conclusions: Soft voice production would hypothetically allow for more direct assessment of the vocal fold cover, since the thyroarytenoid tends to be less engaged at low intensities. Using auditory feedback when measuring PTP could enhance the ability of people to produce voicing at lower intensities.

Relevance to the current work: Auditory feedback should be considered when collecting PTP data during the human-subjects portion of the study.

Mulheren, R. W., & Ludlow, C. L. (2017). Vibration over the larynx increases swallowing and cortical activation for swallowing. *Journal of Neurophysiology 118*(3), 1698–1708. https://doi.org/10.1152/jn.00244.2017

Purpose of the study: This study investigated the effect of extralaryngeal vibration on fundamental frequency (to determine if tissue was penetrated), swallowing frequency, and cortical activation during stimulation and swallowing.

Method: Participants were selected based on no history of dysphagia and right-handedness. For the first part of the study examining fundamental frequency, six participants were fitted with a custom vibration device that had two motors, one for each thyroid lamina, that was strapped around the neck. Acoustic data were collected during trials of /i/ sustained for 10 seconds, with at least 20 seconds of rest between trials. This was repeated six times; half the trials were with the device on (without warning the patient) and half were with the device off. Fundamental frequency data were then extracted from these recordings and compared using a paired *t*-test.

For the second part of the study regarding cortical activation during swallowing, similar devices were used on 10 participants to create eight different conditions: six vibratory conditions with different frequency combinations (continuous 30 Hz, 70 Hz, 110 Hz, and 150 Hz bilateral stimulation; 70 Hz and 110 Hz continuous stimulation; and 70 Hz and 110 Hz pulsed stimulation) and two sham conditions with no vibration. A pressure-reading device was placed between the neck strap and the subjects' neck to maintain consistent pressure of the vibration device. Swallowing frequency was tracked during all conditions using three criteria: neck accelerometer movement associated with hyolaryngeal elevation, respiratory interruption as tracked by an Inductotrace® device, and visual tracking by a trained observer looking for laryngeal movement. Cortical activation was measured by functional near-infrared spectroscopy (fNIRS), which offers higher temporal resolution than fMRI.

Results: Fundamental frequency was significantly lower during the vibration conditions, indicating that the vibration reached the level of the laryngeal tissue. Swallowing frequency significantly increased in the 70 Hz and 150 Hz continuous bilateral stimulation conditions. fNIRS data showed significant differences in cortical hemodynamic response for swallows during stimulation vs. swallows during rest vs. swallows during sham conditions.

Conclusions: Extralaryngeal vibration affected F_0, indicating tissue penetration. It also stimulated increased swallow frequency, indicating likely excitation of the central pattern generator for swallowing. Extralaryngeal vibration appeared to suppress cortical activity despite the increase in spontaneous swallow frequency, which was unexpected. This suggests that different aspects of the swallowing system may be affected differently by external vibration. These results taken together suggest that external laryngeal vibration may be a beneficial component of swallowing therapy by both increasing spontaneous swallow frequency and increasing cortical activation of swallow-related motor areas.

Relevance to the current work: This study shows an ideal external vibration device and also discusses many of the potential effects that external vibration may have on voicing, including mechanical and neurological.

Nascimento, A., Korn, G. P., Sacaloski, M., & Azevedo, R. R. (2021). Effects of mechanical vibration stimulation of the larynx on voice production. *Journal of Voice*. https://doi.org/10.1016/j.jvoice.2020.12.024

Purpose of the study: To determine what effect applying vibration to the larynx has on voice production, in combination with voice exercises.

Method: Participants included six women and eight men, all of whom were healthy professional voice users. They were randomly assigned to a treatment group (n=7; completed humming exercises and vibration) and a control group (n=7; completed humming exercises only). They completed the exercises daily for a month and tracked their progress throughout the experiment. The exercise sequence included maximum phonation time at modal and high pitches, an ascending pitch glide, and small five-note scales, all of which was repeated and took approximately 20 minutes to complete. Various data were collected before intervention, after the first session, and after the 30-day training period; these included self-reported data of the Voice Signs and Symptoms Questionnaire, GRBASI ratings, acoustic analysis using PRAAT (including HNR, perturbation measures, and spectrogram analysis), and maximum phonation time obtained from averaging three different maximum vowel productions.

Results: The treatment group had improved maximum phonation time and reduced perturbation measures, both immediately after the first session and also after 30 days of intervention compared to the control group. The treatment group also had better GRBAS ratings and VSSQ results after 30 days of treatment compared to the control group.

Conclusions: Combining vibration with vocal exercises can be beneficial to voice outcomes for healthy voice users. Experiments should be conducted to examine effects in dysphonic individuals.

Relevance to the current work: It is important to understand the different mechanisms by which vibration might affect phonation in humans, since we will be applying vibration to the larynx in the human-subjects portion of the study.

Orr, R., & Cranen, B. (2005). The effect of the flow mask on phonation. *BMC Neuroscience*. 1000-1004. https://www.isca-speech.org/archive/pdfs/maveba_2005/orr05_maveba.pdf

Purpose of the study: To look at how phonation may be influenced by collection of aerodynamic measures of voicing using a mask.

Method: A single-subject design was implemented to control for possible confounding factors that could arise from inter-subject variability. The subject chosen was a female with experience producing different voice qualities, and the ability to reproduce phonatory characteristics with a high degree of accuracy. The task involved repeating the syllable string /paepaepaepae/ a total of 40 times (20 times with a microphone and 20 times with a flow mask) for each of three voicing conditions: breathy, creaky, and modal. Open quotient (OQ), closed quotient (ClQ), and H1-H2 data were extracted from the recording and compared.

Results: Data collected showed lower values for most of the parameters in the masked voicing conditions compared to the unmasked conditions. There was a large effect size for these differences. These results appear to indicate that phonation was more efficient in the masked condition than in the unmasked condition.

Conclusions: These results could be due to increased muscular tension introduced by the mask, decreased auditory feedback leading to increased output, or a combination of the two.

Relevance to the current work: Phonating into a flow mask is likely to produce different phonation characteristics than phonating without a mask. This is important to consider when interpreting the results of the pilot human-subject data. This also brings up the potential confounding factor of auditory feedback when attempting to produce PTP with the electrolarynx.

Plexico, L. W., & Sandage, M. J. (2012). Influence of vowel selection on determination of phonation threshold pressure. *Journal of Voice*, *26*(5), 673.e7-673.e12. https://doi.org/10.1016/j.jvoice.2011.12.005

Purpose of the study: To investigate the effects of different vowels on PTP measurements.

Method: Participants included twelve healthy females, between the ages of 20 and 27. PTP was measured for each participant using five repetitions of the syllables /pi/, /pae/, and /pa/ at three different pitch levels (low, modal, and high).

Results: There was no significant difference in PTP values between the three different vowel conditions. Similar to previous studies, PTP was significantly higher for the high pitch condition across all three vowels.

Conclusions: Vowel appears to have no significant effect on PTP, although it should still be standardized for maximum comparison value.

Relevance to the current work: PTP measurements can be made using different vowel elicitations. PTP data elicited using different values can reasonably be compared.

Plexico, L. W., Sandage, M. J., & Faver, K. Y. (2011). Assessment of phonation threshold pressure: A critical review and clinical implications. *American Journal of Speech-Language Pathology*, *20*(4), 348–366. https://doi.org/10.1044/1058-0360(2011/10-0066)

Purpose of the study: To examine variables that affect phonation threshold pressure elicitation and data collection by reviewing the literature and surveying clinicians.

Method: The authors searched EBSCO and FirstSearch for terms related to phonation threshold pressure, looking for articles that covered PTP assessment published between 1980 and 2009. The results of the literature review were then used to create a survey that was sent to clinicians and researchers within the field. For the survey, participants were recruited via the SIG 3 email list, as well as directly contacting experts within the field.

Results: For the literature review, most of the studies examined, used young adult subjects that were primarily female. Various other procedural variables were found, including different vowels, syllable train lengths, analysis procedures, and equipment. The survey results indicated a variety of uses and methods for PTP data collection.

Conclusions: A standardized clinical protocol for PTP collection is proposed, including taking a subject history and procedures for data collection and analysis.

Relevance to the current work: A version of this clinical protocol can be used for the human-subjects portion of the current study.

Rosenthal, A. L., Lowell, S. Y., & Colton, R. H. (2014). Aerodynamic and acoustic features of vocal effort. *Journal of Voice*, *28*(2), 144–153. https://doi.org/10.1016/j.jvoice.2013.09.007

Purpose of the study: To investigate quantitative characteristics of vocal effort and their potential clinical utility.

Method: This study used 18 participants (12 female and six male) between 18 and 26 years old who were self-reported to be vocally healthy, and who were screened as having normal vocal quality. Each subject produced syllable strings of /pi/ repetitions at each of three levels of vocal effort: minimal, comfortable, and maximal. Acoustic (CPP, CPP SD) and aerodynamic (subglottal pressure, translaryngeal resistance, MFDR, and translaryngeal airflow) data were collected during these productions.

Results: All acoustic and aerodynamic measures showed significant differences among the experimental conditions. Participants' subglottal pressure increased in the maximal effort condition and decreased in the minimal effort condition relative to the comfortable effort condition.

Conclusions: Phonatory effort is correlated with subglottal pressure in healthy young adults. The increased subglottal pressure could be affected by both respiratory and laryngeal aspects of voicing, including increased respiratory drive and increased laryngeal tension.

Relevance to the current work: This study demonstrates a correlation between vocal effort, strained vocal quality, and subglottal pressure. This connects to other studies showing similar correlation between phonation threshold pressure and vocal fatigue.

Smitheran, J. R., & Hixon, T. J. (1981). A clinical method for estimating laryngeal airway resistance during vowel production. *Journal of Speech and Hearing Disorders*, *46*(2), 138-146. https://doi.org/10.1044/jshd.4602.138

Purpose of the study: To investigate the potential use of a non-invasive method for estimating laryngeal aerodynamic measures, specifically by collecting oral pressure and flow measurements during repeated bilabial stop consonant-vowel alternations.

Method: Significant pilot testing was undertaken to lay the groundwork for this study. Subjects included 15 males, between 21 and 40 years old, with no history of health problems and no apparent voice impairments or disorders at the time of data collection. The utterance used for the study was a syllable string of /pi/ repeated seven times. This syllable string was repeated three times by each participant. This utterance was selected for the following reasons: /p/ allows for closure with the least amount of required insertion; /i/ is a high-front vowel, which tends to be less nasal in non-nasal contexts than low-back vowels; and syllable repetition allowed for closer approximation of true speaking conditions by requiring more breath and some aspects of suprasegmental speech (although each syllable was intended to have equal emphasis, and were only produced at a rate of 1.5 syllables per second). Subjects were given instruction and production models by the investigators, and were given repeated prompts until they produced three syllable trains that met the criteria for inclusion (clean pressure peaks, equal stress, etc.). For analysis, the middle three syllables of each train were included to avoid performance end-effects.

Results: The reliability coefficient for the data collected was .96, indicating that the results could be interpreted with confidence. Mean laryngeal airway resistance (pressure divided by flow) was 35.7 cmH_2O/LPS.

Conclusions: The results from this experimental, non-invasive method of laryngeal aerodynamic measurement estimation were in line with previous studies that employed tracheal puncture to obtain direct laryngeal aerodynamic measures. This suggests that the estimation provided by this method is accurate enough for clinical use.

Relevance to the current work: This study helps to provide the basis for the method of PTP/PTF collection used in the human-subjects portion of the research.

Sundarrajan, A., Erickson-Levendoski, E., & Sivasankar, M. P. (2015). A preliminary investigation of potential biases in phonation threshold pressure analysis. *Journal of Voice*, *29*(1), 22–25. https://doi.org/10.1016/j.jvoice.2014.07.001

Purpose of the study: To investigate the potential effects of researcher bias (due to lack of blinding and lack of training) on PTP analysis.

Method: Two researchers analyzed PTP datasets following PTP analysis training from the same individual. Each researcher analyzed a dataset first when blinded to the purpose of the study, and then again after being informed of the purpose of the study and the expected PTP findings. All four data sets (blinded and unblinded for each researcher) contained the same data but were labeled differently so that the researchers were not aware. Intrarater and interrater reliability were calculated using two-way mixed, absolute, single-measures intraclass correlation coefficients.

Results: Intrarater reliability was excellent for both researchers, indicating that knowledge of the experimental hypothesis likely had no impact on the analysis. However, interrater reliability was significantly lower, indicating that more analysis training may have been needed to eliminate potential bias.

Conclusions: Bias should be carefully considered in studies of PTP, and blinding and a single researcher for data analysis should be considered, due to higher intrarater reliability compared to interrater reliability.

Relevance to the current work: In our study of PTP, PTF, and other aerodynamic measures, bias must be accounted for in our data analysis process.

Thomson, S. L., Mongeau, L., & Frankel, S. H. (2005). Aerodynamic transfer of energy to the vocal folds. *The Journal of the Acoustical Society of America*, *118*(3), 1689–1700. https://doi.org/10.1121/1.2000787

Purpose of the study: To describe the mechanics of how airflow induces vocal fold vibration by transferring energy from the airstream to the vocal fold tissues.

Method: A synthetic physical model of the vocal folds was used in combination with a numerical model to model phonation. These models were designed to closely represent human vocal fold properties.

Results: The data from both models showed that, in agreement with previous research by Titze, the alternating pattern of convergence and divergence of the glottis was an important part of the energy transfer process.

Conclusions: Self-oscillating phonation is driven and maintained due to temporal variation of laryngeal wall pressure, i.e., lower net pressure during the divergent phase of the mucosal wave than during the convergent phase.

Relevance to the current work: This study is foundational in helping to describe the mechanical bases for phonation and serves as an important background for discussing the potential effects of adding an external oscillation to the system.

Yiu, E. M., & Lee, S. C. (2021). Comparing the effects of self-generated and platform-generated whole body vibration on vocal fatigue. *Journal of Voice*. https://doi.org/10.1016/j.jvoice.2021.01.027

Purpose of the study: To examine the influence that different whole body vibration (WBV) conditions may have on vocal fatigue.

Method: Participants were 24 females who ranged from 20 and 39 years old. All subjects had no history of voice problems, and no medical conditions or current behaviors that could negatively impact voice. Participants were then divided into three groups: machine-generated WBV (approximately 8-10 Hz), self-generated WBV, and a control group that received a sham localized vibration treatment. All three groups completed a vocal loading task of continuous singing for at least 95 minutes without rest or hydration to ensure vocal fatigue. After the vocal loading task, each group underwent 10 minutes of its corresponding treatment condition. Highest fundamental frequency and Vocal Fatigue Score (VFS) were collected from each participant pre-loading, post-loading, and post-intervention.

Results: All groups demonstrated a significant reduction in highest fundamental frequency, and significant increase in VFS after the loading task. All three groups showed an increase of highest fundamental frequency post-intervention, but only the machine-generated WBV group reached statistical significance. The machine-generated WBV and placebo groups both achieved significant reduction in VFS post-intervention, while the VFS reduction in the self-generated WBV group did not reach statistical significance.

Conclusions: These results suggest that an external source of vibration may be beneficial for recovering after heavy voice use. Possible mechanisms for this effect include increased blood flow and reduction of excessive muscle tension.

Relevance to the current work: It is important to consider all possible effects that vibration might have on phonation: mechanical, physiological, perceptual, etc. This study suggests that external sources may offer more potential benefit than self-generated vibration.

Yiu, E. M. L., Liu, C. C. Y., Chan, C. Y. P., Barrett, E., & Lu, D. (2021). Vibrational therapies for vocal fatigue. *Journal of Voice*, *35*(1), 29–39. https://doi.org/10.1016/j.jvoice.2019.07.009

Purpose of the study: To investigate the effects two different vibration conditions on phonation in healthy individuals after a vocal loading task.

Method: Participants (24 male, 20 female) with normal voice were randomly assigned to three conditions: whole body vibration (n=15), localized perilaryngeal vibration (n=14), and control (hand-held vibration device, n=15). Each completed a vocal loading task of singing karaoke for at least 95 minutes prior to receiving a 10-minute vibration treatment (or control), which they were told might improve their vocal function. After intervention, participants completed both a high-pitch task (highest pitch produced on a glide) across three trials and a brief self-assessment of vocal fatigue.

Results: Highest pitch was significantly reduced for all groups after singing, and vocal fatigue self-rating was significantly increased. Highest pitch significantly increased following intervention for both vibration groups, but not for the control group. Vocal fatigue self-ratings also decreased following all three treatment conditions, though significantly more for the vibrational treatments than for the control group.

Conclusions: Vibrational therapies show promise in treating vocal fatigue.

Relevance to the current work: Application of a vibratory device to the larynx could have many potential effects on the voice, including reduction of excess muscle tension if the frequency is appropriate. This relates to the ultimate aims of the current study in investigating the effect of a vibratory device on objective measures of phonation including PTP and PTF.

Zhuang, P., Sprecher, A. J., Hoffman, M. R., Zhang, Y., Fourakis, M., Jiang, J. J., & Wei, C. (2009). Phonation threshold flow measurements in normal and pathological phonation. *The Laryngoscope*, *119*(4), 811-815. https://doi.org/10.1002/lary.20165

Purpose of the study: To examine the effects of healthy vs. abnormal vocal folds on phonation threshold flow.

Method: Participants were comprised of three groups based on the state of their vocal folds: normal (n=40), nodules (n=21), and polyps (n=23). Mean flow rate and phonation threshold flow were measured and compared across participants using an ANOVA, while a *t* test was used to compare males to females.

Results: Both measures of flow were significantly different between males and females. After accounting for this difference, both mean flow rate and phonation threshold flow were found to be significantly elevated for the groups with vocal fold pathologies compared to the normal group.

Conclusions: Phonation threshold flow can be a useful measure for assessing vocal fold pathologies, specifically nodules and polyps (mass lesions that tend to decrease glottic closure).

Relevance to the current work: This study supports the use of PTF in voice assessment by demonstrating correlation between elevated PTF values and the presence of vocal fold pathology.