Quantifying Vocal Power: Correlation of Whole Body Anaerobic Power to Vocal Function Measures

by

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Abstract

PURPOSE: The purpose of this preliminary study was to identify a vocal task that could be used as a clinical indicator of the vocal aptitude or vocal fitness required for vocally demanding occupations in a manner similar to that of the anaerobic power tests commonly used in exercise science. Performance outcomes for vocal tasks that require rapid acceleration and high force production may be useful as an indirect indicator of muscle fiber complement and bioenergetic fitness of the vocal folds, an organ that is difficult to study directly.

METHODS: Sixteen females (age range: 19-24; mean age: 22) were consented for participation and completed the following performance measures: forced vital capacity, three adapted vocal function tasks, and the horizontal sprint test.

RESULTS: Using a within-participant correlational analyses, results indicated a positive relationship between the rate of the last second of a laryngeal diadochokinetic task that was produced at a high fundamental frequency/high sound level and whole body anaerobic power performance. Forced vital capacity was not correlated with any of the vocal function tasks.

CONCLUSIONS: These preliminary results indicate that aspects of the LDDK task produced at a high f0 and high sound level may be useful as an ecologically valid measure of vocal power ability. Quantification of vocal power ability may be useful as an outcomes measure for voice rehabilitation and habilitation for patients with vocally demanding jobs.

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List of Abbreviations

DDK	Diadochokinesis
LDDK	Laryngeal Diadochokinesis
SLP	Speech-Language Pathologist
ALS	Amyotrophic Lateral Sclerosis
FVC	Forced Vital Capacity
COPD	Chronic Obstruction Pulmonary Disease
PTP	Phonation Threshold Pressure
CSID	Cepstral Spectral Index of Dysphonia
PPE	Perceived Phonatory Effort
VPS	Vocal Premenstrual Syndrome
MDVP	Multidimensional Voice Program
FEV1	Forced Expiratory Volume in One Second
DLCO	Diffusing Capacity
ASM	Airway Smooth Muscle
SPL	Sound Pressure Level

W	Watts
PR_{max}	Maximum Phonation Resistance
MPT_{max}	Maximum Phonation Time
$LDDK_{max}$	Maximum Laryngeal Diadochokinesis
$LDDK_1$	Laryngeal Diadochokinesis rate in One Second
dB	Decibels
PAS	Phonatory Aerodynamic System
P_s	Subglottal Pressure
ILSM	Intrinsic Laryngeal Skeletal Muscles

Chapter I

INTRODUCTION

There is currently a lack of an objective means to quantify aptitude for voice demands that require acoustic power. If we apply an exercise physiology model to the study of vocal power, then we would be interested in vocal tasks that mimic the rapid acceleration and high force production similar to that of a whole body anaerobic power test. Because we lack these performance-based measures in voice science, correlating voice tasks such as laryngeal diadochokinesis (LDDK), maximum phonation time (MPT), and phonation resistance (PR) to whole body anaerobic power tests may be a reasonable starting place. A correlation of lung volume using forced vital capacity (FVC) with whole body anaerobic power may also be useful given that higher lung volumes support production of more vocal power. Evidence of a correlation between an assessment of whole body anaerobic power and vocal function measures may provide a starting place for determination of the type of vocal “athlete” each individual is, which could ultimately help in the development of voice habilitation and rehabilitation strategies.

Chapter II

REVIEW OF LITERATURE

Vocal Power

At the present time, there are no published, validated assessments to determine aptitude for production of vocal power. For researchers, the sound pressure level produced is aligned with constructs of vocal power. Titze and Sundberg (1992) described vocal power, intensity, or sound pressure level (SPL), as a function of fundamental frequency and lung pressure. They asserted that aerodynamic power quantified in decibels would be relative to typical measures of power in Watts (Titze & Sundberg, 1992). The human communication system is complex and changes in sound level can be attributed to contributions from one or more of the three subsystems of speech: respiration, phonation, and vocal tract.

Sound pressure level depends on lung pressure and will increase 8-9 dB an octave if lung pressure is proportionally equivalent to phonation threshold pressure. In a study done by Holmberg, Hillman, and Perkell (1988), 25 male and 20 female participants were required to produce syllable sequences in soft, normal, and loud voice while measurements of inverse airflow, transglottal pressure, and glottal airflow were recorded. Results showed that both males and females produced a louder voice with increased pressure from an increase in flow and maximum airflow declination rate. There was no significant difference between pressure in males and females during the loud voice task, indicating that despite differences in overall pulmonary capacity between men and women, the production of subglottal pressure for loud voice was similar for both sexes.

Vocal efficiency is defined as the ability to convert subglottal power to acoustic power and can be a measure of the functional status of the larynx (Jiang, Chen, Stern, & Solomon, 2004). In a study done by Jiang et al. (2004), vocal efficiency was hypothesized to be reduced in patients with vocal nodules or polyps. Subglottal pressure was estimated by an intraoral pressure plateau during flow interruption by a balloon-type valve located within the piping of a pneumotachograph mask into which the participants phonated. Subglottal power and acoustic power were used to derive a quotient (acoustic power/subglottal power) that determined vocal efficiency, where acoustic power was calculated by the following equation: $4 \times \pi \times r^2 \times I$; I (intensity) = 10^{-12} W/m^2 x 10(measured decibel level)/10. Subglottal power was calculated by the following equation: flow (mL/s) x subglottal pressure (kPa). Subjects included 22 typical voices, 14 voices with polyps, and 16 voices with nodules. Results indicated that vocal efficiency was significantly reduced in patients with polyps or nodules.

In a study done by Isshiki (1964), a formula was created to try to explain the importance of subglottic power (W), glottal efficiency (E_g), and radiation efficiency from the vocal tract (E_{tr}) as it relates to intensity of voice measured in dB SPL (I): $I=WE_gE_{tr}$. Isshiki concluded that glottal efficiency increases with increases in sound pressure levels due to the decrease in the opening quotient of the vocal folds secondary to the increasing pressure below the glottis to sustain a louder voice. He also concluded that at low pitches, acoustic intensity is controlled by three laryngeal factors (flow rate, glottal resistance, and efficiency), while at high pitches, the expiratory muscles are more important in controlling intensity. Schutte (1992) concurred that subglottal pressure and mean flow rate contribute to vocal power. Subglottal pressure differences were the main aerodynamic differences underlying loudness variation at different pitches sung by 10 singers (Sundberg, Titze, & Scherer, 1993).

Fundamental frequency also matters when calculating vocal power. Titze (1992) described vocal efficiency as the ratio of radiated power (p_r) and aerodynamic power (p_a), creating a calculation measure for radiated power in (W): $P_r=u_m^2f_o^2G$, where u_m is peak AC glottal flow, f_o is fundamental frequency, and G is a function that includes physical constants. He concluded that radiated acoustic power is between .0001% and 1% of the available aerodynamic power at the laryngeal source, which is less than 1% of the metabolic power consumption of our entire body (Titze, 1992). Titze also described a strong dependence of glottal efficiency on the fundamental frequency produced, asserting that glottal efficiency calculations would favor higher f_0, even if it is produced with more effort or strain.

The coordination of the subsystems when speaking in habitual voice was studied by Croake, Andreatta, Stemple (2019). After obtaining acoustic, aerodynamic, and respiratory measures, results indicated there were significant differences in the way participants used these subsystems to produce acoustic output. Their findings indicated that participants could be classified into 3 different groups, assigned by the manner in which they produced the acoustic output. Subglottal pressure (P_s) was the only variable out of the 7 variables measured (lung volume initiation, lung volume termination, lung volume excursion, subglottal pressure, airflow rate, and distance between formants) to correlate with at least one other variable in the 3 groups. In the first group, a higher lung volume initiation measure correlated with higher P_s measures. This group had the largest lung volume initiation and lung volume termination measures which are associated with higher P_s measures, indicating that these participants initiated speech at higher lung volumes. The first group may have relied more on their respiratory system to drive phonation.

In the second group, P_s and lung volumes were negatively correlated with the distance between F2-F1, meaning that higher P_s and lung volumes correlated with a narrow spacing between formants. The spacing of the formants indicated that this group had decreased tongue height and a forward tongue placement compared with other participants. This group also had lower airflow rates compared to the other groups, indicating that they used other variables to increase vocal efficiency or it was a sign of hyperlaryngeal function. This group also had smaller frequency spacing of F4-F5, a sign of epilaryngeal narrowing to increase sound pressure levels.

The third group had the largest correlations between variables, whereby P_s was positively correlated with airflow and was negatively correlated with the spacing between F5-F4, also indicating epilaryngeal narrowing to increase sound pressure levels. Lung volume initiation and termination values were positively correlated with each other and with the spacing between F2-F1, indicating that this group had sufficient or increased tongue height and position compared with the other groups. This group had the second largest P_s and flow values next to group 1 and the lowest values for lung volumes. This study described the different ways a vocally healthy person can use their subsystems for speech and the manner in which these subsystems interact with each other. For example, there were strong correlations between the respiratory and phonatory systems and the respiratory and resonance systems, but a weak correlation between the phonatory and resonance systems (Croake et al., 2019).

In exercise science, power is an expression of the rate of work done and is typically measured by dividing work by time represented by Watts (W; Adams & Beam, 2008). The proposed construct of vocal power in this investigation is distinct from the construct of acoustic power described by Titze. This study explored clinically useful ways to quantify vocal power by examining existing voicing tasks in a novel manner. The tasks selected addressed aspects of anaerobic muscle engagement that include use of intrinsic laryngeal muscles against a resistance and with rapid acceleration. This study used three laryngeal function tasks (LDDK, sustained /a/, and phonation resistance (PR)) and FVC to attempt to quantify vocal power and account for the muscle fiber type and bioenergetic mechanisms that may contribute to production of vocal power.

Anaerobic Power Tests

Anaerobic power tests measure anaerobic power and capacity through force velocity tests, vertical jump, staircase tests, and cycle tests (Vandewalle, Peres, Heller, Panel, & Monod, 1987). These exercise assessments of anaerobic power production capability are used in exercise performance settings as an indicator of athletic aptitude as well as a measurable outcome for exercise training programs. Anaerobic power is the amount of work done in a short period of time and is not reliant on the transport and extraction of oxygen during the test (Adams & Beam, 2008). Some tests include factors such as average power, instantaneous power, active muscle mass, maximal power at the beginning of exercise or after a few seconds, and inertia of the body. Four anaerobic power tests that are commonly used include the Wingate Anaerobic Test, Anaerobic Step test, the Margaria anaerobic power test, and the horizontal sprint test. Of these tests, the Wingate test relies on added weight as the resistance against which the participant cycles on a stationary cycle ergometer. The Anaerobic Step test and the Margaria test rely on vertical displacement of the participants body weight as the resistance against which the skeletal muscles work.

The Wingate anaerobic test is a popular cycling test that determines peak anaerobic power, mean anaerobic power, total work, and fatigue index using a cycle ergometer with added resistance. Peak power is the highest average power produced over 5 seconds, mean power is the average power over the entire 30 seconds of the test. The total work is the product of the number of pedal revolutions and the resistance setting the participant cycled against during the 30 second test. The test consists of a warm up period of 5 minutes of low to moderate intensity pedaling around 50-60 rpm, a recovery interval between 2-5 minutes, an acceleration period consisting of two phases of increasing rpm between 7-15 seconds, the Wingate Test duration consisting of full out cycling for 30 seconds, and a cool down period lasting 2-3 minutes. Peak anaerobic power in Watts, or the maximum power produced in any of the 5 second intervals during the 30 second Wingate Test, is the product of the force times the distance cycled (number of revolutions times 6 meters per revolutions) divided by 5 seconds. The force is found by multiplying the weight loaded on the bike (kg) by 9.80665 (Adams & Beam, 2008). The Wingate Test was used as a predictor of elite Olympic performance for men and women during the summer training for the 1500 m speed skating (Hofman, Orie, Hoozemans, Foster, & de Koning, 2017). Due to the 30 second maximum power performance time required for the Wingate Anaerobic Test protocol it does not temporally correlate to vocal function tasks, which are typically less than 10 seconds in length (Smith et al., 2017; Titze, Švec, & Popolo, 2003).

The Anaerobic Step Test involves the testing of large muscle groups and requires little investment in special equipment. Preparation before the test consists of 2 minutes of walking, 1 minute of stretching, 2 minutes of stepping at a moderate pace, and 2 minutes of more of mild walking and stretching. The test itself is 1 minute of the participant stepping up onto the top of a box and then back down to the floor using a single leg. Using kilograms body weight as the mass being moved against the resistance of gravity, calculations from this test include: positive work, total work, and mean power. To calculate mean power in Watts, divide the total work which is described as positive work (Newtons x meters) *1.33, by the time (s) (Adams & Beam, 2008). This test provides a vertical measure of power, meaning that the force of gravity is working against the participant as a form of resistance. Because this test is longer in length compared to the laryngeal function tasks, and focuses on larger leg muscles, it also has little correlation with laryngeal function tasks.

The Margaria anaerobic power test is similar to the anaerobic step test in that it also calculates power by calculating the vertical displacement of the individual's mass (kg) up a short flight of stairs (Luebbers et al., 2003; Margaria, Aghemo, & Rovelli, 1966). This test is also considered to be a vertical power test because it requires the participant to work against gravity as they run up the stairs. The test is completed by a participant running up at least 9 stairs or more that is approximately 17.5 cm high. This test lasts only a few seconds and would be an appropriate test to correlate with the laryngeal function tasks, however, there is risk of injury.

Anaerobic power can also be derived from a 40-60 yard horizontal sprint which can provide information about muscle power and elasticity to maintain and contribute to maximal velocity (Adams & Beam, 2008). The hypothesis for this test is that the faster sprint is an indicator of more power production. Weight is a factor in this test as well, as a heavier mass will produce more power than a lighter mass if time (s) is held constant. This test is performed horizontally, using the participant's weight as the resistance measure in lieu of a vertical mass displacement component for the resistance. Because this test lasts less than 10 seconds, it is classified an anaerobic test. Sprinting is more dependent on Types IIa and IIb for rapid force and acceleration. The test consists of a 5-10 minute warm up at moderate intensity and stretching, the sprint, and a cool down. Two trials of the sprint are performed, with a rest period of about 1-2 minutes. Horizontal power is calculated by multiplying the body mass of the participant by the average speed (distance divided by sprint time). The short test length correlates well to laryngeal function tasks.

Vocal fold vibration also lacks a vertical mass displacement component, as they produce lateral intraglottal velocity during phonation. The mass of the vocal folds may be an important factor in determining power. Men typically have larger vocal fold mass and larger pulmonary volumes, resulting in different vocal power measures than women due to subglottal pressure differences. Since the length of the vocal folds are shorter in women than in men, this may also cause differences in vocal power due to the raised fundamental frequency. The mass of the vocal folds may also decrease with aging due to hormonal effects observed with aging, creating incomplete closure patterns and pitch differences. Thus, if vocal power is measured acoustically, the age and sex of the participant will be variables that may influence vocal power values.

Factors Affecting Anaerobic Power Values

Body mass is a factor in determining horizontal power, therefore, an increase in body mass at the same speed, or an increase in speed at the same body mass will increase horizontal power (Adams & Beam, 2008). In this way, the horizontal power and sprinting speed produced by men and women of the same body mass can be compared in data collection. The height of the participants is a factor to consider and measure when administering an anaerobic power test. Football players, female soccer players, basketball players, track and field athletes, wrestlers, and baseball players from the NCAA division II program participated in a study to validate repetitive jump tests through the Pro-Vitsa system to assess anaerobic power (Hoffman & Kang, 2002).

Anaerobic power was assessed through the Wingate test and the 30-jumps test on the Pro-Vista system. Results showed that football backs weighed less and had a higher jump and more mean power (W) than lineman. Basketball players were taller by 2 cm than lineman and had a higher jump and more mean power. Wrestlers were shorter, had a shorter jump, and smaller mean power in general. Women soccer players were taller than physical education students and had a higher jump and larger mean power. This study concluded that height had a direct correlation to the anaerobic power a participant could produce.

Sex differences in anaerobic power tests were analyzed within a study done by Maud and Shultz (1986). Untrained men and women were tested over 4 weeks to determine anthropometric dimensions (age, height, mass, lean body mass, %fat, six skinfolds, endomorphy, mesomorphy, and ectomorphy), leg strength, neuromuscular function from an agility run, vertical jump, the M-K test, and the 36.5 m dash. Men were significantly different than women on all anthropometric differences except for ectomorphy, and all power, strength, and neuromuscular tasks except reaction time. The anthropometric differences were significantly related to anaerobic performance: body mass, lean body mass, and thigh circumference impacted the performance on the vertical jump. Leg strength in men was a more important factor in the vertical jump than women. In the study done by Hoffman and Kang (2002), male athlete participants were overall taller and heavier, and had a larger peak power (W and W/kg) and mean power (W and W/kg) than female athlete participants.

The amount of exercise and the type of exercise have been found to have an effect on tongue strength and endurance (VanRavenhorst-Bell, Coufal, Patterson, & Mefferd, 2018). In this study, 45 active men and women between the ages 19-29 years of age who performed resistance training (weightlifting) or endurance training (running) at least 4 days a week were included. Hand-grip strength and cardiovascular endurance were recorded as measures to ensure athletes were one of the two. Weightlifters had more grip strength, whereas, runners had higher cardiovascular endurance. Tongue strength was measured by having participants complete the IOPI system by pushing a bulb against the roof of their mouth as hard as they could for 1-2 seconds with each region of their tongue. Tongue endurance was measured by using 50% of their strength to push the bulb against the roof of their mouth for as long as they could, while maintaining a consistent pressure against the bulb. Results concluded that tongue strength was higher in weightlifters, while tongue endurance was higher in runners (VanRavenhorst-Bell et al., 2018). This difference between athletes could be due to the difference in muscle composition between weightlifters and runners. Athletes who excel in strength training may have more Type II muscle fibers which improves strength and speed, whereas athletes who pursue endurance exercise may have more Type I muscle fibers which has a lower rate of fatigue (VanRavenhorst-Bell et al., 2018).

Vocal Function Tasks

Of the vocal function tasks that are most commonly used clinically and in research, three tasks emerged as potentially useful to quantify vocal power. These three voice function assessments include laryngeal diadochokinesis (LDDK), straw phonation, and sustained phonation. With adaptations, each of these measures provides a unique parameter that may support measurement of vocal power. Minor adjustment to the typical manner in which these vocal function tasks are quantified, at modal speaking fundamental frequency and sound level, may provide a resistance at the level of the larynx that mimics the resistance loading and rapid acceleration aspects of whole body anaerobic power tests.

Laryngeal Diadochokinesis

Diadochokinesis (DDK) in a motor speech assessment is the rapid production of phonemes requiring typical motor coordination. A laryngeal DDK, or LDDK, measures the coordination of the intrinsic laryngeal muscles by repeating either "/ʌ/" or "/hʌ/" as fast and precisely as possible in a single breath (Ptacek, Sander, Maloney, and Jackson, 1966). LDDK measures laryngeal function by testing the rapid movements of the laryngeal muscles during adduction (closing) and abduction (opening) of the vocal folds. These maneuvers are implemented in rapid succession for the laryngeal role as an articulator in connected speech. The tasks, "/ʌ/," a voiced vowel sound that requires the adduction of the vocal folds and "/hʌ/," a voiceless-to-voiced phoneme sequence, requires rapid adduction-abduction of the vocal folds at the fastest rate with the most clarity possible. The difference between the two LDDK tasks is the manner in which the larynx is physiologically entrained. With one task assessing rapid production of /ʌ/, it is speculated by Ptacek, Sander, Maloney, and Jackson (1966) that producing the glottal vowel in isolation causes the vocal folds themselves to act as articulators by initiating and terminating the sound. According to Canter (1965), testing /hʌ/ may create a continuous stream of air that requires greater laryngeal function to compensate, making this a more valid measure of laryngeal function. While there are some studies that use only /ʌ/ (Fung et al., 2001; Gartner-Schmidt & Rosen, 2009; Leeper & Jones, 1991; Ptacek et al., 1966) and some that only use /hʌ/ (Canter, 1965; Renout, Leeper, Bandur, & Hudson, 1995; Shanks, 1966), the most recent studies on LDDK performance use both tasks (Gratzmiller, 2012; Howse, 2016; Hynson, 2014; Mack, 2015; Yates, 2015).

Traditionally, LDDK measures have been used clinically to determine neurological disorders such as Amyotrophic Lateral Sclerosis (ALS) and Parkinson’s disease, as well as other vocal pathologies. There are a few studies that report rate and consistency of LDDK measures that correlate between male, female, pediatric, and geriatric differences. One study done by Lombard and Solomon (2019) examined LDDK rates using the syllables /ʌ/ and /hʌ/ across the lifespan. Out of 404 men and women between the ages of 20 and 89, the largest differences in LDDK rate were seen between the youngest and oldest age groups. No differences were observed between the sexes (Lombard & Solomon, 2019). These differences were thought to be due to the typical aging seen in older adults, including the neuromuscular and structural laryngeal changes, increasing risk of ossification in laryngeal joints, and increasing collagen fiber types, all affecting the flexibility and speed of vocal fold movement (Lombard & Solomon, 2019).

In a study by Renout, Leeper, and Bandur (1995) subjects who had confirmed diagnoses of ALS volunteered to be evaluated over an 18-month period to compare LDDK measures. The volunteers were asked to use their “habitual” voice while testing. Periodicity of LDDK and pattern of LDDK were studied to “examine the changes in motor control of vocal fold diadochokinetic characteristics during production of the syllable ‘/hʌ/’ for two subgroups (bulbar and nonbulbar) with ALS during progression of the disease processes” (Renout, Leeper, & Bandur, 1995, pg. 76). Within the bulbar group, the subjects had a reduced rate and periodicity than the nonbulbar group. Overall, the study provided evidence for the progressive speech deterioration that occurs in patients with ALS. Over the course of the 18-month period, there was an overall reduced rate and aperiodic production of LDDK. Renout, et al. (1995) stated that LDDK measures could be used for early detection of deterioration in the speech system of patients with ALS. Parkinson’s disease is a disorder of the basal ganglia and affects control of movement and results in a tremor. This disease may result in a decrease in strength of LDDK measures and difficulty in adduction of the vocal folds for a glottal stop (Verdolini, 1997; Verdolini & Palmer, 1997).

Spasmodic dysphonia and unilateral vocal fold paralysis were evaluated through LDDK measures as well. LDDK served as a measure of spasmodic dysphonia severity when determining effect for the treatment of Botox® (Boutsen, Cannito, Taylor, & Bender, 2002). Verdolini and Palmer (1997) concluded that LDDK performance on patients who had unilateral vocal fold paralysis showed decreases in rate and rhythm. A unilateral vocal fold paralysis would not allow for the complete adduction of the vocal folds, creating a problem in producing utterances “/ʌ/” and “/hʌ/” to obtain valid measures of LDDK performance. Any pathology of the vocal fold, including nodules or polyps, could result in dysphonia and breathiness caused by incomplete closure of the vocal folds, both of which would affect the quality of the voice during vocal function tasks (Stemple, Roy, & Klaben, 2014). Even vocal fatigue will reduce the quality of voice and loss of endurance, which will impact vocal performance (Stemple et al., 2014). Acquired laryngeal disorders may be a result of intubation during surgery, creating a granuloma on the vocal folds, or a traumatic blow to the head or neck, resulting in damage to the structure of the larynx, both impacting LDDK performance (Hixon, Weismer, & Hoit, 2014).

To date, little has been published correlating forced vital capacity (FVC) and anaerobic power measures to LDDK performance. LDDK, with its rapid acceleration component, may be a useful vocal function task to indirectly quantify anaerobic muscle activity of the intrinsic laryngeal skeletal muscles. To best understand the usefulness of LDDK performance as a measure of vocal aptitude for production of vocal power, correlations of pulmonary function and anaerobic power with LDDK may be useful.

Straw Phonation

In the realm of voice habilitation and rehabilitation, straw phonation, as a semi-occluded vocal tract exercise has been used to improve vocal quality and encourage the feeling of resonant voice (Maxfield et al., 2016; Tangney et al., 2019; Mills et al., 1997; Andrade, et al., 2016). Straw phonation creates an optimal environment for sustained oscillation by decreasing PTP and by causing an impedance in the airway which increases positive reactance that has an inertive component that facilitates oscillation (Tangney et al., 2019; Mills et al., 1997). The diameter of the straw and how it changes the occlusion, or resistance, was studied by many scholars (Tangney et al., 2019). These studies examined the influence of straw diameter on PTP when these straws were used as a semi-occluded voice task. The results of a study on canine cadavers by (Tangney et al., 2019) indicated that the 3mm diameter straw, what speech pathologists consider is the most impactful diameter for voice rehabilitation (Titze, 2006), made it almost impossible for phonation to be achieved (Tangney et al., 2019). These results were inconsistent with clinician reports of efficacy. The 9mm, 15mm, and 21mm diameter straws produced higher PTP measures, requiring more force at the vocal folds to start and sustain phonation (Tangney et al., 2019).

Maxfield, et al. (2016) discussed the differences in intraoral pressures produced via multiple semi-occluded voice exercises, with differing straw diameters being one of the parameters. This study indicated that smaller diameter straws (3.5mm wide and 14.1cm long) were most consistent in producing intraoral pressures that maximized vocal efficiency for both males and females than larger diameter straws of 6mm wide and 19.5cm long (Maxfield et al., 2016). Phonating through a straw in water created even more intraoral pressures (Maxfield et al., 2016).

Although a smaller straw had more intraoral pressure than the larger drinking straw, the differences in length may have altered resistance to the airway. In a study that examined the pressure/flow relationships between different straw lengths, more pressure (cmH2O) was required to eject air (bubbles) from longer lengths of straws (Andrade et al., 2016), with the longest straw being 15cm. In another study comparing tube lengths of 7.5cm, 15cm, and 30cm, with diameters of 2cm, it was hypothesized that a longer straw would equate to more efficient vocal economy (Mills et al., 1997). Based on the results after many conditions of short and long treatments with straw phonation exercises this study determined that straw length had an effect on measurement of voice perception and function. For example, after increasing the length of the phonatory task, participants reported feeling more tired with the shorter straw than the longer straw (Mills et al., 1997). In the study done by Tangney et al., (2019) PTP measures were obtained based on varying lengths of straws, which indicated higher PTP measures for longer straws of 50 and 75cm.

Based on the current literature on straw phonation exercises, longer and smaller diameter straws will create the highest PTP required for generation of phonation. When producing this much pressure, the voice may come through the straw louder than they usually speak. This task is typically done at the individual’s modal fundamental frequency; however, it could be hypothesized that straw phonation performed at higher fundamental frequencies and at higher sound level would likely result in higher phonation threshold production. Production of a louder voice through straw phonation with a high fundamental frequency may be a means to quantify vocal power due to the larger PTP measure needed to produce phonation through a straw.

Sustained Phonation

The most widely used vocal function task, sustained /a/, is used to acoustically assess fundamental frequency, cepstral peak prominence and other perturbation measures (Patel et al., 2018). Sustained phonation can and is used as a tool to detect laryngeal pathologies and hoarseness (Kitajima & Gould, 1976).

This task is typically done at the individual's modal fundamental frequency; however, production of this task at 80% of the semitone range and the loudest sound pressure level possible could be useful as a measure of acoustic power production. Production of a prolonged sound at a high frequency and sound level will require more subglottal pressure and laryngeal resistance, which could work as the resistance component for anaerobic entrainment of the intrinsic laryngeal skeletal muscles.

Physiologic Aspects of Vocal Power

To better understand what vocal function tasks assess, a review of the anatomy and physiology of laryngeal function is needed. The larynx is a structure comprised of cartilages and muscles that connects the oral cavity, which is superior to the larynx, to the lungs located inferiorly to the larynx. These structures comprise the three subsystems of speech: respiration, phonation, and articulation/vocal tract tuning (Stemple et al., 2014). The respiratory system provides the breath supply and subglottic pressure to oscillate the vocal folds and produce speech sounds. The construct of vocal power is complex and may be influenced in three ways: greater lung compression to increase subglottal pressure, increasing force of vibration at the source of the vocal folds due to the higher subglottic pressure, and vocal tract tuning.

Lung volumes drive the phonatory system. Without sufficient air support from the lungs, voicing would not occur. In the study done by Croake et al. (2019), group 1 participants had a positive correlation between lung volume initiation/termination measures and P_s indicating that these participants rely on their respiratory system as the driving force for phonation. The breathing apparatus contributes to dB SPL, frequency, linguistic emphasis or stress, and the segmentation of speech units (Hoit & Weismer, 2018). To speak at a habitual dB SPL, a steady P_s around 8 cmH_2O is maintained by generating negative pressures through checking action using the inspiratory muscles and laryngeal controls. As the capacity of the lungs decrease during the utterance (typically below 40-50% capacity), and relaxation pressure is less than subglottal pressure, the expiratory and abdominal muscles may activate to generate positive pressure to maintain the required P_s at 8 cmH_2O needed for phonation (Hoit & Weismer, 2018). However, for speaking at a loud sound level, the participant will need a larger amount of air to support the phonatory system. Louder speech is initiated at larger vital capacities than soft speech, and higher P_s values are required and maintained by expiratory and abdominal muscles by generating more positive pressure (Hoit & Weismer, 2018). Lung volumes will differ with different people according to their age, sex, ethnicity, weight, and height. For example, it may be more difficult for a shorter person than a taller person to achieve greater lung volumes due to the smaller chest cavity.

Laryngeal biomechanics may also contribute to vocal power. The larynx is composed of intrinsic muscles that allow the vocal folds to close (adduction) for protection and vegetative functions (swallowing and cough clearance) or open (abduction) for resting breathing. The larynx has extrinsic and intrinsic muscles to provide flexibility and movement within and surrounding the larynx. Intrinsic muscles are attached within the larynx and include functions such as repositioning cartilage that house the vocal folds, change the length, tension, and shape of the vocal folds, and increase/decrease glottic space between the vocal folds (Stemple et al., 2014). The cricothyroid is a muscle that attaches from the cricoid to the thyroid, decreasing distance between these two cartilages, while also creating tension within the larynx and increasing stiffness of the vocal fold, and is a primary contributor to fundamental frequency control, especially in higher frequencies (Hirano, 1981; Kirchner, 1984; McHenry, Kuna, Minton, Vanoye, & Calhoun, 1997; Noordzij & Ossoff, 2006; Tucker, 1987).

To sustain self-oscillatory properties of the vocal folds, three phenomena must occur: glottal asymmetry, transfer of energy, and pressure differences. The intrinsic muscles of the larynx provide the glottal shapes, while subglottic pressure drives the oscillatory motion. When a person is in the pre-phonatory phase, their lateral cricoarytenoid and interarytenoid will approximate the vocal folds by way of the arytenoid cartilages rocking down and in, adducting the vocal folds. The interarytenoid draws the medial walls of the arytenoid cartilage together. The lateral cricoarytenoid then fine-tunes the laryngeal adductory posture (Hirano, 1981; Kirchner, 1984; Noordzij & Ossoff, 2006; Stemple et al., 2014; Tucker, 1987). The subglottal pressure created by laryngeal approximation and egressive airflow from the lungs will start the vibratory motion as pressure builds under the approximated vocal folds. Larger inspiratory volumes support higher subglottic pressure and a more powerful voice.

The thyroarytenoid is composed of two muscular compartments, the thyromuscularis, which is thought to contribute more to vocal fold adduction because it has fast-twitch fibers, and the thyrovocalis which is thought to exert greater control over phonation (Saunders, Han, Wang, & Biller, 1999; Stemple et al., 2014). The thyromuscularis muscle is the main body of the vocal fold and contributes to tonicity, stability, and mass as it contracts and relaxes. The thyrovocalis influences the glottal shape and closure pattern as it shortens and thickens the vocal folds (Stemple et al., 2014). The thyroarytenoid is an important muscle for vocal performance because it provides laryngeal control and participates in the self-oscillatory nature of vocal fold vibration. As the vocal folds converge in an adducted position, elastic and inertial properties act on the vocal folds to create positive lateral intraglottal pressure and outward net velocity. After being overcome by elastic properties, the vocal folds drive back toward the midline with inward net velocity and a reduction in lateral intraglottal pressure relative to the airway. Subglottal pressure builds up again as the vocal folds diverge in an adducted position, starting the cycle over and over again. Due to senescence or a vocal pathology, the body of the vocal folds could be impaired, creating difficulty in providing sufficient closure for building enough subglottal pressure for clear voice quality, sufficient loudness, and adequate self-oscillatory support for the vocal function tasks.

The third way to increase vocal power would be to tune the vocal tract. Each individual is made with a different shape or area of the vocal tract, creating different resonances or voices for each person (Story, 2006). Some singers, as the sopranos in a study done by Garnier, Henrich, Smith, and Wolfe (2010), used a technique as simple as increasing their mouth area to sing higher frequencies, while other sopranos use that technique for their entire range. Using a more resonant voice will not only clarify phonemes and improve overall communication, but will also add to vocal efficiency and dB SPL (Wolfe, Garnier, & Smith, 2009). Classical singers are trained to have a “ringing” vocal quality to be heard clearly over music and to reach everyone in an audience. This skill was studied by Omori, Kacker, Carroll, Riley, and Blaugrund (1996) by comparing spectrum and perceptual analyses in singers and nonsingers to determine a way to characterize the “ringing” in the singers’ voices. The study concluded that the singing power ratio was greater in singers than nonsingers, years of training had a significant effect on singing power ratio, and as the power ratio increased, the perceptual score of “ringing” or rich voice quality also increased.

Factors That Affect Voice Function

Many physiological factors may directly influence vocal function. These physiologic variables include but are not limited to: pulmonary diseases, structural differences due to laryngeal trauma, desiccation of the laryngeal epithelium, trained coordination of the voice, age and sex differences, and pulmonary function.

Pulmonary diseases such as chronic obstructive pulmonary disease (COPD) or asthma will irritate healthy lung tissue, thereby obstructing airflow and reducing inspiratory and exhalatory gas exchange. COPD and asthma create difficulty obtaining a full breath to produce prolonged utterances and proper airflow control in producing utterances during vocal function tasks (Stemple et al., 2014). Pulmonary disease also would impact the forced vital capacity measures.

Structural differences in the larynx that could affect a person’s laryngeal function may be due to laryngeal trauma or neurologic etiology. Trauma to the larynx and vocal folds causes injury to the cartilages that make the framework of the larynx or the soft tissues. Internal trauma to the larynx includes exposure to toxic chemicals, hypersensitivity to airborne irritants, or throat pain. Short term symptoms include pain, inflammation, ulceration of the posterior laryngeal mucosa, and granulomas. Long term symptoms include scarring, glottic web formation, and stenosis (Stemple et al., 2014). External trauma such as blunt force or penetrating wounds also injure cartilages and soft tissues. Depending on the area in which the trauma resides, arytenoid dislocation can occur. Arytenoid dislocation or subluxation most commonly is misdiagnosed with a recurrent laryngeal nerve paralysis and includes symptoms of reduced vocal cord mobility and arytenoid edema (Hoffman, Brunberg, Sullivan, Winter, & Kileny, 1991). Unilateral or bilateral vocal fold paralysis secondary to surgical intervention, neuromuscular disease, or brain injury may also alter laryngeal biomechanics and influence the ability to produce sufficient subglottal pressure.

Hydration of the vocal folds is very important for laryngeal function. Usually, hydration is used for treating voice disorders by recommending to increase fluid intake, and to create a more humid environment (Verdolini, Titze, & Fennell, 1994). In a study done by Verdolini et al. (1994), the relationship between hydration levels and phonatory efforts were assessed by providing each subject a 4-hour hydration treatment, a 4-hour dehydration treatment, and a 4-hour placebo treatment. After each treatment, a measure of phonatory effort, phonation threshold pressure (PTP), and direct magnitude estimation of perceived phonatory effort were taken. PTP was obtained through the laryngeal airway resistance task at the individual’s softest sound level they could produce. The study tested if hydration level affected viscosity of the vocal folds and if PTP was directly proportional to the viscosity changes. Results for PTP were highest following dehydration conditions and lowest following hydration conditions, while perceived effort was greatest following dehydration conditions and lowest following hydration conditions. However, these measures were pitch dependent; at low pitches, PTP changes from dry to wet conditions were small, but at high pitches, PTP changes were varied by 21%. The same results for perceived phonatory effort were concluded, that perceived effort changes from dry to wet environments was more sensitive at high pitches than at low pitches.

Tanner et al. (2016) conducted a study to examine effects of environmental humidity manipulation on the voices of men by observing PTP after nasal and oral breathing tasks. The study used a double-blind, within-subjects crossover design where 20 men (10 singers, 10 nonsingers) performed a 30-minute desiccation challenge transorally and nebulized 3-9ml of isotonic saline through a mister. Immediately after desiccation and at the 5, 35, and 65-minute mark after nebulization, the following measures were taken: PTP, cepstral spectral index of dysphonia (CSID), vocal effort, mouth dryness, and throat dryness measures. Results indicated that for speaking and singing vocal effort, mouth and throat dryness, and CSID increased significantly after the desiccation of mouth breathing in medical grade dry air. PTP differences were found to be insignificant after desiccation, findings consistent with those of Sandage, Connor, and Pascoe (2014). Work from Sandage et al. (2014) hypothesized that drier air and mouth breathing would drive PTP and perceived phonatory effort (PPE) measures higher, while higher humidity and nose breathing would facilitate lower PTP and PPE measures. These hypotheses were not evidence supported and the authors postulated that this may have been due to the upper airway epithelium compensating for airway surface liquid water loss with water vapor that largely saturates every expired pulmonary volume. Humidity and superficial viscosity may influence LDDK production given that there is other evidence that it affects other laryngeal function measures such as PTP. However, there is other evidence that contradicts the thought that humidity will influence laryngeal function to some degree due to healthy lungs and homeostasis.

Voice training may have an impact on laryngeal function. Singers are known to be vocal athletes in the sense that they are trained to have higher phonatory agility, stamina, and strength (Gunjawate, Ravi, & Bellur, 2018). In the work done by Tanner et al. (2016), the effects of laryngeal desiccation were analyzed for singers versus non-singers. At baseline, before desiccation, singers only had lower values for CSID vowels than nonsingers. After desiccation, the study concluded that the male trained singers reported a lower mean value for speaking vocal effort, CSID for sustained vowels, PTP and a smaller magnitude of throat dryness than nonsingers. Given that PTP requires fine-motor control of laryngeal function for the task, it may be hypothesized that these findings suggest a training effect for laryngeal motor control and an upregulation of upper airway surface liquid maintenance in the singers.

In another study examining the differences in vocal fold length in classical singers, relating to body mass and height, computed tomography revealed a positive correlation between body mass and height of the singer (Claros et al., 2019). Differences in vocal fold length were also seen between the types of singers (tenor, alto, soprano, etc.), where the soprano singers had the shortest vocal folds with a mean of 17.03 mm, and bass singers had the longest vocal folds with a mean of 25.17 mm (Claros et al., 2019). These differences in length between singer types also create different vocal ranges (Claros et al., 2019). The sopranos were found to have the broadest vocal range, whereas the bass singers had the narrowest (Claros et al., 2019). Vocal fold length was also found to change based on BMI and height of the singer. Taller and larger men were found to have longer vocal folds, whereas shorter and smaller women had shorter vocal folds (Claros et al., 2019). Therefore, individual factors such as singing ability, BMI, height, and gender have an effect on vocal fold length.

Pulmonary function could also change laryngeal function. Speech breathing is different for people of different sizes and shapes, age, and sex. Between endomorphic (relatively fat) and ectomorphic (lean) men, speech breathing was studied (Hoit & Hixon, 1986). The endomorphic men kept the abdominal wall held inward farther and tended to move the abdominal wall a greater distance than ectomorphic men during speech breathing. The diaphragm is also positioned differently in these two types of men. A large abdomen pulls down the diaphragm and shortens its muscle fibers, thus making the diaphragm have a disadvantage for generating inspiratory forces (Hixon et al., 2014). However, the ectomorphic man with a flat abdomen, the diaphragm maintains its dome shape and elongated muscle fibers, to achieve ultimate inspiratory force (Hixon et al., 2014). An older person will usually waste air when they speak, use more of the vital capacity, and expel more air per syllable (Hixon et al., 2014). Before puberty, speech breathing between boys and girls is typically the same; after puberty, the lung volumes for speech breathing are larger in boys than in girls because boys are typically taller than girls (Hixon et al., 2014).

Differences in Age and Sex that Affect Laryngeal Function

There are biological differences between age and sex that play a role in laryngeal function and therefore, may influence vocal function. The anatomy between men and women differ and these differences are further delineated through the lifespan. The discussion below will explain the natural biological changes that span adolescence and senescence.

During childhood, the anatomy of the larynx of boys and girls are very similar. But, when children go through puberty the body changes, including the larynx. The boys develop a “chest” voice as a secondary characteristic during adolescence, as their fundamental frequency drops an octave lower due to the thickening and lengthening of the vocal folds (Hixon et al., 2014). Men also have a more prominent angle of the thyroid notch at 90 degrees. This shift in the structure of the male larynx increases the length of the vocal folds, causing a decrease in pitch. An increase in length of the vocal tract to 16.9 cm in males and 14.1 cm in females also contributes to the lowering of fundamental frequency after puberty (Goldstein, 1980; Markova et al., 2016).

The layer structure of the vocal folds also changes with puberty. As a newborn, the vocal folds are seen as a uniform structure containing no vocal ligament, layer structure, or Reinke's space and has an incomplete extracellular matrix consisting of collagenous, reticular and elastic fibers, glycoprotein and hyaluronic acid (Sato, Umeno, & Nakashima, 2010). In relation to the complete adduction of the vocal folds, men usually demonstrate full approximation of the vocal folds during voice production whereas, women usually leave a small space to create a spindle-shaped opening that results in the typically perceived breathy voice of a woman (Hixon et al., 2014). Men may experience more voice change as a function of age than women because there is an increase in fundamental frequency that is attributed to muscle atrophy, thinning of the lamina propria, and general loss of mass (Hirano, Kurita, & Sakaguchi, 1989; Hixon et al., 2014; Kahane, 1987; Segre, 1971).

The structure of the larynx also changes with age, also known as presbylaryngis, or "old larynx." Hyaline cartilage in the larynx begins to ossify, becoming stiff and brittle and causing some joint problems at the cricoarytenoid complex. Movement in the cricoarytenoid joints decrease in the geriatric population, which can limit the degree to which the vocal folds can be approximated (Hixon et al., 2014; Kahane & Fujimura, 1988). Nerve fiber loss and muscle atrophy in the vocal folds and surrounding structures lead to loss of mass in the vocal folds, or bowing, and loss of endurance (Aronson, 1990; Cooper, 1990; Ferreri, 1959; Hixon et al., 2014).

The bowing of the vocal fold occurs because the loss of muscle tissue is made up by the gain of connective tissue and changes the structure of the lamina propria. This loss of mass creates the incomplete closure pattern during phonation which increases breathiness, hoarseness, and loss of vocal intensity (Lenell, Sandage, & Johnson, 2019; Linville, 1996; Lundy, Silva, Casiano, Lu, & Xue, 1998). Old age may have an impact on vocal performance because of these changes; however, decreased pulmonary function might also influence performance and will be discussed later.

Fundamental frequency changes throughout the lifespan for both men and women. When women go through menopause, there is a lowering of fundamental frequency in women (Hixon et al., 2014; Meurer, Garcez, von Eye Corleta, & Capp, 2009; Pisanski, Bhardwaj, & Reby, 2018). The menstrual cycle and contraceptive method may influence laryngeal function. By taking a cytological smear of the vocal folds, similar to the cervical smear, receptors for the hormones estrogen and progesterone were found on the vocal fold epithelium (Amir, Biron-Shental, & Shabtai, 2006). During the menstrual cycle, estrogen could cause mucosal hypertrophy and proliferation, while progesterone counteracts the effect of estrogen and could cause a decrease in mucus secretions and thickens the secretions (Amir et al., 2006). Estrogen increases before ovulation occurs around the 14th day of the cycle, where there is a significant decrease in estrogen and an increase in progesterone until menstruation occurs (Amir et al., 2006). Symptoms of hormonal levels across the menstrual cycle include vocal fatigue, reduction in the intensity range, and a decrease in frequency and amplitude stability, and can be called a vocal premenstrual syndrome (VPMS) (Abitbol, Abitbol, & Abitbol, 1999; Amir et al., 2006; Meurer et al., 2009). With a contraceptive pill, women do not have traditional menstrual cycles and instead a steady hormonal climate is created which could reduce the symptoms of VPMS

(Amir et al., 2006). Another reason why women's fundamental frequency lowers the older they become is because of the increase in edema that is proposed to be secondary to loss of estrogen with menopause (Ferreri, 1959; Hixon et al., 2014; Honjo & Isshiki, 1980). Men also undergo hormonal changes that could influence the quality and frequency of the voice. After the age of 30, testosterone in men decrease 1% per year, which could lead to the thinning of the vocal folds and bowing (Lenell et al., 2019; Matsumoto, 2002; Mueller, Sweeney, & Baribeau, 1985; Tanaka, Hirano, & Chijiwa, 1994). The thinning of the vocal folds may cause a higher fundamental frequency, while the bowing of the vocal folds can cause more breathiness heard in men (Brown, 1991; Gugatschka et al., 2010; Lenell et al., 2019).

More studies have been done to compare LDDK measures between the sexes to account for strength of production. Howse (2016) conducted research to obtain normative data to analyze strength of LDDK performance between male and female participants, if there was a difference in the strength of adductory and abductory tasks, and if there was a difference in normative values of strength of LDDK performance between men and women of ages 40-59 years. Strength of the adductory and abductory tasks were defined by decibel (dB) magnitude using the Kay Pentax Multidimensional Voice Program (MDVP) software, with higher dB measures indicating higher strength. The study described no statistically significant decibel difference between the strength of LDDK performance between the production of "/ʌ/" and "/hʌ/" (Howse, 2016) The results of the analysis of strength of LDDK performance were that the normative decibel values for adult men were between 44.34-70.13 for the production of "/ʌ/", 38.99-70.96 for "/hʌ/", and for adult women were between 39.29-68.85 for "/ʌ/" and 40.62-66.51 for "/hʌ/" (Howse, 2016). The gap within the range of strength of LDDK performance could be because the factor of hydration was not considered, which could cause the vocal folds to have superficial dryness and a loss of easily gliding and sliding. Another factor that could cause the gap is the phase of the menstrual cycle of the women who participated. Depending on where the women were in their menstrual cycle, their vocal quality and amplitude stability may decrease. Also, if the participants had prior voice training, they might be trained to have neuromuscular control over their breathing and laryngeal muscles during singing (Gunjawate, Ravi, & Bellur, 2018).

Factors that affect Pulmonary Function

The lungs provide the breath support and subglottal pressure for humans to phonate. Vital capacity is the sum of the inspiratory reserve volume, tidal volume, and the expiratory reserve volume. It is the amount of air a person can forcefully exhale out of the lungs after a maximum inhalation and is measured with a spirometer. Spirometry is a diagnostic assessment that measures how an individual inhales or exhales air as a function of time relative to volume and provides measures of forced vital capacity (FVC) and forced expiratory volume in one second (FEV1; Miller et al, 2005). Volume differences in forced vital capacity vary according to the following variables that are used in automated spirometry to determine predicted FVC and FEV1: height, weight, sex, age, and ethnicity.

The height of a person will have an effect on pulmonary volumes due to the room in the chest cavity. Total lung capacity, vital capacity, residual volume, FVC, and FEV1 are affected by height which means that a taller individual may experience a greater decrease in lung volumes as they get older (Barroso, Martín, Romero, & Ruiz, 2018). In a study done to determine the relationship between height and lung volumes in men, lung volumes correlate to the metric calculation of height cubed, e.g., $182cm^3$, since the body is three-dimensional and on a logarithmic scale (Hepper, Fowler, & Helmholz, 1960). The men who participated in this study were between the ages 21-44 years old to eliminate the effects of aging, with a height range from 120-206 centimeters. Vital capacity and total lung capacity measures were obtained in relationship to height, resulting in a cubic power of height. This study used a larger range of differing height than previous studies done by Hepper et al. (1960) so the previous claim a linear relationship between lung volumes and height was challenged.

The weight of an individual can also cause differences in pulmonary volumes. The passive forces in respiration include gravity, elastic recoil, and rib torque. With a heavier person, gravity will have a greater force against the inspiratory forces. This will cause the person to use more inspiratory effort when breathing. Obese men between the ages 46-80 who participated in a weight loss program who lost 21% body fat, waist circumference by 8%, waist-hip ratio by 2%, and fat-free mass by 3% resulted in a 3% increase in FVC, a 5% increase in total lung capacity, and a 18% increase in functional residual capacity, and an 8% increase in residual volume (Womack et al., 2000). In a study on obese children, when compared with the predicted values for sex, height, and body surface, decreases were found in expiratory reserve volume, forced respiratory volume in 1 second (FEV1), forced expiratory flow between 25-75% of vital capacity, and diffusing capacity (Inselman, Milanese, & Deurloo, 1993). Because these children were obese, they had altered pulmonary function, characterized by reductions in diffusing capacity, ventilatory muscle endurance, airway narrowing that may result from decreases in alveolar surface area relative to pulmonary volumes (Inselman et al., 1993).

Pulmonary differences between sexes would result in very different forced vital capacity measures. These differences include smaller vital capacity, reduced airway diameter, and a smaller diffusion surface than age- and height-matched men (Harms, 2006). The reproductive hormones in women such as estrogen and progesterone can also influence pulmonary function during exercise (Harms, 2006). During the menstrual cycle, progesterone may reduce the airway diameter during exercise, causing limitations in flow (Harms, 2006; McClaran, Harms, Pegelow, & Dempsey, 1998). Estrogen increases fluid absorption and blood volume, which may affect diffusing capacity (DLCO) in the lungs (Harms, 2006; Sansores, Abboud, Kennell, & Haynes, 1995). Respiratory muscle strength has also been noted as a difference between men and women. In a study done by Leutzinger et al. (2018), sex differences in lung size, body composition, muscle mass, and muscle fiber composition were thought to cause these differences in respiratory muscle strength. FVC and FEV1 measures showed no significant difference between women and men (112+/-14% vs. 105+/-15%; 92+/-12% vs. 93+/-13%), but maximum inspiratory and expiratory pressure values were lower in women than in men (68+/-16cmH$_2$0 vs. 88+/-19cmH$_2$0; 69+/-13cmH$_2$0 vs. 94+/-17cmH$_2$0).

Because of maturation, children and adults differ in many ways physiologically. One of these differences is pulmonary volumes. Around age 20-25 years, alveolar dead space increases and respiratory muscle strength decreases (Sharma & Goodwin, 2006). FVC and FEV1 decrease with age while volumes and capacities like residual volume and functional residual capacity increase (Barroso et al., 2018). The entire respiratory system requires lung and chest compliance as pressure influences lung volumes during breathing (Sharma & Goodwin, 2006). With aging, osteoporosis reduces the height of the thoracic vertebrae, reducing the ability of rib cage expansion during breathing. The results of their study of effects of aging on the respiratory system concluded that air space, functional residual capacity, and residual volume increased with age. On the other hand, chest wall compliance, total respiratory muscle strength, FEV1, FVC, vital capacity, and diffusing capacity of carbon monoxide decreased with age.

Variation in FVC attributed to phenotype has been taken into consideration as well. Miller, Ashcroft, Swan, and Beadnell (1970) examined the differences in lung volume among various ethnic groups due to anthropomorphic variations. A similar study was done by Rossiter and Weill (1974), for a group of male cement workers who demonstrated marked differences in pulmonary function attributed to ethnic differences in height. Anthropometric evidence described individuals of Caucasian-European descent as having a larger chest cavity and volume at full inspiration than people of African descent and Indians. Differences in total lung capacity, vital capacity, forced vital capacity, forced expiratory flow rate and alveolar volume were found between Caucasians and men of African descent. African men were found to have a larger vital capacity than Indian men in Guayana. Both studies excluded people of mixed ethnic origin and analyzed the differences in lung function relative to age and height (Rossiter and Weill, 1974).

Differences in pulmonary function between Asian Americans and European Americans were also studied by Korotzer, Ong, and Hansen (2000). Asian Americans were defined as Asian if both parents and grandparents were born in eastern Asia (China, Korea, Vietnam, Japan, & Philippines), while European Americans were defined as European if both parents and grandparents were born in either the United States or in a country in western/eastern Europe. The participants were nonsmokers and had no history of lung or heart disease and performed the FVC and FEV1 task seated. Variables other than ethnicity were taken into consideration, with height, ethnicity, and sex being the most influential variables in this study. FVC and FEV1 values were significantly lower in Asian Americans than European Americans, even when controlling for height and age.

Other Factors that Affect Pulmonary Volumes

A structural problem that could have an effect on breathing might be scoliosis. If the chest cavity isn’t aligned properly, then the lungs may not have room to expand because of its association with gross motor impairment and other comorbidities (Blackmore et al., 2016). A thesis was written about the effects on pulmonary function using FVC due to smartphone use on children’s upper posture among boys and girls around ages 8-13 and were assigned either to an addicted group or non-addicted group based on their scores on the Smartphone Addiction Scale Short Version (Alonazi, 2017). Concerns have been made due to constant neck flexion, neck movement limitation, and decreases in pulmonary function because of the changes in spinal posture. The results of the study showed that FVC and FEV1 were significantly lower in addicted boys than non-addicted boys due to limited cervical range of motion and maximum inspiratory pressures to measure muscle strength was significantly lower in addicted girls than in non-addicted girls (Alonazi, 2017).

Other postural conditions such as kyphosis and osteoporosis occurring in the older population will have an effect on pulmonary volumes and function. In a systematic review done on the relationship between osteoporosis and kyphosis on pulmonary function, four case studies were included that reported reductions in forced vital capacity ranging from 68-94% of their predicted values (Harrison, Siminoski, Vethanayagam, & Majumdar, 2007). This systematic review provided evidence that osteoporosis related kyphosis has a negative effect on pulmonary function. The angle of the kyphosis also has an impact on the vital capacity. Angles over 55 degrees would result in a lower vital capacity. Declines in forced expiratory flows were noticed in women who had an osteoporotic fracture as well, and had an increased mortality rate of two to three times more from dying from pulmonary causes than women who did not have fractures. Severe kyphosis is a strong predictor of pulmonary death.

Smoking can cause many problems with the function of the lungs and could cause serious problems in breath support. The correlation of vital capacities between women smokers and nonsmokers was analyzed to provide effects of smoking on respiratory capacity (Awan & Alphonso, 2007). The participants in this study were 75 women of the ages 18-30, 45 of them being nonsmokers and 30 being smokers. This study defined smoking as any subject who had smoked at least 2 cigarettes a day for at least a year, and nonsmoking as any subject who had not smoked in the past 5 years. Vital capacity measures were taken with a digital spirometer. The conclusions of the study showed that there were significantly lower vital capacities in smokers vs. nonsmokers. This reduced respiratory capacity and control may be associated with increased bronchial reactivity to exposure of cigarette smoke, mild airway obstruction, increased glottal gap size during phonation, and increased vocal fold mass (Awan & Alphonso, 2007). A vocal fold pathology that may occur with smoking could be Reinke's edema. Symptoms of this pathology include increased mass due to swelling and lower fundamental frequency and a husky hoarseness (Stemple et al., 2014).

Asthma is a chronic pulmonary disease that effects over 300 million individuals (Kudo, Ishigatsubo, & Aoki, 2013). The disease typically develops during childhood due to over sensitization of inhaled allergens, which cause inflammation in the airway and reversible airflow obstruction (Holgate, 2012; Kudo et al., 2013). In a study to determine importance of airway thickening and narrowing in asthma, James, Hogg, Dunn, and Paré (1988) concluded that the airway walls were thickened by chronic inflammation and could be as important as airway smooth muscle contraction in determining responsiveness of allergens. However, new perspectives on how asthma effects lung function are examining factors like epithelial damage, inflammatory cells and mediators, and neural stimuli facilitating the response of airway narrowing (Papa, Pellegrino, & Pellegrino, 2014). Reversible airway smooth muscle (ASM) contraction is another important symptom of the disease and can be caused by two things such as myosin binding and plasticity (Kudo et al., 2013). ASM also contributes to the inflammatory mechanism, extracellular matrix turnover, and airway remodeling (Kudo et al., 2013). A correlation of lung volumes during speech tasks between 14 asthmatic patients and 10 healthy subjects was made in a study done by Loudon, Lee, and Holcomb (1988). The results of this study determined that the ratio of the FEV1 and FVC expressed in percentage was averaged at 80% in healthy subjects and 68.3% in asthmatic patients. Also, asthmatic patients started speaking at a higher vital capacity (41%) than healthy subjects (32%). The volume expired was separated into the volume used by speaking and the volume without speech. Asthmatic patients expired less volume during speech than healthy speakers, and more volume that did not contain speech than healthy speakers, which could be observed during conversation tasks. The asthmatic patients had slower inspiratory rate and a faster expiratory rate than healthy speakers. The explanation for these differences was assumed that asthmatic patients require their breath for respiratory rather than communicative purposes.

Each factor that negatively affects forced vital capacity measures may indicate a lower amount of vocal power.

Justification

Given that vocal power is a complex construct, an initial effort to determine anaerobic power capacity of laryngeal function may be initiated by correlating validated whole body anaerobic power tests developed in exercise science with vocal function tasks and lung capacity measures. The purpose of this study was to correlate a whole body anaerobic power measure with vocal function and lung capacity measures as a preliminary effort to develop a validated measure of vocal power. Vocal function measures were collected at a target frequency that represented 80% of the participants' semitone range and the highest sound pressure level that could be produced with comfort during the following tasks: maximum phonation time, LDDK, and phonation resistance (PR_{max}). It was hypothesized that 1) measures of whole body anaerobic power (Watts) would correlate with vocal function tasks that are characterized by a resistance component; 2) higher values for the adapted vocal function tasks will correlate with higher FVC; and, 3) the values of the first second of the adapted vocal function tasks will correlate more closely with the anaerobic power value (Watts) as a measure of peak vocal power.

Chapter II

Quantifying Vocal Power: Correlation of Whole Body Anaerobic Power to Vocal Function Measures

Introduction

Ecologically-valid methods to assess vocal fitness or aptitude for extensive voice work that is required for occupations such as teaching or fitness instruction have not been developed to date. At the present time, a standard objective voice assessment gathers data regarding vocal function that is typically limited to sustained vocal productions and production of brief standard reading passages (Patel et al., 2018). Extensive vocal function assessment that captures the features of voice that are required for extensive occupational voice use is not typical. In exercise science, fitness assessments for anaerobic performance and endurance performance have been in use for some time (Vandewalle et al., 1987). Performance assessments are used to determine fitness for a particular muscle performance (anaerobic) or cardiovascular (aerobic) performance goal. These assessments can be used to determine aptitude for power or endurance activity and, in doing so, can indirectly assess which bioenergetic pathways predominate for an individual. Performance on these fitness assessments are used to infer the skeletal muscle fiber complement of the individual. Given that there is an emerging body of literature addressing the probable bioenergetics pathways of the intrinsic laryngeal skeletal muscles, it is time to now consider a new approach to voice assessment that includes tasks that may better support our assessment of functional voice ability. This preliminary investigation used existing voicing tasks in a novel manner to determine if vocal function could be quantified methodologically to evaluate aptitude for extensive voice work and as an outcome measure for voice habilitation and rehabilitation.

The application of anaerobic exercise performance assessments to the quantification of vocal ability (power) is based on the theoretical construct that bioenergetics/muscle fiber complement of the larynx may be inferred from vocal performance tasks. Identification of vocal function tasks that rely predominately on the recruitment of Type II muscle fiber types for use against a resistance as an anaerobic performance measure could mimic exercise performance assessments. Sandage and Smith (2017) discussed the three primary bioenergetic pathways including the immediate energy system, glycolysis, and oxidative phosphorylation, and proposed that anaerobic metabolism may predominate for voice function. Type II skeletal muscles rely in part or whole on anaerobic sources for muscle fuel. A summary of cadaver intrinsic laryngeal muscle fiber complement described that the intrinsic laryngeal skeletal muscles used for adduction, tensing, and lengthening were predominately comprised of Type II muscle fibers (Sandage & Smith, 2017). Unlike Type I muscle fibers, which are phenotypically resistant to fatigue and rely on oxidative phosphorylation (oxygen) to produced muscle fuel, Type II muscle fibers are more fatigable and rely predominately on glycolytic or immediate energy bioenergetic pathways. Oxidative phosphorylation is initiated at the start of exercise but does not become the predominant bioenergetic pathway until after 2-3 minutes of exercise. Given the temporal constraints for duration of voicing in connected speech (Smith et al., 2017; Titze et al., 2003) and the rapid acceleration that is required for laryngeal articulation, it is likely that the intrinsic laryngeal skeletal muscles, except for the PCA, are more reliant on anaerobic metabolism from the immediate energy system and glycolysis, and less reliant on oxidative phosphorylation (Sandage & Smith, 2017).

Analyses of the extrafusal and intrafusal skeletal muscle fiber types of the interarytenoid (IA) muscle from laryngectomy specimens described that the IA had similar phenotypic features to those of limb skeletal muscle (Tellis, Thekdi, & Rosen, 2004). More specifically, the IA extrafusal muscles had elevated levels of glycolytic metabolites rather than oxidative metabolites, indicating the use of anaerobic metabolism (Tellis et al., 2004). These findings support the hypothesis that the IA is involved in rapid adduction/abduction tasks such as phonation for speech, swallowing, and laughing.

Like in limb skeletal muscles, there is variability between individuals in the percentage of Type I or Type II muscle fiber types in the larynx (Rosenfield, Miller, Sessions, & Patten, 1982; Shiotani, et al., 1999), resulting in a proposed varying native ability to be more vocally powerful with or without fatigue (Johnson & Sandage, 2019). A person who was predisposed to a higher percentage of Type II muscle fiber types in the intrinsic laryngeal skeletal muscles may have the ability to produce more vocal power than a person predisposed to Type I muscle fiber types. Vocally demanding careers, such as classroom teachers, do not typically train their vocal ability to match the demand of their occupationally-required vocal load, like an athlete might for maximal performance, leading to vocal fatigue and bioenergetic stress (Nanjundeswaran, 2013; Smith et al., 2017). In a study done by Nanjundeswaran (2013), vocally fatigued participants reported increased vocal effort with conversational and loud speech, possibly due to their slow uptake of oxygen during performance. This slow uptake of oxygen in these participants can be attributable to the reliance of anaerobic metabolism during voice tasks, creating an oxygen deficit which could be reported as the feeling of vocal fatigue (Nanjundeswaran, 2013). By developing vocal tasks that mimic validated anaerobic power tests and evaluating the outcomes through the lens of anaerobic performance, we may identify new, ecologically valid, vocal function outcome measures to infer bioenergetic aptitude and fitness for individuals who have vocally demanding careers.

Anaerobic power is quantified as the amount of work done in a short period of time that is not wholly reliant on the transport and extraction of oxygen during a performance assessment (Adams & Beam, 2008). Anaerobic power tests are used in exercise science to determine an individual’s ability to produce power and indirectly assesses an individual’s probable skeletal muscle fiber type complement: an individual with a high percentage of Type II muscle fibers will be able to produce more power (Watts) during anaerobic power assessments than an individual who has a higher percentage of Type I skeletal muscle fibers. Endurance performance assessments, such as graded treadmill tests using exhaled gas analysis, are useful to determine the degree to which an individual can efficiently utilize aerobic bioenergetics, the performance outcomes of which provide physiological evidence of aptitude for endurance exercise. Put simply, if matched for cardiorespiratory fitness, an individual with a predominance of Type II skeletal muscle fibers will outperform an individual with a predominance of Type I skeletal muscle fibers during anaerobic power testing. This provides a rationale for use of bioenergetically-driven performance assessments in applied voice physiology. Figure 1 illustrates this rationale.

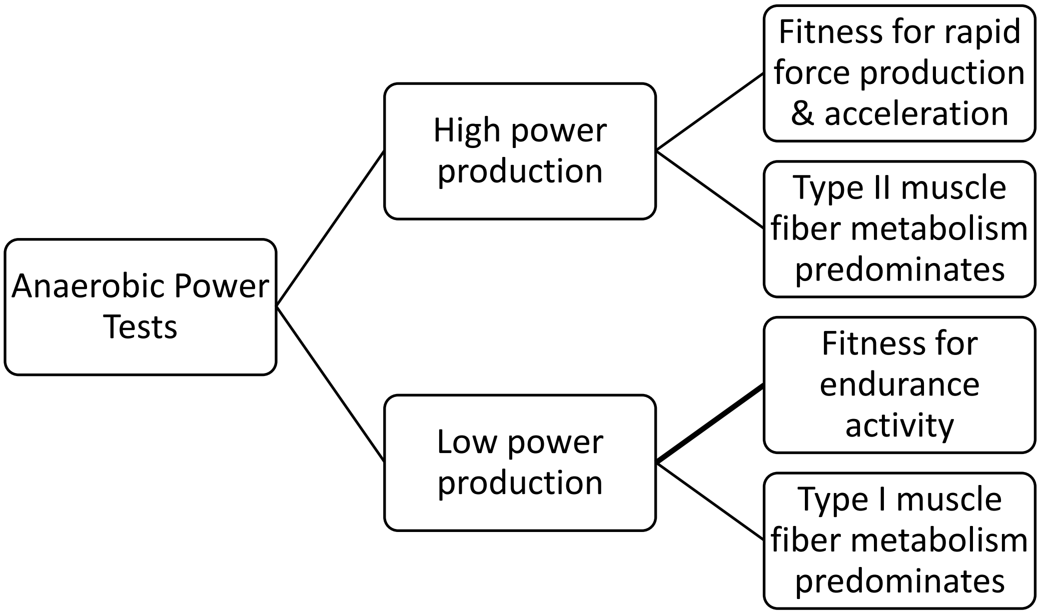

Figure 1. Physiological construct for study.

In exercise science, power is an expression of the rate of work done. Power is typically measured by dividing work by time and Watts (W) are used to represent this value (Adams & Beam, 2008). Anaerobic power tests in kinesiology measure anaerobic power and capacity through force velocity tests, vertical jump, staircase tests, and cycle tests (Vandewalle et al., 1987). These exercise assessments of anaerobic power production capability are used in exercise performance settings as an indicator of athletic aptitude as well as a measurable outcome for exercise training programs. Four anaerobic power tests that are commonly used include the Wingate Anaerobic Test, Anaerobic Step test, the Margaria anaerobic power test, and the horizontal sprint test. The Wingate Anaerobic Test is a 30 second cycling test that determines peak anaerobic power, mean anaerobic power, total work, and a fatigue index using a cycle ergometer during which the participant cycles against a set resistance weight (Bar-Or, Dotan, & Inbar, 1977). The Anaerobic Step Test requires the participant to step up on a 12-inch step repeatedly with a single leg as fast as possible for 60 seconds using the participant’s body weight as the resistance load (Brouha, 1943). The Margaria anaerobic power test is similar to the anaerobic step test in that it also determines power by calculating the vertical displacement of the individual's mass (kg) up a short flight of stairs (Kalamen, 1968; Margaria et al., 1966). Anaerobic power can also be derived from a 40-60 yard horizontal sprint which can provide information about muscle power and elasticity to maintain and contribute to maximal velocity while working against gravity (Adams & Beam, 2008). Sprinting is more dependent on Types II muscle fibers for rapid force production.

Contributors to Vocal Power Production

For vocal function assessment, the quantification of the sound pressure level produced, a construct of vocal power, may most align with anaerobic power quantification. Titze and Sundberg (1992) described vocal power, intensity, or sound pressure level (SPL), as a function of fundamental frequency and lung pressure and they asserted that aerodynamic power quantified in decibels would be relative to typical measures of power in Watts. They also described a strong dependence of glottal efficiency on the fundamental frequency produced, asserting that glottal efficiency calculations would favor higher f_0, even if it is produced with more effort or strain. This indicates that fundamental frequency also matters when calculating vocal power.

Isshiki (1964) concluded that efficiency increases with increases in sound pressure levels due to the decrease in the opening quotient of the vocal folds because of the increasing pressure below the glottis to sustain a louder voice. He also concluded that at low pitches, the intensity is controlled by three laryngeal factors (flow rate, glottal resistance, and efficiency), while at high pitches, the expiratory muscles are important for controlling intensity. Schutte (1992) concurred that subglottal pressure and mean flow rate would contribute to vocal power. Subglottal pressure differences were the main difference underlying loudness variation at different pitches sung by

10 singers (Sundberg et al., 1993). Years of classical voice training had an effect on the singing power ratio, and as the power ratio increased, the perceptual score of “ringing” or rich voice quality also increased (Omori et al., 1996). Using a more resonant voice added to vocal efficiency and dB SPL (Wolfe et al., 2009).

Changes in sound level can be attributed to contributions from one or more of the three subsystems of speech: respiration, phonation, and vocal tract tuning. Sound pressure level depends on lung pressure and will increase 8-9 dB an octave if lung pressure is proportionally equivalent to phonation threshold pressure. While the contributions of these subsystems for production of sound level are not disputed, the degree to which the subsystems may be entrained to produce a target sound level may be more idiosyncratic. The coordination of the subsystems when speaking in habitual voice was described in a study that quantified the different ways a vocally healthy person can use their subsystems for speech and the way these subsystems interact with each other (Croake, Andreatta, & Stemple, 2019). For example, there were strong correlations between the respiratory and phonatory systems and the respiratory and resonance systems, but a weak correlation between the phonatory and resonance systems (Croake et al., 2019).

Louder speech is initiated at larger vital capacities than soft speech (Hoit & Weismer, 2018). Volume differences in forced vital capacity vary according to the following variables used in automated spirometry to determine predicted FVC and FEV1: height, weight, sex, age, and ethnicity (Barroso et al., 2018; Harms, 2006; Inselman et al., 1993; Korotzer et al., 2000; Miller et al., 1970; Sharma & Goodwin, 2006; Womack et al., 2000). For example, it may be more difficult for a shorter person than a taller person to achieve greater lung volumes due to the smaller chest cavity. Recent evidence described sex differences in pulmonary physiology that may account for increased vocal fatigue in female versus male teachers (Hunter, Maxfield, & Graetzer, 2019).

Presence of a resistance is an essential component of anaerobic power testing. For example, in the Wingate, there a resistance weight dropped while the individual cycles as fast as they can. With the Margaria and the step test, the individual's body weight being moved against gravity serves as the resistance. Commonly used acoustic and aerodynamic measures of voice function do not include a resistance component against which laryngeal function must be produced; however, vocal function assessment tasks may be adapted with this resistance component included.

Given that vocal power is a complex construct, determination of anaerobic power capacity of voice production may be accomplished by correlating a validated whole body anaerobic power test developed in exercise science with vocal function tasks and lung capacity measures. In the study done by VanRavenhorst-Bell et al. (2018) that compared tongue endurance and tongue strength in athletes, results concluded that tongue strength was higher in weightlifters, while tongue endurance was higher in runners, possibly indicatory of the different muscle composition in weightlifters and runners. Athletes who excel in strength training may have more Type II muscle fibers which improves strength and speed, whereas athletes who pursue endurance exercise may have more Type I muscle fibers which has a lower rate of fatigue (VanRavenhorst-Bell et al., 2018). If we apply an exercise physiology model to the study of vocal power, then we would be interested in vocal tasks that mimic the rapid acceleration and high force production similar to the muscle activity targeted during anaerobic power testing. Because we lack these performance-based measures in voice science, adapting voice tasks that include resistance features of high f0, high dB SPL, and straw semi-occlusion to correlate with whole body anaerobic power tests may be a reasonable starting place. A correlation of lung volume using forced vital capacity (FVC) with whole body anaerobic power and the vocal function tasks may also be useful due to the evidence that higher lung capacities support production of more vocal power (Barroso et al., 2018; Harms, 2006; Hepper et al., 1960). If results and analyses provide evidence of a correlation, hypotheses could be made about the type of vocal "athlete" each individual is, which could help in the development of voice habilitation and rehabilitation strategies.

For this preliminary investigation of the relationship between whole body anaerobic power and adapted vocal function measures, it was hypothesized that 1) measures of whole body anaerobic power (Watts) will correlate with vocal function tasks that are characterized by a resistance component; 2) higher values for the adapted vocal function tasks will correlate with higher FVC; and, 3) the values of the first second of the adapted vocal function tasks will correlate more closely with the anaerobic power value (Watts) as a measure of peak vocal power.

Methods

Participants

Following receipt of approval from the Institutional Review Board, women between the ages of 19-40 were recruited for participation in this preliminary study. Inclusion criteria were as follows: the ability to match pitch, the physical ability to run, no prior history of classical voice training, no history of voice disorder or neurological impairment, no history of pulmonary disease or smoking, no active allergies during data collection, no drying medication, and not pregnant. Many physiological factors may directly influence vocal function including but not limited to: pulmonary diseases, structural differences due to laryngeal trauma, desiccation of the laryngeal epithelium, trained coordination of the voice, age and sex differences, and pulmonary function (Gunjawate et al., 2018; Hixon et al., 2014; Hoffman et al., 1991; Hoit & Hixon, 1986; Lenell et al., 2019; Sandage et al., 2014; Tanner et al., 2016; Verdolini et al., 1994). These factors were taken into account when determining exclusionary criteria to participate in this study. The ability to match pitch was an inclusion factor because the participants were required to replicate their target frequency for each vocal task produced.

Screening and Pretrial Procedures

Prior to inclusion for participation in the study, each participant was assessed for a voice disorder with a videostroboscopic laryngeal structure and function screening using the Digital Videostroboscopy System Model 9295 with a rigid 9106 endoscope (PENTAX Medical, Tokyo, Japan). Following the voice screening, consent was obtained and pretrial training was completed. During the pretrial visit, forced vital capacity (FVC) measures were taken using the AstraTouch Spirometer (SDI Diagnostics, Easton, Massachusetts) to determine FVC and recorded for later analyses. The FVC procedure was repeated a minimum of three times with the largest volume and the largest volume in one second (FEV_1) recorded for data analyses. Body mass index (BMI) was calculated using the height and weight values used for spirometry. Participants were counseled regarding pretrial avoidance of a heavy meal or exercise for at least 2 hours prior to data collection.

The target fundamental frequency and sound level for the vocal function measures being studied were determined using the Voice Range Profile software (CSL Model 4500, PENTAX Medical, Tokyo, Japan). A functional frequency range was first obtained, characterized as the highest and lowest frequencies that could be sustained for more than 1 second. From this frequency range, the target fundamental frequency was determined at the 80% point of the entire frequency range. To determine the participant's highest produced frequency, each participant was instructed to glide up in frequency while producing /a/ until they reached their highest, clearest produced note, and replicated it three times to control for reliability in a standing position (Coleman, 1993). Determination of the lowest fundamental frequency employed the same glide strategy, replicated three times for reliability. Then, the 80% semitone target was determined from the total range in semitones. The participant was then instructed to produce the 80% semitone frequency at the loudest dB SPL they could produce. Once these measures were determined, the participant was trained to produce the three vocal function tasks that would be quantified during the actual trial. If the participant had trouble reaching their targeted frequency, the keyboard was used to remind them of the pitch they produced.

Adapted Vocal Function Tasks

Of the vocal function tasks that are most commonly used clinically and in research, two tasks were selected as adaptable for inclusion of a resistance component in a manner that may align these tasks with an anaerobic power assessment: laryngeal diadochokinesis (LDDK) and sustained phonation. The third task used in this study, maximum phonation resistance (PRmax), was created by combining a maximum phonation time task with a semi-occluded resistance to better align the task with the loaded resistance component of an anaerobic power assessment. With adaptations, each of these measures provides a unique parameter that may support measurement of extensive vocal ability or what may be considered vocal power. Adaptation of these vocal function tasks, that are typically quantified at modal speaking fundamental frequency and sound level, provided a resistance at the level of the larynx or vocal tract that mimicked the resistance loading and rapid acceleration aspects of whole body anaerobic power tests.

The most widely used vocal function task, sustained /a/, is typically recorded at the modal frequency and conversational sound level (Patel et al., 2018). For the purpose of this study, this task was completed at 80% of the individual's semitone range at the loudest sound pressure level they could produce as the resistance. This task was termed maximum phonation time ($\mathrm{MPT}_{\mathrm{max}}$) for data analyses. The $\mathrm{MPT}_{\mathrm{max}}$ measure was collected for analysis using the Real Time Pitch (CSL Model 4500, PENTAX Medical, Tokyo, Japan) to determine the length in seconds of steady production at the pre-determined target frequency and the greatest achievable sound pressure level. Three trials were conducted and the longest sample at their target sound was used for data analyses. Considering this is a maximum performance task, a longer phonation time might indicate a higher amount of vocal power due to the larger airflow measure and control for consistent prolongation.

Laryngeal diadochokinesis (LDDK) measures the coordination of the intrinsic laryngeal muscles by repeating either "/ʌ/" or "/hʌ/" as fast and as precisely as possible in a single breath. While it is most often used to screen for neurologic laryngeal impairment, it was chosen for this study because of the task specificity of the intrinsic laryngeal muscles to produce rapid changes in acceleration, a performance feature of anaerobic muscle performance. In this study, the syllable "/hʌ/" was used based on the quick muscle acceleration transitions from a voiceless to voiced sound, increasing the potential correlation between vocal power and anaerobic power (Canter, 1965; Howse, 2016).

Typically, LDDK is done at the individual's conversational sound level, but for the purpose of this study, this task was adapted for a resistance component via use of the participant target frequency at 80% of their semitone range and the loudest sound pressure level they could produce. The adapted task was called $\mathrm{LDDK}_{\mathrm{max}}$. Each participant was instructed to repeatedly produce the syllable /hʌ/ as fast as they could at the same target sound produced during the maximum phonation task for three separate samples. To provide accuracy of the target sound produced at the participants pretrial, pitch-matching ability was reviewed with a keyboard prior to the start of data collection. The LDDK task was collected using Real Time Pitch (CSL Model 4500, PENTAX Medical, Tokyo, Japan) and analyzed in the Main Program (CSL Model 4500, PENTAX Medical, Tokyo, Japan) to calculate syllable rate per second (rps). The best of the three trials was used to correlate with the best performance of anaerobic power. The rate per second for the first second of production, the average for the entire production of LDDK_{max}, and the rate per second for the last second of production were recorded for data analyses.

A third voice task was created by combining features of the maximum sustained phonation time and straw phonation semi-occluded vocal task and was termed maximum phonation resistance (PR_{max}). For this task, straw phonation was added to provide an extra resistance against which phonation would be produced, mimicking the added resistance load that is characteristic of anaerobic power tests. A study done by Maxfield et al., (2016) indicated that smaller diameter straws, such as a 3.5mm wide and 14.1cm long, were most consistent in producing intraoral pressures that maximized vocal efficiency for both males and females than larger diameter straws of 6mm wide and 19.5cm long. However, the results of a study on canine cadavers by Tangney et al., 2019 indicated that the 3mm diameter straw, what speech pathologists consider is the most impactful diameter for voice rehabilitation (Titze, 2006), made it almost nearly impossible for phonation to be achieved (Tangney et al., 2019). Given the inconsistencies in the literature and the observed difficulty producing a high and loud voice through a small straw, the 5mm straw was chosen for this investigation.

This task was completed at the individual's target frequency at 80% of their semitone range and the loudest sound pressure level as they produce the sound /u/ through a 10 cm, 5mm diameter straw. The length of the straw was limited to 10 cm to allow data capture via a circumferential pneumotachograph mask. The data was collected using the Phonatory Aerodynamic System (PAS) Model 6600 (PENTAX Medical, Tokyo, Japan) after calibration following manufacture guidelines. Since this is a maximum performance task, a longer phonation time through the straw while maintaining a high frequency and sound pressure level may indicate a higher power measure. Sound pressure levels (dB SPL) were used for data analyses. Three trials were collected and the participant's best performance was used to correlate with the best performance. The participant's first second average dB SPL, the average dB SPL for the entire production, and the average dB SPL for the last second of production were used for data analyses.

Trial Data Procedures

The phenomenon of circadian rhythms was taken into consideration during scheduling. It is known that for the majority of people, flexibility, muscle strength, and short-term high power usage varies throughout the day (Atkinson & Reilly, 1996). Tasks that require high heart rate tend to peak in the morning, whereas post-lunch activity show a decrease in muscle strength (Atkinson & Reilly, 1996). With this in mind, trials were scheduled during the morning hours for all participants.

On the day of data collection, a urine sample was obtained to determine systemic hydration level to a criterion of less than or equal to 1.02 g/ml, a well-established threshold for appropriate systemic hydration in exercise science (Pascoe & Fisher, 2009; Sandage et al., 2014).

To provide accuracy of the target frequency determined at the participants pretrial, pitch-matching ability was reviewed with a keyboard prior to the start of data collection. See Table 1 for data collection time points.

Table 1. Study Design.

Day of Collection	Data Collected
Pretrial Visit	Laryngeal structure and function screening Consent Form Forced Vital Capacity measures Target Frequency (80%) Target Sound Level Training of Voice Tasks
Trial Visit	Urine Sample MPT_{max} task $LDDK_{max}$ task PR_{max} task Horizontal Power Test

Anaerobic Horizontal Power Test Procedure

Based on equipment required, participant safety, and performance time compared to the laryngeal function tasks being used in this investigation, the horizontal power test (40-yard dash) was selected as the whole body power test for this study. The duration of this test most closely matched the duration of the voice tasks used, whereas the other tests, such as the Wingate (30 seconds) or Anaerobic Step test (60 seconds) were far longer. Horizontal power was determined by multiplying the body mass of the participant by the sprint speed (Adams & Beam, 2008).

$$\text{Horizontal Power (W)} = \text{Body Mass (N)} * \text{Average speed (m/s)}$$

Pre-trial warm-up was not included in the protocol due to evidence of stretching potentially reducing force production (Adams & Beam, 2008). Two trials of the 40-yard sprint were conducted unless there was a difference greater than 1second between the two trials, then a third trial was performed. There was a rest period between trials of 30 seconds of active movement. Only one of the participants required a third trial.

Data Analyses

Using a within-participant design, measures of $LDDK_{max}$ (rps), MPT_{max} (seconds), PR_{max} average (dB SPL), $PRmax_1$ (first second dB SPL), $LDDKmax_1$ (first second rps), PR_{max} last second (dB SPL), and $LDDK_{max}$ last second (rps) were correlated with the horizontal power assessment (Watts) and FVC (liters) using SPSS (IBM SPSS Statistics, Version 25). Significance was set at α <.05. Normality assumptions were evaluated via visual inspection of histograms and QQ plots. Observation of outliers in the power (W) data indicated the need to perform a logarithmic transformation, which resolved the observation of outliers. Therefore, the transformed data for the power calculation (W) was used for data analyses. All other variables analyzed were raw values obtained. A correlation analysis was used to determine relationships between whole body anaerobic power and the vocal function measures. Correlation analyses were also conducted to compare FVC to the other measures. A one-tailed, bivariate correlation analysis was conducted with the following variables: FVC, MPT_{max}, PR_{max}, $LDDK_{max}$, $PRmax_1$, $LDDKmax_1$, PR_{max} last second average, $LDDK_{max}$ last second average, and power (W).

Results

Participants

Following receipt of approval from the Institutional Review Board, sixteen women (age range: 19-24; mean age: 22 years) were consented for participation in the investigation after meeting all inclusion criteria. The ethnicity of the participant pool consisted of 14 Caucasian women, 1 Hispanic woman, and 1 African American woman. Remarkable athletic ability was also recorded for select participants. Participant F1 was a powerlifter, F6 and F9 were mixed athletes playing soccer, F11 played club soccer and CrossFit®, and F14 played college and professional basketball within the past year and participated in intramural basketball at the time of data collection. Participant demographics are described in Table 2.

Table 2. Participant Raw Data used for Descriptive Analysis

Participant	Age	BMI	Predicted/Best FVC (L)	Target Fo (Hz)	Target dB
F1	24	22.7	4.15/4.14	587.33	97
F2	22	26.6	3.66/3.77	622.25	95
F3	22	19.96	3.9/3.82	659.26	100
F4	20	20.36	4.15/4.62	739.99	103
F5	23	25.74	3.81/3.96	622.25	101
F6	23	21.65	3.91/3.97	783.99	108
F7	21	23.17	3.8/3.85	698.46	109
F8	21	24.03	3.8/3.3	783.99	99
F9	23	22.14	3.66/3.89	698.46	101
F10	19	21.41	4.4/4.7	587.33	104
F11	23	27.45	3.91/4.2	783.99	103
F12	24	24.13	3.91/3.8	783.99	103
F13	22	19.47	3.9/4.24	739.99	113
F14	23	24.36	4.41/4.14	523.25	105
F15	22	22.8	4.3/4.25	783.99	110
F16	20	23.01	4.67/5.21	622.25	102
Average	22	23.06	3.48/4.12	688.8	103.31

Note: BMI=body mass index; FVC=forced vital capacity; L=liters; Fo=fundamental frequency; Hz=Hertz; dB=decibels

Descriptive Analyses

Descriptive analyses identified a positive linear relationship between faster LDDK$_{max}$ rate and higher anaerobic power as can be seen in Figure 2. No relationships between anaerobic power and longer MPT$_{max}$ or louder PR$_{max}$ were observed.

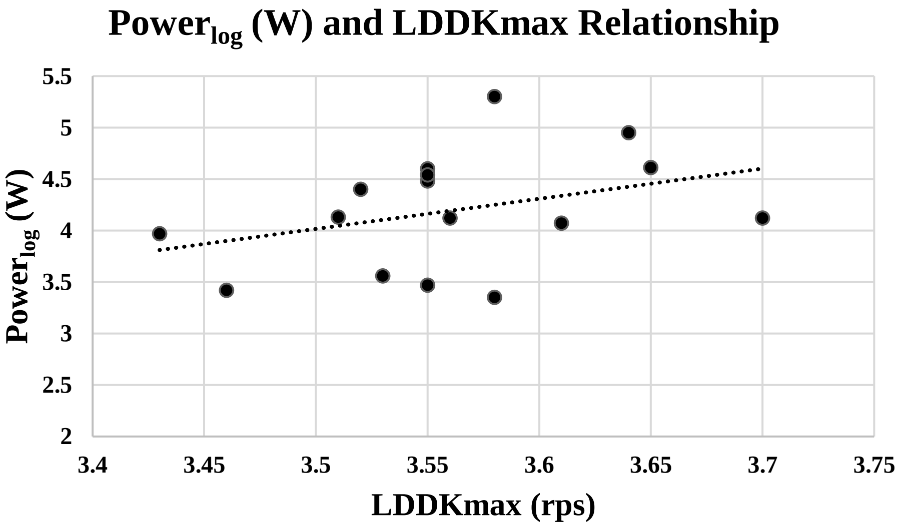

Figure 2. The positive relationship of LDDK$_{max}$ with a natural trendline of results.

Descriptive analyses of participant raw data indicated a negative linear relationship between FVC and MPT$_{max}$, as shown in Figure 3, in that larger FVC did not result in longer phonation time.

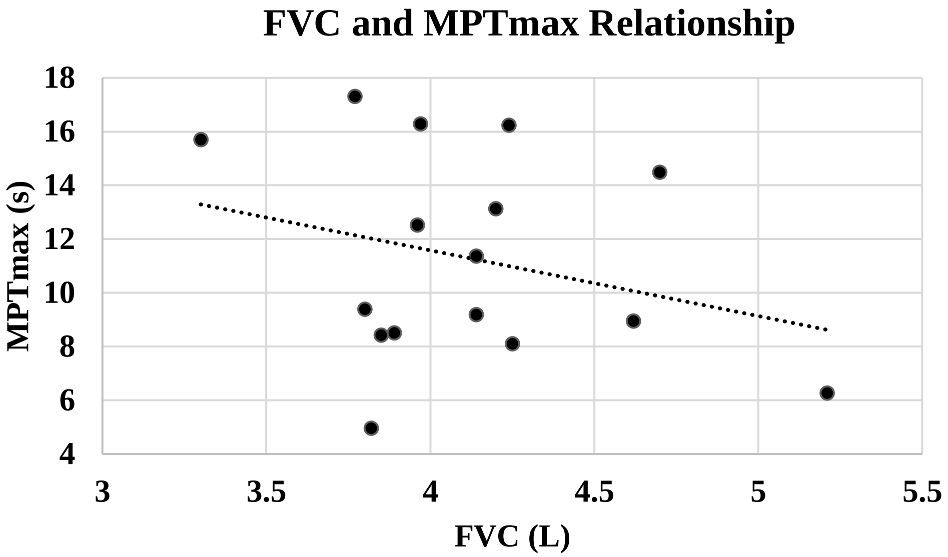

Figure 3. The negative relationship of FVC and MPT_{max} with the natural trendline of results.

Statistical Analyses

A moderate correlation (0.44, p=0.042) was identified between power (W) and the last second of the $LDDK_{max}$. Strong correlations were identified between PR_{max} and PR_{max} last second (0.89; p<0.001); PR_{max} and $PRmax_1$ (0.91; p<0.001) as well between $LDDK_{max}$ and $LDDK_{max}$ last second (0.84; p<0.001); and $LDDK_{max}$ and $LDDKmax_1$ (0.86; p<0.001). An additional significant correlation was identified in this preliminary investigation that was unrelated to the study hypotheses: FVC and $PRmax_1$ (-0.52; p= 0.02). The full correlational analyses are displayed in Table 3.

Table 3. Bivariate Correlations for Experimental measures (N=16)

	FVC	MPTmax	PRmax	PRmax$_1$	PRmax (last)	LDDKmax	LDDKmax$_1$	LDDKmax (last)	Power_log
FVC									
MPTmax	-0.28								
	0.15								
PRmax	-0.35	0.19							
	0.09	0.24							
PRmax$_1$	-0.52	0.43	0.91						
	0.02*	0.05	0.00**						
PRmax (last)	-0.29	-0.09	0.89	0.71					
	0.14	0.37	0.00**	0.00**					
LDDKmax	0.07	0.11	0.08	0.21	0.01				
	0.40	0.34	0.38	0.21	0.48				
LDDKmax$_1$	-0.06	-0.04	0.07	0.22	-0.04	0.86			
	0.41	0.44	0.40	0.21	0.45	0.00**			
LDDKmax (last)	0.19	0.22	0.01	0.11	-0.16	0.84	0.67		
	0.24	0.21	0.49	0.34	0.28	0.00**	0.00**		
Power_log	0.34	-0.19	0.02	-0.06	0.01	0.35	0.21	0.44	
	0.10	0.25	0.47	0.42	0.49	0.09	0.22	0.04*	

Note: Power was transformed to log; *Correlation is significant α<.05 (1-tailed); **Correlation is significant at α<.001 (1-tailed). BMI=body mass index; FVC=forced vital capacity; L=liters; Fo=fundamental frequency; Hz=Hertz; dB=decibels

Discussion

This investigation describes a novel merger of exercise science and voice science in a new theoretical paradigm to identify a vocal function task produced with a resistance component that best mimicked a whole-body anaerobic power test. The goal of this investigation was to identify a measure of vocal function that could infer the bioenergetic profile of the ILSMs and serve as a performance indicator of the vocal ability requirements for those who work in vocally demanding occupations. It was hypothesized that participants with higher whole-body anaerobic power measures would have a faster $LDDK_{max}$ rate, a longer MPT_{max}, and a louder average PR_{max}. Results of the correlational analyses provided evidence to support components of the $LDDK_{max}$ task as a possible indicator of ILSM Type II muscle fiber complement. The correlations identified between PR_{max} values and $LDDK_{max}$ values indicate reliability and stability of these measures within-participant. The relationship between these measures warrants further study. Statistically and descriptively, the other two tasks, MPT_{max} and PR_{max}, did not correlate to whole-body anaerobic power and may be less useful as a bioenergetic indices.

$LDDK_{max}$ was the only vocal measure conducted against laryngeal resistance that also demanded fast transitions from adduction to abduction. This intrinsic laryngeal skeletal muscle activity most closely aligns with the work that is characteristically accomplished with Type II muscle fibers – rapid force production and acceleration. The correlation of the last second of the $LDDK_{max}$ task with whole-body anaerobic power combined with the muscle performance characteristics of the $LDDK_{max}$ task supports the theoretical construct that individuals who have a higher complement of Type II skeletal muscle fibers in the limbs may also have a higher complement of Type II skeletal muscle fibers in the larynx.

Given that the limited muscle fiber typing evidence for ILSMs describes variations in muscle fiber complement between individuals as similar to limb skeletal muscles, the $LDDK_{max}$ task may be useful to infer probable muscle fiber complement of the ILSMs in much the same manner as the anaerobic power tests are used in exercise science to infer limb skeletal muscle fiber complement. Individuals with higher prevalence of Type II muscle fibers would produce higher power values when compared to individuals with higher prevalence of Type I muscle fibers. This theoretical construct as applied to vocal function requires further study.

It could be proposed that athletes who pursue anaerobic or mixed sports (ballistic, short bursts of rapid acceleration) and demonstrated larger anaerobic power would have faster production of $LDDK_{max}$. The participants who identified as athletic did not demonstrate higher average $LDDK_{max}$ or last second values of $LDDK_{max}$. These participants had an average of 4.1 rps during the last second, while the entire participant pool had an average of 4.3 rps during the last second. Athleticism or predictions regarding vocal power aptitude based from the type of athlete were not possible in this preliminary investigation given that of the top 5 participants with the highest power, only 3 reported they were power or mixed athletes. Two of the five participants who identified as athletes had the best rps during the last second of $LDDK_{max}$ being that of 5 rps. The type of athletic endeavor that a given individual pursues may not reflect the aptitude that may be implied by muscle fiber complement. Further investigation into this hypothesis may benefit from study of elite power athletes and limb muscle fiber complement analyses.

One interesting finding from this study was the lack of correlation between the other voice tasks, MPT_{max} and PR_{max}, and anaerobic power. A potential reason why this phenomenon occurred is that although there was a similar resistance put on the vocal folds, being high frequency and high loudness, these two tasks may have required more endurance to hold a steady tone for as long as they could, relying possibly more on their pulmonary control than their larynx. The $\mathrm{LDDK}_{\mathrm{max}}$ task required participants to alternate between adduction and abduction of the vocal folds as quickly as possible, relying more on laryngeal-focused muscle coordination. The $\mathrm{LDDK}_{\mathrm{max}}$ task might have been the only task to correlate with anaerobic power based on its greater reliance on intrinsic laryngeal muscles, rather than respiratory muscle coordination or vocal tract tuning, providing a more accurate depiction of vocal power.

An ancillary finding of this study was the lack of correlation between FVC and $\mathrm{MPT}_{\mathrm{max}}$. It was hypothesized that a person with larger lung volumes would have the capacity to hold out a single frequency longer that a person with smaller lung volumes. This finding is consistent with findings reported by Solomon et al. (2000) in an investigation of the respiratory and laryngeal factors that could contribute to MPT, where no relationship between MPT and FVC was identified. The lack of a relationship between these measures suggests motor learning differences between individuals and the heterogeneous strategies individuals use to increase subglottal pressure for a louder voice (Croake et al., 2019). It is for these reasons that, in the present investigation, $\mathrm{MPT}_{\mathrm{max}}$ and $\mathrm{PR}_{\mathrm{max}}$ may not have realized correlations with whole-body anaerobic power. Unlike the $\mathrm{LDDK}_{\mathrm{max}}$ task, it could be proposed that $\mathrm{MPT}_{\mathrm{max}}$ and $\mathrm{PR}_{\mathrm{max}}$ were less laryngeal-focused with a greater reliance on smooth coordination of the three subsystems throughout the tasks. Further, the lack of correlation between higher pulmonary volumes and louder voice production conflicts with current clinical approaches that rely primarily on taking a larger breath to support louder voice. Referring back to Table 2, it is apparent that FVC, which is our primary measure of pulmonary volume, lacks an obvious positive relationship with the $\mathrm{MPT}_{\mathrm{max}}$ and $\mathrm{PR}_{\mathrm{max}}$ measures.

Determination of a valid, reliable, and specific vocal function task to infer muscle fiber complement is of great clinical value. Anaerobic power tests are used in exercise science to determine physical ability or fitness level of an athlete. Because $\mathrm{LDDK}_{\mathrm{max}}$ was the only vocal function task that best correlated to anaerobic power, it may be clinically useful task as a vocal “fitness” assessment measure for use as a habilitation or rehabilitation outcome measure. Based on the research done by Croake et al. (2019) on the multiple ways to increase dB SPL, techniques to increase vocal power could be trained to prevent vocal injury, especially in high vocally demanding workplaces. In a study done by Hunter et al. (2019), female teachers were more likely to feel vocal fatigue than male teachers due to their need to compensate for smaller lung volumes by relying heavily on their laryngeal muscles to increase dB SPL, increasing their risk of vocal pathologies. $\mathrm{LDDK}_{\mathrm{max}}$ performance at baseline and after a voice habilitation training program may be useful to determine if functional ability improved as a result of clinical intervention.

In exercise science, the difference in performance between the first and last second of the Wingate cycling ergometer test of anaerobic power test is used to calculate a fatigue index. The development of a vocal performance fatigue index, as a measure of fatigue susceptibility or resistance to fatigue, is a line of inquiry that could extend from the current investigation. The construct of voice fatigue resistance training and upregulation of laryngeal physiology to mitigate vocal fatigue (Sandage & Hoch, 2019; Hunter et al., 2020) requires objective measures to evaluate response to training programs. As in exercise science, performance-based voice fatigue measures could be used as baseline measures of an individual’s laryngeal muscle fiber bioenergetic (metabolic) fitness for occupational voice demands and to evaluate physiological response to habilitation and rehabilitation training programs. Determination of a vocal task-based fatigue index would improve the current constructs of vocal fatigue which are primarily based in perceptual constructs (Nanjundeswaran, Jacobson, Gartner-Schmidt, & Abbott, 2015; Hunter et al., 2020).

A strength of this study was the novel merger of exercise science constructs of performance aptitude and fitness assessment in the context of voice function. To date, we lack voice performance assessments to determine if individuals are fit for extensive voice required by many occupations or vulnerable for the development of voice disorder. As with fitness requirements to do certain jobs, i.e., landscaping, quantification of the acoustic requirements for occupations will allow for benchmarks of vocal fitness to be established. Once vocal work load is understood with regard to how long and how loudly the voice needs to be produced, vocal aptitude assessments can be developed from which voice habilitation programs can be developed.

It is acknowledged that primary limitations of this study were the inclusion of only young, female participants and the small sample size. Given that voice disorders affect far more women than men, the exclusion of men in this preliminary study was in part justified. Exclusion of men from this preliminary investigation was further supported by the evidence of significant sex differences for pulmonary and laryngeal anatomy and physiology. The inclusion of only young women limits the generalization of the study findings to men and older adults. Findings from this investigation may be strengthened with a larger, more heterogeneous participant pool to establish significance between the LDDK_{max} task and whole body anaerobic power testing and further develop this vocal power aptitude construct.

Another limitation of the study was use of the standard straw for the PR_{max} measure. The literature describes greater pressures produced by smaller inner diameter straws (Tangney et al., 2019; Maxfield et al., 2016; Titze, 2006) and a correlation between PR_{max} and the whole-body anaerobic power test may have been identified with use of a smaller straw. Individuals often report difficulty using the smaller diameter straw at modal f_0 and conversational sound level, therefore, the larger straw was chosen for greater ease of voice production at the extreme f_0 and sound levels used in this study. Future efforts comparing the differences in PR_{max} with use of different straw sizes are warranted.

Conclusion

This study was a preliminary, novel merger of the fields of exercise science and voice to find a vocal function measure that best mimicked anaerobic performance as an indirect measure of probable intrinsic laryngeal muscle fiber complement. The results of this study indicated that only one of the three hypothesized vocal measures completed with a high and loud voice, $LDDK_{max}$, was correlated with anaerobic power. Other findings such as the relationship between average, first, and last second performance within one trial could lead to development of a vocal fatigue measure that would further laryngeal physiological investigations in the field of voice science. The negative relationship identified between FVC and MPT_{max} supports the premise that vocal training is important for optimal voice use and vocal efficiency. The development of novel outcome measures of vocal function will be important as the field continues to embrace exercise science constructs for vocal habilitation and rehabilitation.

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