Temporal Features of Voice in Connected Speech: Bioenergetic Implications

by

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Abstract

Purpose: Translating exercise science methodology for determination of muscle bioenergetics, it was hypothesized that the temporal voice use patterns for classroom and music teachers would indicate a reliance on the immediate energy system for laryngeal skeletal muscle metabolism. It was also hypothesized that the music teacher group would produce longer voiced segments that the classroom teachers.

Method: Using a between-within group repeated measures design (5 female classroom teachers; 7 music teachers, 1 male and 6 females) fundamental frequency data collected via an abulatory phonation monitor were analyzed for length (seconds) of voicing and silence intervals. Data were collected for 7.5 hours during the workday, over the course of several workdays for each teacher.

Results: Descriptive analyses of voice and silence intervals indicated that over 99% of voiced segments for both groups were no longer than 3.15 seconds, supporting the hypothesis of reliance on the immediate energy system for muscle bioenergetics. Between-within group data were analyzed using a multivariate analysis of variance. Significant differences were identified between the classroom and music teacher groups as well as within each group.

Conclusions: Knowledge of probable intrinsic laryngeal skeletal muscle bioenergetic requirements could inform new interdisciplinary considerations for voice habilitation and rehabilitation.

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List of Abbreviations

Intrinsic Laryngeal Skeletal Muscle	(ILSM)
Adenosine Triphosphate	(ATP)
Ambulatory Phonation Monitor	(APM)
Adenosine Diphosphate	(ADP)
Adenosine Monophosphate	(AMP)
Creatine Phosphate	(CP)
Myosin Heavy Chain	(MHC)
Fatigue-Resistant, Oxidative Glycolytic Fibers	(FOG)
Fast, Fatigable Glycolytic Fibers	(FF)
Succinate Dehydrogenase	(SHD)
Thyroarytenoid	(TA)
Lateral Cricoarytenoid	(LCA)
Posterior Cricoarytenoid	(PCA)
Cricothyroid	(CT)
Interarytenoid	(IA)
Sodium Dodecyl Sulfate Polyacrylamide Gel Electrophoresis	(SDS-PAGE)
Vocalis	(VOC)
Slow Tonic Muscle Fiber	(STF)
Sound Pressure Level	(SPL)

Fundamental Frequency .... (F_0)

I. Introduction

The prevalence of voice disorders in the United States is approximately 3-9% of the population according to most estimates (Leske, 1981; Ramig & Verdolini, 1998; Roy, Merrill, Gray, & Smith, 2005; Verdolini & Ramig, 2001). Occupational voice users are thought to be at a higher risk of developing a voice disorder than the rest of the population. Teachers worldwide are considered to be an occupational group at high risk and have a higher prevalence of voice problems than non-teachers. Several research studies have been conducted to describe the prevalence of voice disorders, characteristics of voice disorders, variables that contribute to greater risk for voice disorders, and the financial impact of lost days at work and reduction in overall work productivity (Morrow & Connor, 2011; Roy et al., 2005; Russell, Oates, & Greenwood, 1998; Smith, Gray, Dove, Kirchner, & Heras, 1997; Thibeault, Merrill, Roy, Gray, & Smith, 2004). The financial impact of these aspects of teacher voice disorders as well as medical interventions provided to diagnose and treat the disorders mirrors that of treatment for pediatric ear infection (Ramig & Verdolini, 1998).

There are, however, some limitations to the research conducted on teacher voice disorders thus far. Morrow and Connor (2011) described “a need for objective, quantitative data about the amount and type of daily voice use for teachers.” Research conducted with the ambulatory phonation monitor (APM) analyzed the aggregate vocal dose from several days of voice use in elementary classroom and music teachers (Morrow & Connor, 2011). This analysis has informed our understanding that a typical classroom teacher’s vocal fold vibration travels

3688 meters, or 3.6 kilometers per day, averaged over the course of a typical 5 day work week. Knowledge of aggregate voice load is valuable, however, analyzing voice use patterns from a temporal perspective could offer insight into the bioenergetic requirements of the muscles used for occupation-specific voicing.

Bioenergetics is an area of exercise science that describes the fuel sources that specific muscle fiber types use for work. The human body primarily uses adenosine triphosphate (ATP) as a fuel, which is produced by one of three basic processes: two anaerobic pathways (immediate energy source and glycolysis) and one aerobic pathway (oxidative phosphorylation), the primary energy source for steady state exercise. In applied exercise science, muscle metabolism is determined in part, by duration of the muscle activity (Brooks, Fahey, & Baldwin, 2004). The application of temporal assessment based muscle fuel substrate pathway timeframes to voice use patterns can help infer which bioenergetic pathways are used for specific voicing tasks. The impact from this novel multidisciplinary perspective could inform new considerations for voice habilitation and rehabilitation such as voice techniques or approaches in teacher training or therapy once voice disorder develops. Novel aspects for therapy may include new considerations for neuromuscular and motor learning perspectives.

II. Literature Review

Prevalence of Occupational Voice Disorders

The prevalence of voice disorders in the United States is approximately 3-9% of the population according to most estimates (Leske, 1981; Ramig & Verdolini, 1998; Roy et al., 2005; Verdolini & Ramig, 2001). Particular groups, such as occupational voice users, are thought to be at a greater risk of developing voice disorders than the rest of the population (Russell et al., 1998; Smith et al., 1997; Thibeault et al., 2004). Titze, Lemke, and Montequin (1997) defined occupational voice users as professionals who rely on stable voice quality as a primary tool of trade, and who would encounter difficulty in job performance in the presence of abnormal or disordered voice quality. These authors identified occupational voice users as singers, actors, telemarketers, teachers, receptionists, emergency vehicle dispatchers, and broadcasters. Professional voice users often speak for long periods of time, speak with high intensity, and/or speak in noisy environments, all of which can contribute to the development and maintenance of a voice disorder (Herrington-Hall, Lee, Stemple, Niemi, & McHone, 1988; Mattiske, Oates, & Greenwood, 1998; Titze et al., 1997). Verdolini and Ramig (2001) proposed that if professional voice users make up a greater percentage of a caseload in a voice clinic than their percentage in the population, it indicates a risk factor for a voice disorder. Professional voice users comprise approximately 45% of the working population and 57% of voice clinic caseloads Titze et al. (1997).

Prevalence of Voice Disorders in Teachers

It is commonly accepted that teachers worldwide have a higher prevalence of voice-use problems than non-teachers, but there is an exceptionally large range in prevalence statistics described in the literature, ranging from 4.4 – 90% (Morrow & Connor, 2011; Russell et al., 1998). Although there are some discrepancies in what percentage of teachers have a voice problem, it has been shown that teachers report voice problems at a higher rate than the rest of the population (Russell et al., 1998; Smith et al., 1997; Thibeault et al., 2004). Titze et al. (1997) reported that while teachers comprise only 4.4% of the workforce, they make up 20% of a university hospital voice clinic caseload. Variability in the criteria used to determine the presence of a voice disorder and differences in method between research studies are possible explanations for the discrepancies in the prevalence of voice disorders in teachers (Mattiske et al., 1998; Roy et al., 2005; Roy et al., 2004; Russell et al., 1998; Verdolini & Ramig, 2001). Sample size, population selection, and subjective and perceptual data, such as self-report or perceived phonatory effort (PPE), not supported by instrumental data, are examples of the methodological differences (Mattiske et al., 1998; Roy et al., 2004). Despite these methodological differences it is apparent that teachers comprise a larger percentage of voice clinic caseloads than other occupations. Furthermore, the financial impact of lost days at work, diagnosis and treatment, and reduction in overall work productivity for teachers with voice disorders parallels that for healthcare costs spent to treat pediatric ear infections (Ramig & Verdolini, 1998). Understanding the variables that contribute to more risk in the teacher population is important for voice habilitation and rehabilitation.

Several studies on teachers with voice disorders have been conducted. In a study conducted by Smith et al. (1997), teachers reported voice symptoms at a significantly higher rate and with a higher frequency for each symptom than the non-teacher control group solicited from the community, and were twice as likely to report physical discomfort related to voice use. Furthermore, this study indicated that teachers were three times as likely to have vocal symptoms interfere with their job performance; one-fifth of the teachers reporting missing work as a result of voice problems. The outcomes of this study indicate that teaching is a high risk occupation for voice disorders due to the higher frequency of vocal symptoms reported by teachers (67%) compared with non-teachers (33%). Russell et al. (1998) conducted a study examining the prevalence of self-reported voice problems in teachers in South Australia. Seventy-six percent of teachers reported having voice problems during the school year at the time of the study. This study indicated 21.3% of male and 11.2% of female teachers did not report voice problems during their teaching career, 65.8% of males and 66.8% of females reported infrequent voice problems, and 12.9% of males and 22.0% of females reported voice problems every 6 months or more frequently. A significant relationship between sex and reporting a voice problem was found, with women being more likely to report a voice disorder than men. These teachers were asked to rate the severity of their voice disorder on a 5-point scale and the results were as follows: 11.6% rated their voice disorder as very mild, 29.4% as mild, 40.8% as moderate, 14.4% as severe, and 3.6% as very severe.

Thibeault et al. (2004) conducted a large cross-sectional research study to determine occupational risk factors associated with teachers and the development of voice disorders. Employed, full time elementary and secondary school teachers from Utah and Iowa were invited to participate in the research study. A questionnaire was developed and administered to 1,234 teacher participants targeting symptoms, consequences, and potential risk factors of voice disorders. An operational definition of voice disorders was formed based off the responses of the participants on the questionnaire; the authors defined voice disorders as anytime the voice interfered with communication either by not working or sounding different than normal. The results of this study indicated 58% of teachers experienced a voice disorder during their teaching career, which is consistent with the finding of 57.7% byRoy et al. (2004), but higher than the 29.9% reported in a later paper by Roy et al. (2005). The likelihood of reporting a voice disorder was significantly higher among female teachers and teachers who taught chemical science, vocal music, and performing arts classes. This study indicated physical education teachers were not more likely to report a voice disorder even though they have traditionally been found to do so Smith, Kirchner, Taylor, Hoffman, & Lemke, 1998; Thibeault et al., 2004). Teachers of special and vocational education, who reported the highest percentages of quiet talking and the lowest percentages of talking loudly, exhibited the lowest risk of developing a voice disorder, which supports the premise that the voice use patterns and demands of teachers of particular subjects are risk factors for voice disorder development. Furthermore, teachers who reported intense voice use (i.e., singing and loud talking) were associated with a greater risk of voice disorder development. These results indicate that vocally intense activities may increase the risk of vocal fold injury, which is consistent with the findings of Roy et al. (2005). These findings also suggest that all teachers do not experience the same vocal load or vocal dose within the occupation.

Quantifying Vocal Dose

Until recently, the amount of voice use and duration of total phonation time during the workday were measured mainly through self-report by teachers, which often provided an inaccurate depiction of the amount vocal fold vibration (Hillman, Heaton, Masaki, Zeitels, & Cheyne, 2006; Morrow & Connor, 2011). Morrow and Connor (2011) suggested that self-reports of vocal usage are often overinflated and unreliable because total phonation time does not include moments when the vocal folds are not actively vibrating, such as voiceless consonants and intervals of breathing. Rather than relying exclusively on self-reported measures of vocal use, it is important to accurately quantify the amount of phonation a teacher produces as integral to assessing the effects of prolonged phonation on their voices (Švec, Popolo, & Titze, 2003) . These authors listed duration of voicing, vocal intensity, and fundamental frequency as fundamental factors to consider when assessing prolonged voice use.

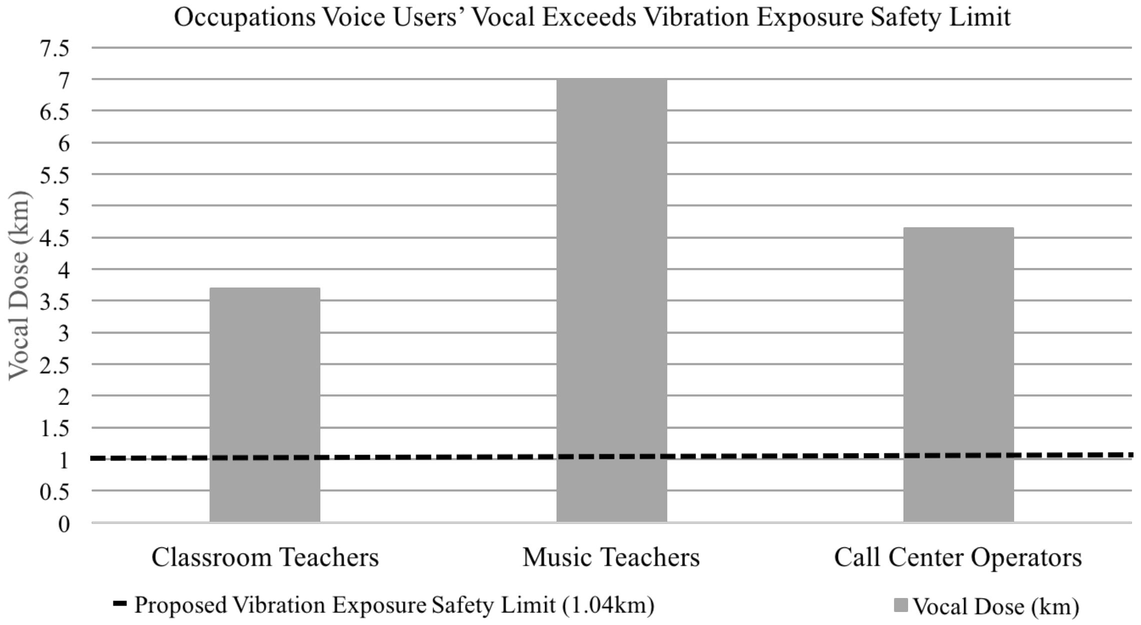
Prolonged voice use has been likened to an exposure problem (e.g., exposure to sun rays or chemicals) because the surface tissues of the vocal folds are subjected to phonotraumatic tissue deformation and impact closure forces by rapid accelerations and decelerations between the vocal folds themselves and, therefore, can be quantified as vocal dose (Švec et al., 2003; Titze, Šve, & Popolo, 2003). Titze et al. (2003) discuss two mechanisms that potentially cause vocal problems: (1) energy dissipated in the vocal folds, with thermal agitation possibly breaking down molecular bonds, and (2) rapid acceleration and deceleration of the vocal fold tissue, causing an internal “whiplash.” These authors proposed that the dissipated energy in the vocal folds is proportional to amplitude squared and frequency squared, inversely proportional to vocal fold thickness squared, and directly proportional to tissue viscosity. Furthermore, these authors compared vocal fold vibrations to hand-transmitted vibrations in industrial tool use and vocal dose to the safety limits established for industrial tool use. Even though there are significant morphological differences between vocal fold vibration and hand-transmitted vibration, similar principles for calculating the tissue exposure through vibration were applied (Titze et al. 2003).

Given that hand-transmitted safety distance dose was limited to 500 meters per day, Titze et al., 2003 hypothesized a safety limit of .520 kilometers (approximately 17 minutes of continuous voicing) of accumulated distance for vocal fold vibration exposure. Pauses in phonation potentially allow the vocal fold tissues to recover from acceleration stress, so the authors asserted that the unvoiced pauses in connected speech decrease the voicing ratio to approximately .5 (50%), thus doubling the safe duration of phonation to approximately 35 minutes of continuous voicing (Titze et al., 2003).

Previous studies have reported elementary school classroom and school music teachers to have a daily average vocal dose of 3.688 kilometers (79 minutes of phonation) and 7.001 kilometers (107 minutes of phonation) respectively over the course of 5 days (Morrow & Connor, 2011). Cantarella et al. (2014) found the distance dose range of call center operators to range from .349 to 4.641 kilometers (range of 15-135 minutes) during work hours for a single work day. The vocal doses reported for elementary classroom and music teachers as well as the higher end of the range of call center operators are well above the suggested vibration exposure safety limit of 1.04 kilometers and 35 minutes of phonation proposed by Titze et al. (2003) as shown in Figure 1.

[Figure 1]

Figure 1: Vocal Doses Compared to Proposed Vibration Exposure Safety Limit



The vocal doses of various occupational voice users reported by Morrow and Connor (2011) and Cantarella, et al. (2014) exceed the vibration exposure safety limit for voice use proposed by Titze et al. (2003).

In addition to vocal dose, vocal load, which refers to the amount of work the laryngeal mechanism completes during phonation, is another measure to consider (Morrow & Connor, 2011). Vilkman, Lauri, Alku, Sala, and Sihvo (1999) described vocal loading as a combination of extended voice use and additional factors, such as background noise, acoustics, or air quality, all of which can affect the vibratory characteristics of the vocal folds, such as fundamental frequency, phonation type and loudness. Cantarella et al. (2014) indicated vocal load as a risk factor for the development of voice disorders and discussed the importance of evaluating vocal load via ambulatory phonation monitoring for occupational voice users.

Švec et al. (2003) defined five different vocal doses and developed formulas to calculate time dose, cycle dose, distance dose, energy dissipation dose, and radiated energy dose. The time, cycle, and distance calculations are most relevant to determining aggregate vocal dose for teachers. Technological advancement over the past several years has improved the accuracy and reliability of voice dose measurements, including total phonation time, fundamental frequency (F_0), and vocal intensity (dB SPL; Morrow & Connor, 2011). Several devices for voice monitoring were developed, including the Ambulatory Phonation Monitor (APM, PENTAX Medical, Lincoln Park, NJ, USA), the VoxLog (firmware 2.2.3, Sonvox AB, Umeå, Sweden) , and the VocaLog (Griffin Laboratories, Tumecula, CA; Van Stan, Gustafsson, Schalling, & Hillman, 2014). Van Stan et al. (2014) directly compared these three ambulatory monitoring devices and reported that all three devices differed in terms of size, cost, and capabilities, but all three devices registered sound pressure level (SPL) and percent phonation. The APM and VoxLog were capable of measuring fundamental frequency, but the VocaLog did not, which prevented the VocaLog from generating additional measures related to vocal dose. Furthermore, the APM was the only device capable of providing cycle dose and distance dose measurements. The VoxLog was equipped with an AAC and air MIC, which enabled it to estimate noise levels in the subject's environment. All devices were similar for acoustic results with the exception of VocaLog, which overestimated during of phonation time.

While vocal dose provides information about the aggregate amount of vibrations of the vocal folds over a given period of time, it does not provide any indication about the temporal aspects of voice use throughout a typical day, such as patterns of voicing and pauses in conversations or periods of voice rest. Temporal aspects of skeletal muscle use are important to understand when taking into consideration the probable bioenergetic pathways used by the intrinsic laryngeal skeletal muscles.

Titze, Hunter, Švec (2007) analyzed voice accumulation data of teachers for patterns of voice use throughout the entire day. Rather than looking at aggregate vocal dose, these authors identified distributions and durations of continuous voicing and silence periods in the dosimetry data. Logarithmic bins were used to group periods of voicing and periods of silence based on duration in seconds, with data collection intervals of 30 milliseconds. They found the overwhelming majority of voiced segments to be in bins representing 3 seconds or less. Longer voicing periods were found to be very infrequent: voicing between 10 and 31.6 seconds occurred approximately once every 10 hours and voicing between 31.6 and 100 seconds occurred approximately once every two days. These findings are congruent with respiratory constraints placed upon maximum continuous phonation and are consistent with the articulatory sequencing of intermittent voiceless consonants in connected speech. Additionally these authors reported a classroom teacher's voice turned off and on around 20,000 times per day, which they proposed may be a fatiguing factor. They also found voicing and silence periods to be equivalent in number of occurrences.

This data reported on distribution and duration of continuous voicing provides a magnified analysis of how the voice is used throughout reported aggregate vocal doses. Temporal durations of voicing can be interpreted through the lens of exercise science principles to infer which muscle energy systems are used during the day to complete voicing tasks. Durations of silence can be useful in determining recovery periods. Determining which energy systems are used, if they can be upregulated using exercise science training principles and if adequate recovery is present to replenish fuel stores, provides a new framework for habilitating and rehabilitating occupational voice users, such as teachers.

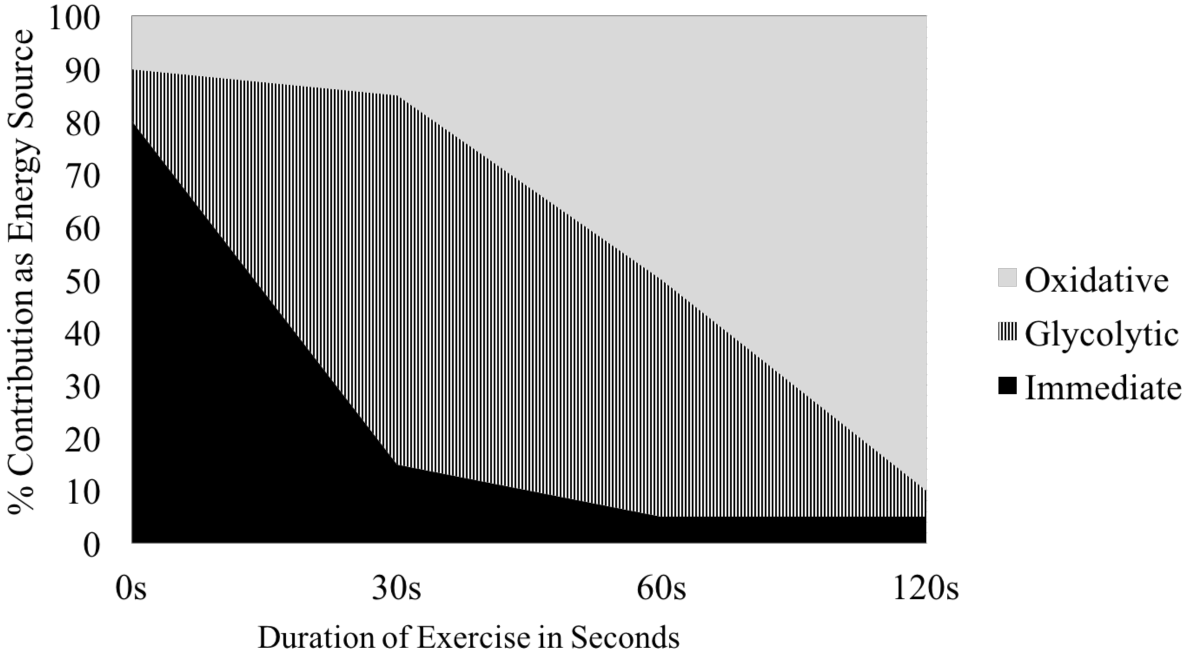
Skeletal Muscle Bioenergetics

Bioenergetics refers to the energy sources muscle fibers use for contraction (Hoffman, 2002). According to Brooks et al. (2004), the human body uses three energy systems to produce adenosine triphosphate (ATP), the primary muscle fuel required to power muscular movements. The three primary energy systems function in different conditions, at different speeds, and for different durations. Each of the energy systems correlate to one of the athletic activities of the body: power (e.g., shot putting), speed (e.g., 100-m sprinting), and endurance (marathon running). Each of these activities requires the biochemical mechanisms that support ATP homeostasis. In the human body, energy conversion occurs within each cell in the presence of a substrate that can both receive energy input from energy-yielding reactions and yield energy to reactions requiring an energy input, usually ATP. ATP is composed of a nitrogenous base (adenine), a five-carbon sugar (ribose), and three phosphates. Removing the terminal phosphate from ATP results in adenosine diphosphate (ADP), and removing two phosphates from ATP results in adenosine monophosphate (AMP). This degradation of ATP supplies the chemical energy required to power muscle contraction, regardless of which energy system is providing the ATP.

In limb skeletal muscle, three primary bioenergetic pathways have been identified: the immediate energy system, glycolysis, and oxidative phosphorylation. The immediate energy system (creatine phosphate as the fuel substrate for production of ATP) and glycolysis (circulating glucose and stored glycogen for ATP substrate) are both anaerobic pathways. Oxidative phosphorylation is an aerobic pathway, relying on oxygen as the fuel substrate (Powers & Howley, 2012). In physical efforts that require power, such as throwing a shot put, muscle activity lasts for only a few seconds, and the muscle cells used rely primarily on the immediate energy system. For speed activities, i.e., rapid and forceful activities lasting from a few seconds to one minute, such as the 100-meter sprint, skeletal muscle relies primarily on non-oxidative glycolytic energy sources as well as immediate energy sources. For endurance activities where skeletal muscles are engaged for longer than 2-3 minutes, such as middle distance and marathon running, oxidative phosphorylation takes over for the primary bioenergetic pathway to support muscle contraction. All three energy systems are “turned on” at the onset of physical activity; however, oxidative phosphorylation becomes the primary system for production of ATP after 2-3 minutes of continuous exercise as shown in Figure 2.

[Figure 2]

Figure 2: Time Based Analysis of Bioenergetic Pathways



All energy systems are activated at the onset of exercise. The immediate energy system is largely depleted after approximately 15 seconds of exercise, therefore, exercise lasting longer requires supplemental energy sources. The glycolytic system is the next muscle fuel that is consumed and is depleted after approximately 45-60 seconds of exercise. Oxidative phosphorylation becomes the primary bioenergetic source after 120-180 seconds of exercise, depending on fitness level.

Immediate energy sources are so named because they are immediately available for muscle contraction (Brooks et al., 2004). Creatine phosphate (CP), the cellular source of immediate energy, is a high-energy phosphorylated compound existing at approximately five times greater concentrations than ATP in resting muscle. CP acts as a reserve of phosphate energy to regenerate the ATP consumed during muscle contraction. The enzyme creatine kinase catalyzes the interaction of CP and ADP to result in ATP. The concentration of ATP and energy reserve prevalent in a cell cannot sustain muscle contraction for more than a few seconds; therefore, muscle contraction lasting longer than 15 seconds require supplemental energy sources.

Glycolytic, non-oxidative energy sources are consumed when muscle activity lasts longer than a few seconds and involves the breakdown of a simple sugar (i.e., glucose) and stored carbohydrates (i.e., glycogen; Brooks et al., 2004). Skeletal muscle tissue contains high concentrations of glycolytic and glycogenolytic enzymes, so muscles specialized in these processes can rapidly break down glucose and glycogen yielding a lactate anion and a proton at physiological pH. Skeletal muscle contains low amounts of free glucose, causing most of the non-oxidative energy to come from breaking down stored glycogen. The glycogen reserves of energy found in skeletal muscles are supplemented with glucose supplied from the blood, stored glycogen in the liver, and fats and amino acids that exist in the muscle. Glucose in the bloodstream is consumed as needed by skeletal muscle, and special receptors move to the surface of the cell during muscle activity to offload circulating glucose. In glycolysis, one molecule of glucose produces 2 molecules of ATP; furthermore, the quantitative energy available from glycolytic energy sources is greater than that available from immediate energy sources, but the combined energy provided by glycolytic and immediate energy sources are a fraction of the energy available from oxidative energy sources.

Oxidative energy sources for muscles include sugars, carbohydrates, fats, and certain amino acids (Brooks et al., 2004). Oxidative mechanisms of energy production allow more energy to be liberated from a glucose molecule than from glycolytic energy production because the breakdown of glucose is longer and more involved, which yields more ATP to be produced (36 molecules of ATP in oxidative vs 2 molecules of ATP in nonoxidative energy production). At the onset of muscle activity, immediate energy systems are activated. If muscle activity continues, depleting the immediate energy supply, glycolysis predominates to power muscle activity, and when muscle activity exceeds the capacity of glycolytic energy, oxidative phosphorylation takes over as the energy source.

Skeletal Muscle Fiber Type Characteristics

Skeletal muscles are composed of thousands of muscle cells called muscle fibers (Hoffman, 2002). Muscle contraction occurs as a result of stimulation of the central nervous system, which initiates an electrical impulse that propagates along the nerve cell, called a neuron. A neuron is comprised of three parts: the cell body or soma; short projections called dendrites; and the axon, which carries the electrical impulse from the soma toward the muscle fiber. The neuromuscular junction is the connection between the neuron and the muscle fiber. Collectively, the neuron and the muscle that it innervates are referred to as a motor unit. The motor unit comprises the functional unit of movement (McArdle, Katch, & Katch, 2010). Although motor units function similarly, they have specific contractile and metabolic characteristics. Some motor units are designed for aerobic metabolism, which refers to energy-generating catabolic reactions when oxygen is present, where other motor units are better suited for anaerobic activity, during which oxygen is absent (Hoffman, 2002; McArdle et al., 2010).

Two distinct muscle fiber types have been identified according to their contractile and metabolic characteristics; slow twitch fibers (type I) and fast-twitch fibers (type II). The contractile properties of skeletal muscle are determined, in part, by the myosin heavy chain (MHC) isoform, which determines the maximum contraction speed of a muscle fiber (Larsson &

Moss, 1993; Shiotani, Westra, & Flint, 1999). MHC composition is important for the functional characterization of muscle fibers. Type I fibers are fatigue resistant fibers, and therefore, are more suited for prolonged, low-to moderate intensity activity and primarily generate energy through aerobic pathways. Type I muscle fibers primarily produce ATP through oxidative pathways; therefore, type I fibers are highly fatigue resistant and suited for prolonged aerobic exercise (McArdle et al., 2010). Type I fibers are most likely found in abundance in endurance athletes, e.g., distance runners, cross country skiers (McArdle et al., 2010).

Type II fibers are better suited for shorter, higher intensity activity and can be broken down into type IIa and type IIx fibers (Hoffman, 2002; McArdle et al., 2010). Type IIa fibers are referred to as fast, fatigue-resistant, oxidative glycolytic fibers (FOG), which means they rely on both oxidative phosphorylation and glycolysis for energy production. They have the capacity for both aerobic and anaerobic metabolisms. Type IIx fibers, or fast, fatigable glycolytic fibers (FF), have the greatest capacity for anaerobic metabolism. Type IIa & IIx fibers are both anaerobic fibers, but in different capacities. Type IIx rely solely on anaerobic (glycolytic) metabolism to produce energy. It should be noted that while biochemical and contractile differences exist between muscle fiber types, these fiber types do not generally function in isolation, but rather form a continuum. Additionally, whole muscles, which are made up of many motor units, are generally comprised of a combination or hybrid of muscle fiber types.

The muscle fiber compliment in limb skeletal muscle is usually estimated at 50% type I fibers and 50% type II fibers, except for in elite athletes (Powers & Howley, 2012). A study of 70 sixteen year old males and 45 sixteen year old females revealed 52% of the vastus lateralis muscle was slow twitch fibers for both sexes, and within the fast twitch fibers, 33% were Type IIa fibers and 14% were Type IIb fibers (Hedberg & Jansson, 1976). These findings were consistent with the percentages of muscle fiber types in adult women (Nygaard & Goricke, 1976). The vastus lateralis, rectus femoris, gastrocnemius, bicep, and deltoid muscles appear to be composed of 50% slow twitch and 50% fast twitch muscle fibers (Saltin, Henriksson, Nygaard, Andersen, & Jansson, 1977).

The literature suggests there are outliers who are genetically predisposed to a greater percentage of one fiber type over another, such as elite athletes. According to Brooks et al. (2004), specialized muscle fiber type compliments have been found in elite athletes. The muscle fiber distribution predisposes the elite athlete to perform the athletic requirements of their sport. For example, according to Brooks et al. (2004), elite sprinters have been found to have a higher proportion of fast glycolytic muscle fibers (i.e., power fibers) while elite distance runners have been found to have a higher proportion of slow-twitch oxidative fibers (i.e., endurance fibers). Type I fibers are most likely found in abundance in endurance athletes, e.g., distance runners, cross country skiers (McArdle et al., 2010). Succinate dehydrogenase (SDH) is an enzyme of the Krebs cycle that is measured to provide a quantitative analysis of the up regulation of the oxidative potential of endurance-trained athletes (Hoffman, 2002). While SDH activity of untrained men and women are 8-9 mM/kg·min, elite distance runners and swimmers have SDH activities of 20-25 mM/kg·min (Saltin et al., 1977). Highly trained cross country runners have SDH activity levels of 21 mM/kg·min in their gastrocnemius muscles, and the activity of the Type II fibers is comparable to the Type I fibers, which suggests Type II fibers can also adapt to increase oxidative capacity (Saltin et al., 1977; Wahren, Felig, Ahlborg, & Jorfeldt, 1971). If there are elite athletes who are outliers to the normal muscle fiber type distribution, the potential of vocal outliers with genetic predisposition to certain vocal tasks over others should be considered and investigated.

Laryngeal Skeletal Muscle Fiber Types and Characteristics

While there is abundant research about the muscle fiber compliment of limb skeletal muscle, there has been limited research done to determine the fiber type profiles of the intrinsic laryngeal skeletal muscles. Most of the research conducted has been based on animal models. The intrinsic laryngeal muscles include four paired muscles, the thyroarytenoid (TA), lateral cricoarytenoid (LCA), posterior cricoarytenoid (PCA), and cricothyroid (CT) and one unpaired muscle, the interarytenoid (IA) (Hoh, 2005). While limb skeletal muscle is primarily responsible for locomotion, intrinsic laryngeal muscles are responsible for airway protection, respiration, and phonation (Hoh, 2005). In animal models skeletal muscle fiber types are classified as type I (slow-contracting) and type II (fast-contracting), which are further sub classified as types IIa, IIb, and IIx (Gorza, 1990). Translation of animal muscle fiber findings to human physiology should be done with care given the physiological differences between the upper airway requirements between species.

Human laryngeal muscles have been described to express type I, IIa, and IIx isoforms similar to fiber types seen in limb skeletal muscle (Tellis, Rosen, Thekdi, & Sciote, 2004). Few studies have been conducted to investigate the specific muscle fiber compliment of the intrinsic laryngeal muscles in humans. The ratio of percent of Type I fibers to Type II fibers in laryngeal muscles varied greatly between three adult human cadavers (Rosenfield, Miller, Sessions, & Patten, 1982). Even though the total number of muscle fibers counted in the whole muscle were similar, each of the three cadavers exhibited a different distribution of type I and II fibers. In the thyroarytenoid muscle, cadaver 1 had a higher composition of type II fibers (37 and 63% type I and II fibers respectively), cadaver 2 had a more equal distribution of type I and II muscle fibers (56% and 42% type I and II fibers respectively), and cadaver 3 had a greater proportion of type I fibers (65 and 35% type I and II fibers respectively). In the lateral cricoarytenoid muscle, cadaver 1 had a 50/50 distribution of type I and II muscle fibers, but cadavers 2 and 3 had an approximate 40/60 distribution of type I and II muscle fibers respectively. Additionally, all three cadavers had a muscle fiber compliment higher in Type I fibers than Type II fibers in the posterior cricoarytenoid muscle and a muscle fiber compliment higher in Type II than Type I in the cricothyroid muscle.

Shiotani et al. (1999) investigated the myosin heavy chain (MHC) composition of human cadaver intrinsic laryngeal muscles of nine middle aged and older adults. These authors used sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) and Western blot analysis to determine MHC composition. They found that human laryngeal muscle composition exhibited a predominance of fast-type MHC in laryngeal adductor (closing) muscles and a mixed fast-slow type in respiratory and phonatory muscles. Additionally, a MHC band migrating between type IIa and type I was found in all laryngeal muscles, which is similar in position to type IIL found in rats. This indicates the possible presence of superfast type IIL muscle fibers in the larynx. The thyroarytenoid muscle is made up of two muscular components: the thyromuscularis and the thyrovocalis, or simply the vocalis (Stemple, Glaze, & Klaben, 2010). Shiotani et al. (1999) reported MHC composition for the vocalis (VOC) specifically and the thyroarytenoid muscles, generally. These authors found higher percentages of type IIa muscle fibers than type IIb or type I in each of the intrinsic laryngeal skeletal muscles (ILSMs).

Overall, Shiotani et al. (1999) reported lower percentages of type I fibers than Rosenfield et al. (1982), particularly for the PCA, which were previously reported to predominantly consist of type I fibers. One explanation for the incongruent findings of these studies could be related to the ages of the cadavers; during the aging process, there tends to be a change from type I to type

II fibers (MacIntosh, Gardiner, & McComas, 2006). Since the ages of the cadavers in the Rosenfield study were not reported, this cannot be confirmed. Additional basic research is needed to better describe the muscle fiber compliment of human ILSMs through the lifespan. Another difficulty in comparing the results of these two studies lies in the nomenclature used and method of reporting muscle fiber types. Rosenfield et al. 1982 reported muscle fiber types as either type I or type II, while Shiotani et al. 1999 reported type I, type IIa, and type IIb. This difference makes translation of data from one study to the other more difficult. Shiotani reported the findings in a table of means and standard deviations, so combining the type II groups is not feasible without the raw data. It should also be noted that in humans, type IIb fibers are currently referred to as type IIx fibers, which are considered to be undifferentiated muscle fibers.

Han, Wang, Fischman, Biller, and Sanders (1999) investigated the presence of slow tonic muscle fibers in the TA muscle of nine human cadavers. Slow tonic muscle fibers (STFs) are unique muscle fibers because they contract in slow, stable, prolonged contractions instead of a twitch (Han et al., 1999). The contractions of STMs are precisely controlled and fatigue resistant. STMs are also found in the human extraocular muscles (Bormioli, Torresan, Sartore, Moschini, & Schiaffino, 1979). Immunofluorescence microscopy and immunoblotting studies indicated the presence of STF in all nine cadaver TA muscles, predominantly in the region of the vocalis muscle. These authors proposed that STF may contribute to the TA's function of pitch modulation and regulation during phonation, as they are found in human larynges and not in the larynges of other mammals.

Skeletal Muscle Adaptations to Exercise

Skeletal muscle adapts in conditions of muscle use, disuse and, detraining. With skeletal muscle exercise of sufficient intensity and frequency, muscle physiology adapts via neurologic, morphologic, and bioenergetics mechanisms (Powers & Howley, 2012). With endurance training significant adaptations occur to the metabolic features of muscle fibers, which are primarily expressed as an increase in mitochondrial proteins and oxidative enzymes that matches the increased demand on oxidative capacity (Brooks et al., 2004). Metabolic and musculoskeletal adaptations that occur during endurance training include increases in: mitochondrial size and number, oxidative enzymes, capillary density, and reliance on stored fat as an energy (Hoffman, 2002). Endurance training increases the body's ability to aerobically produce ATP efficiently (Hoffman, 2002). There are two primary types of athletic endurance: muscular and cardiorespiratory. Muscular endurance refers to the capability of a muscle or group of muscles to engage in sustained, high-intensity, or static activity, while cardiorespiratory endurance is the ability to sustain long-duration exercise (Hoffman, 2002). Improving cardiorespiratory endurance is the goal of many athletes including distance runners, swimmers, and cyclists (Hoffman, 2002). Endurance trained athletes had a high percentage of Type IIa muscle fibers and few to no Type IIb muscle fibers in the muscles involved in training, but the muscles partially engaged or not engaged in training had a normal percentage of Type IIb fibers (Saltin et al., 1977). It has been suggested that the lack of Type IIb fibers is an adaptive response to endurance training (Saltin et al., 1977).

The aim of anaerobic conditioning is to facilitate high-intensity activity with rapid recovery between each bout of exercise. This rapid recovery enables the athlete to engage in repeated activities without experiencing a decrease in performance (Hoffman, 2002). Physiologic adaptations that occur with anaerobic exercise include: transformation of type II fibers to a more glycolytic subtype, significant glycolytic enzyme elevations, an increase in maximum blood lactate concentrations, a decrease in lactate concentrations during submaximal exercise, and an increased buffing capacity (Hoffman, 2002). Athletes such as basketball or football players primarily train for anaerobic conditioning.

Teachers as Vocal Athletes

Currently, habilitation and rehabilitation for teachers is not tailored to their specific voice use patterns. Because athletes train for the physical requirements of their sport (e.g. endurance or power), it is likely that training and rehabilitation specific to voice use patterns would be beneficial for professional voice users. In other words, from a perspective of muscle bioenergetics, it may be more useful to look at the voice use pattern temporally, over the course of a given voice bout or workday in addition to an aggregate measure of vocal load. For elementary school teachers, it is proposed that their laryngeal muscle activity is comparable to that of a football player or a sprinter. Because teachers pose and entertain questions, provide practice problems for students to answer, and engage the class in discussion, it is probable that the voice use of a teacher relies primarily on immediate as well as glycolytic energy sources, e.g., short bursts of high sound level voice with frequent breaks from talking. Individual teaching style, grade and subject taught could all influence the laryngeal muscle activity profile, which in turn, influences the energy sources used for muscle contraction. A college professor, who lectures extensively, may have a different temporal profile than an elementary school teacher. The vocal dose may appear similar as an aggregate measure; however, the manner in which the voice use is distributed over a period of time may differ. Use of voice more extensively over a shorter period of time may indicate a muscle use pattern more similar to that of an endurance athlete. In these ways, teachers may be a heterogeneous population, requiring different voice assessment and treatment approaches that are matched to the specific needs of the individual. In order to describe teachers by their voice use profile, what their vocal folds are doing should be temporally analyzed.

Before we can describe time intervals throughout a day, we have to quantify durations of voicing and silence so we can systemically describe what a voice profile looks like during a given period of time. Therefore, the primary aim of this investigation is to establish temporal profiles for previously collected elementary school classroom and music teachers via custom-designed computer analysis of previously collected APM data (Morrow & Connor, 2011). Given the constraints of pulmonary volume on phrase length during speech and the intermittent use of voiceless sounds (i.e., /t, s/) it was hypothesized that temporal study of phonatory engagement and disengagement intervals using data gathered with an Ambulatory Phonation Monitor (APM) would indicate a reliance on anaerobic bioenergetic pathways for the intrinsic laryngeal skeletal muscles.

III. Manuscript

Elementary School Teachers' Vocal Dose: Muscle Bioenergetic and Training Implications

Introduction

Teachers worldwide have a higher prevalence of voice-use problems than non-teachers and are believed to be at a higher risk for the development of voice disorders (Morrow & Connor, 2011; Russell et al., 1998; Smith et al., 1997). The financial impact of lost days at work, diagnosis and treatment, and reduction in overall work productivity for teachers with voice disorders parallels that for annual healthcare costs spent to treat pediatric ear infections (Ramig & Verdolini, 1998). There is an emerging body of literature dedicated to understanding the vocal requirements of high risk occupations in order to better habilitate and rehabilitate voice disorders of professional voice users. Prevention and remediation of voice disorders in teachers requires additional physiologic inquiry as to the nature of their specific voice use requirements.

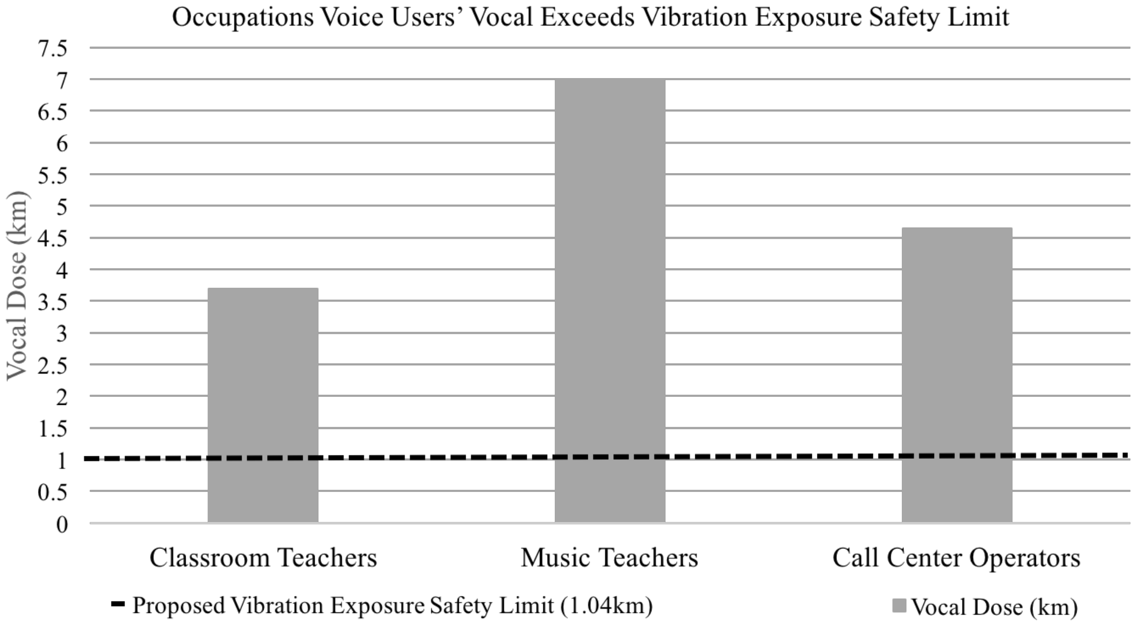
The aggregate amount of voice use during a teacher's workday, referred to as vocal dose, is one performance variable that has been of recent interest. Voice use can be quantified in doses as the total distance the vocal folds travel during a given period of time (Titze et al., 2003). Prolonged voice use and vocal dose measurements have been likened to an exposure problem (e.g., exposure to sun rays or tissue vibration) due to the impact of closure forces and rapid acceleration and deceleration of the vocal folds during phonation over a period of time (Švec et al., 2003; Titze et al., 2003). These authors compared vocal fold vibrations to hand-transmitted vibrations in industrial tool use and vocal dose to the safety limits established for industrial tool use. Even though there are significant morphological differences between vocal fold vibration and hand-transmitted vibration, similar principles for calculating the tissue exposure through vibration were applied (Titze et al., 2003). These authors described a safety limit of .520 kilometers of accumulated distance for vocal fold vibration exposure. This accumulated distance can be quantified as approximately 17 minutes of continuous voicing. Pauses in phonation potentially allow the vocal fold tissues to recover from acceleration stress, so the authors asserted that the unvoiced pauses in connected speech decrease the voicing ratio to approximately .5 (50%), thus doubling the safe duration of phonation to approximately 35 minutes of continuous voicing and 1.04 kilometers (Titze et al., 2003).

Ecologically valid data is preferred to understand the voice requirements for teachers than laboratory conducted studies. Laboratory studies are unable to recreate how the teacher uses his/her voice while at work for an extended period of time. An accurate depiction of how a teacher uses his/her voice throughout the day is important for understanding the requirements of the work, patterns of voice use, and probable bioenergetic pathways required to complete the work. There is an emerging body of literature quantifying the vocal doses of various occupational voice users, including teachers. It is widely accepted that elementary school classroom and music teachers use their voices for extended periods of time and at elevated sound pressure levels. Morrow and Connor (2011) conducted a study to quantify and compare the amount and intensity of vocal use of these two groups. These authors investigated vocal load, which they defined as cycle dose, the number of vibratory cycles, and distance dose, the latter of which was determined as the distance the vocal folds traveled in accordance with Švec et al. (2003). The Ambulatory Phonation Monitor (APM; PENTAX Medical, Montvale, NJ) was used to accumulate the acoustic data and calculate the cycle dose and distance dose each day for each participant. Morrow and Connor (2011) described elementary school classroom and music teachers to have a daily average vocal dose of 3.688 kilometers (79 minutes of phonation) and 7.001 kilometers (107 minutes of phonation) respectively over the course of 5 days. The discrepancy between classroom and music teachers was attributed to the longer phonation intervals, wider range of fundamental frequencies used, and higher vocal sound levels required for music teachers.

Cantarella et al. (2014) investigated the daily vocal dose of call center operators. They found the distance dose range of call center operators to range from .349 to 4.641 kilometers (range of 15-135 minutes) during work hours for a single work day. Additionally, these authors reported a significant difference between the percentage of phonation time during work time (i.e. during hours at work) and in extra work time (i.e. during hours not at work). Interestingly, the subjects with higher percentage of phonation time during work time maintained a high percentage of phonation time during extra work time. The vocal doses reported for elementary classroom and music teachers as well as the higher end of the range of call center operators are well above the vibration exposure safety limit of 1.04 kilometers and 35 minutes of phonation proposed by Titze et al. (2003) as shown in Figure 3.

[Figure 3]

Figure 3: Vocal Doses Compared to Proposed Vibration Exposure Safety Limit



The vocal doses of various occupational voice users reported by Morrow and Connor (2011) and Cantarella, et al. (2014) exceed the vibration exposure safety limit for voice use proposed by Titze et al. (2003).

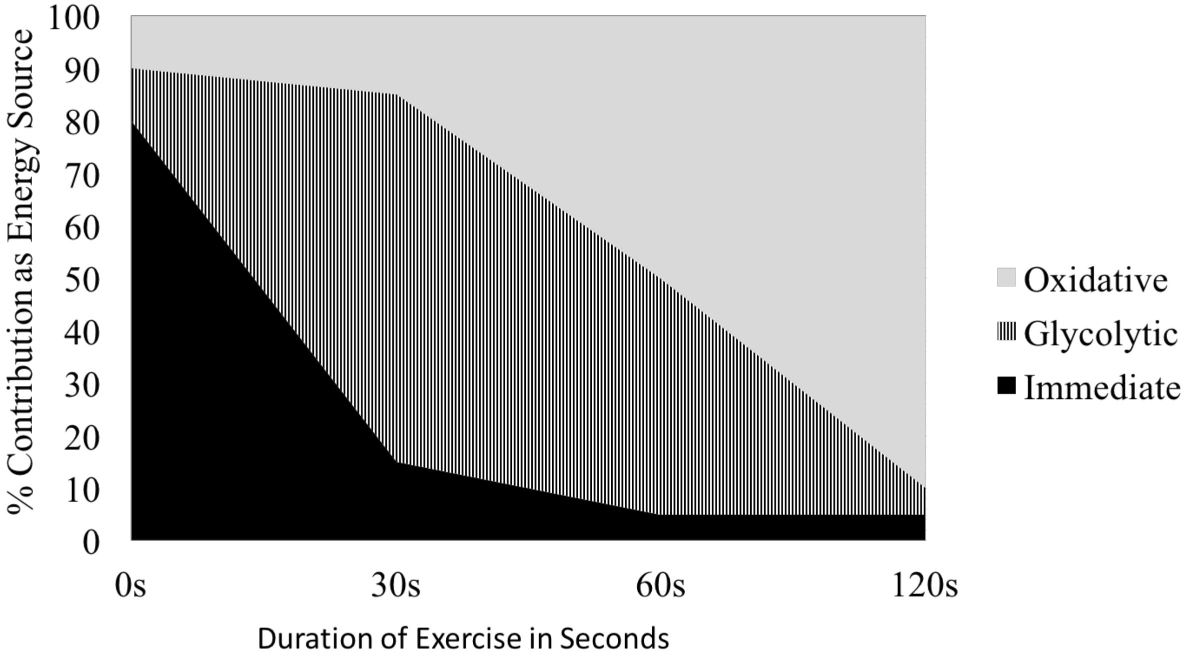
It has generally been assumed that individuals with voice disorders use their voice in a more phonotraumatic manner than individuals without voice disorders. Phonotraumatic behaviors are vocal activities thought to increase the risk of developing vocal lesions and disorders, including speaking at increased sound pressure levels (SPL), abnormal fundamental frequency (F_0), and/or for extended periods of time (Gillespie & Abbott, 2011; Verdolini, 1999). Van Stan et al. (2015) compared voice use profiles of 35 adult females with vocal fold nodules or polyps, and an age, sex, and occupation-matched control group. Ambulatory voice monitoring data were collected for one week for each participant using a miniature accelerometer (ACC; Model BU27135, Knowles Electronics, Itasca, IL). No differences were identified between participants with vocal pathology and matched controls for average SPL, F_0, vocal doses, and voicing/rest periods. Significant differences were found in F_0 between the groups in that the voice disorder group exhibited a lower F_0 than the control group. These findings may indicate a vocal adaptation to the pathology or an acoustic change due to the increased vocal fold mass secondary to the pathology. In any case, the findings did not identify a distinct voicing characteristic that could explain the development of the pathology.

There are several limitations to the use of aggregate vocal dose and vocal load parameters to understand occupation-specific voice use. Titze et al. (2003) compared vocal fold vibration exposure to the safety limits of hand-transmitted vibrations in industrial tool use. Cantarella et al. (2014) discussed two drawbacks to this comparison, the first being that the vocal folds are anatomically designed to sustain prolonged vibration, while other bodily tissues, such as the hands, are not. While this may be true, the nature of prolonged vibration has not been well described in the literature. A trained singer may hold a note for up to thirty seconds; however, in connected speech voicing intervals are rarely longer than 3 seconds, given the constraints of articulation features (i.e., voiced versus voiceless phonemes) and pulmonary volume (Titze, et al. 2007). Prolonged engagement of the intrinsic laryngeal muscles may be different than what we consider prolonged engagement of limb skeletal muscles. Cantarella's second criticism was that the measurement of hand excursion is continuous, therefore, it does not take into account the pauses and recovery periods inherently found in phonation. Recovery periods during muscle performance are an important consideration in exercise science; however, the role of recovery periods in the context of muscle use in the larynx have not been well researched (Bompa & Haff, 2009). To date, little attention has been paid to the muscle training aspects of voice function for teachers and other occupational voice users. Aggregate data is helpful in understanding the overarching profile of voice use; however, identifying the timing aspects of laryngeal muscle use and recovery will allow for application of bioenergetic training principles that are integral in exercise science.

Bioenergetics refers to the energy sources muscle fibers use for contraction (Hoffman, 2002). In limb skeletal muscle, three primary bioenergetic pathways have been identified to produce adenosine triphosphate (ATP), the primary muscle fuel required to power muscular movements: the immediate energy system, glycolysis, and oxidative phosphorylation (Brooks, Fahey, & Baldwin, 2004). Each of the three primary energy systems function in different conditions, at different speeds, and for different durations. The immediate energy system, which uses creatine phosphate as the fuel substrate for production of ATP, and glycolysis, which uses circulating glucose and stored glycogen for ATP substrate, are both anaerobic pathways. Oxidative phosphorylation is an aerobic pathway, relying on oxygen as the fuel substrate (Powers & Howley, 2012). In physical efforts that require power, such as throwing a shot put, muscle activity lasts for only a few seconds, and the muscle fibers used rely primarily on the immediate energy system. For speed activities, such as rapid and forceful activities lasting from a few seconds to one minute (e.g., 100-meter sprint), skeletal muscle relies primarily on non-oxidative glycolytic energy sources as well as immediate energy sources. For endurance activities where skeletal muscles are engaged for longer than 2-3 minutes, such as middle distance and marathon running, oxidative phosphorylation takes over for the primary bioenergetic pathway to support muscle contraction. As can be seen in Figure 4, all three energy systems are “turned on” at the onset of physical activity; however, the primary system for production of ATP is in part temporally dependent.

[Figure 4]

Figure 4: Time Based Analysis of Bioenergetic Pathways



All energy systems are activated at the onset of exercise. The immediate energy system is largely depleted after approximately 15 seconds of exercise, therefore, exercise lasting longer requires supplemental energy sources. The glycolytic system is the next muscle fuel that is consumed and is depleted after approximately 45-60 seconds of exercise. Oxidative phosphorylation becomes the primary bioenergetic source after 120-180 seconds of exercise, depending on fitness level.

While these bioenergetic pathways have a general temporal outline, they can be upregulated to become more efficient through skeletal muscle adaptation. Skeletal muscle adapts in conditions of muscle use, disuse and, detraining. With skeletal muscle exercise of sufficient intensity and frequency, muscle physiology adapts via neurologic, morphologic, and bioenergetics mechanisms (Powers & Howley, 2012). Athletic training is designed to produce specific skeletal muscle adaptations depending upon the specific muscle requirements of the sport, including bioenergetic pathways used to produce ATP. Training programs for power sports, such as soccer or football, would look very different than a training program for endurance sports, such as cross country running or skiing. The primary goal of endurance training is to increase the body’s ability to aerobically produce ATP efficiently, by adapting metabolic features of muscle fibers (Brooks et al., 2004). The aim of anaerobic conditioning is to facilitate high-intensity activity with rapid recovery between each bout of exercise. This rapid recovery enables the athlete to engage in repeated activities without experiencing a decrease in performance (Hoffman, 2002).

Currently, habilitation and rehabilitation for teachers is not tailored to their specific voice use patterns and little attention has been paid to the specific voice abilities required for work as a teacher. Because athletes train for the physical requirements (i.e., skill acquisition and fatigue resistance) of their sport (e.g. endurance or power), it is likely that training and rehabilitation specific to voice use patterns would be beneficial for professional voice users. In other words, from a perspective of muscle bioenergetics, it may be more useful to look at the voice use pattern temporally, over the course of a given voice bout or workday in addition to an aggregate measure of vocal load. The goals of this investigation were as follows: identify patterns of voice and silence intervals during a teacher’s workday, compare voice interval patterns between elementary school classroom and music teachers, and identify probable bioenergetic pathways used for patterns of voice use based on durations of voiced intervals. It was hypothesized that the majority of voiced interval use for both classroom and music teachers would be three seconds or less (Titze et al. 2007) indicating a reliance on the immediate energy system. Additionally, it was hypothesized that music teachers would have longer bouts of continuous phonation than classroom teachers due to the frequency of holding out notes when singing.

Methods

Participants

Data from seven elementary school music teachers and five elementary school classroom teachers who ranged in age from 24 to 58 years (mean age was 42.5 + 12.1 years) participated in a study conducted by Morrow and Connor (2011). Six of the seven music teachers and all classroom teachers were females. Participants did not have a history of vocal fold lesions, previous laryngeal surgery, or vocal trauma. The only exclusion criterion previous clinically established vocal fold pathology via self-report (Morrow & Connor, 2011).

Data Collection

Previously collected acoustic data gathered with the Ambulatory Phonation Monitor, Model 3200 (APM; PENTAX Medical, Montvale, NJ) was used for this investigation (Morrow & Connor, 2011). Each teacher wore the APM for 7.5 continuous working hours over the course of several days. The APM recorded the fundamental frequency, vocal intensity, and phonation time twenty times per second for each workday. Calibration protocols were conducted as indicated by the manufacturer prior to each trial (Morrow & Connor, 2011).

Data Analysis

Applying the temporal aspects of muscle bioenergetic utilization, the raw APM data were analyzed for durations of continuous voicing and silence. The analysis was performed using an algorithmic procedure with the R Programing Language (www.r-project.org), for all participants (5 classroom teachers and 7 music teachers). The data collected for each teacher varied from 3 to 14 work days. The length of the *voicing* and *silence* intervals were calculated in increments of 0.05 seconds, the factory setting for the APM. The data were first analyzed for voicing and silence durations. These durations were determined via R analyses of the data cells from the

APM that recorded fundamental frequency. The cells were analyzed for presence or absence of a fundamental number and if the value was zero, it was classified as silence and if a fundamental frequency value was present it was classified as voicing. Contiguous cells of silence were calculated for interval length, and the length of the interval was recorded in increments of 50 milliseconds, according to the recorded cell unit parameter of the APM. The same procedure was completed for contiguous cells of voicing. Reliability of the R-generated algorithm was verified through simulation with a known data set. Due to the large range of the voicing and silence intervals, they were organized into 9 different bins based on the voicing and silence intervals, each of which had a defined temporal range described in seconds (s), as described by Titze et al. (2007). This resulted in in the following bins: [0,0.05],(0.05,0.1],(0.1,0.35],(0.35,1],(1,3.15], (3.15,10],(10,31.5],(31.5,100],(100,+∞).

A multivariate analysis of variance (MANOVA) was used to test for the differences between and within the two groups, classroom teachers and music teachers, for the voicing and silence intervals when multiple response variables were present. Three MANOVA tests were completed (differences between classroom and music teacher groups, differences within the classroom teacher group, and differences within the music teacher group), and each test consisted of two analyses (differences between voicing intervals and differences between voicing intervals). When evaluating the MANOVA, the last 3 bins - (10, 31.5), (31.5, 100), (100, ∞) – were excluded from the voicing percentages, since no voicing observations were present in these bins. Descriptive statistics were used to evaluate the data for probable bioenergetics pathways used for the intrinsic laryngeal muscles during the teachers' work day.

Results

Data were visually analyzed in a time based fashion to look at probable bioenergetic pathways used throughout the day using the temporal constraints described in Figure 4. The mean voicing/silence interval data for each participant are described in Tables 1 and 2. Table 3 describes the means and standard deviations for each group. The aggregate voice use data is presented in a bar chart in Figure 5, with the height of each bin drawn in a logarithmic scale, to better represent the large variation among the bins (Titze et al., 2007). The analysis revealed that 99.98% of classroom teachers' voicing intervals and 99.95% of music teachers' voicing intervals were in the bins representing 3.15 seconds or less.

[Table 1]

Table 1: Classroom Teacher Means and Standard Deviations

Participant	Classroom/ Music	Days Analyzed	Voicing/ Silence	0.05	0.1	0.36	1.0	3.15	10.0	31.5	100.0	100.0+
CF1	Classroom	5	Voicing	12.0% (7.5%)	7.4% (0.5%)	20.0% (5.1%)	9.9% (2.1%)	0.7% (0.2%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	5.7% (3.5%)	8.8% (0.5%)	19.3% (3.7%)	6.8% (1.1%)	5.8% (0.5%)	2.5% (0.6%)	0.8% (0.3%)	0.2% (0.1%)	0.1% (0.0%)
CF2	Classroom	5	Voicing	24.7% (0.8%)	6.8% (0.2%)	10.2% (0.3%)	6.9% (0.4%)	1.4% (0.1%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	14.6% (0.6%)	8.7% (0.2%)	13.5% (0.2%)	8.4% (0.3%)	4.2% (0.4%)	0.7% (0.2)	<0.01% (<0.01%)	<0.01% (<0.01%)	0.0% (0.0%)
CF3	Classroom	6	Voicing	19.7% (1.6%)	5.8% (0.3%)	14.8% (0.9%)	8.7% (0.6%)	0.9% (0.2%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	13.4% (0.9%)	8.7% (0.5%)	10.8% (0.4%)	8.0% (0.6%)	6.9% (0.7%)	1.9% (0.3%)	0.2% (0.1%)	<0.01% (<0.01%)	<0.01% (<0.01%)
CF4	Classroom	5	Voicing	22.3% (1.6%)	5.9% (0.2%)	12.2% (0.6%)	8.6% (0.9%)	1.0% (0.2%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	11.8% (0.9%)	8.3% (0.5%)	11.8% (0.5%)	8.1% (0.4%)	7.3% (0.7%)	2.3% (0.7%)	0.4% (0.2%)	<0.01% (<0.01%)	0.0% (0.0%)
CF5	Classroom	3	Voicing	19.9% (1.7%)	7.1% (0.2%)	14.0% (1.0%)	8.2% (0.6%)	0.8% (0.0%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	15.4% (0.6%)	9.9% (0.5%)	11.2% (0.4%)	07.5% (0.7%)	05.0% (0.1%)	0.9% (0.1%)	0.1% (0.0%)	<0.01% (<0.01%)	0.0% (0.0%)

[Table 2]

Table 2: Music Teacher Means and Standard Deviations

Participant	Classroom/ Music	Days Analyzed	Voicing/ Silence	0.05	0.1	0.36	1.0	3.15	10.0	31.5	100.0	100.0+
MF1	Music	10	Voicing	15.2% (4.9%)	6.4% (0.9%)	17.3% (3.1%)	9.9% (1.1%)	1.2% (0.3%)	<0.01% (<0.01%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	10.1% (4.5%)	10.6% (0.8%)	15.3% (4.1%)	7.6% (0.4%)	4.6% (0.5%)	1.3% (0.3%)	0.3% (0.1%)	0.1% (0.0%)	<0.01% (<0.01%)
MF2	Music	10	Voicing	18.4% (1.8%)	5.5% (0.4%)	14.9% (1.2%)	10.0% (0.9%)	1.3% (0.3%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.1% (0.0%)
			Silence	13.0% (0.5%)	9.6% (0.7%)	11.1% (0.5%)	7.3% (0.6%)	6.2% (0.6%)	2.3% (0.4%)	0.4% (0.1%)	0.10% (0.0%)	<0.01% (<0.01%)
MF3	Music	12	Voicing	21.2% (1.8%)	6.3% (0.3%)	14.3% (1.2%)	7.3% (0.8%)	0.8% (0.2%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	13.5% (0.6%)	8.4% (0.2%)	12.9% (0.6%)	8.5% (0.4%)	5.2% (0.4%)	1.3% (0.3%)	0.2% (0.1%)	<0.01% (<0.01%)	<0.01% (<0.01%)
MF4	Music	14	Voicing	19.0% (1.8%)	5.5% (0.3%)	15.4% (1.0%)	9.1% (0.8%)	1.0% (0.3%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	13.6% (0.8%)	9.3% (0.5%)	11.4% (1.0%)	7.4% (0.6%)	6.0% (1.0%)	2.0% (0.5%)	0.3% (0.1%)	<0.01% (<0.01%)	<0.01% (<0.01%)
MF5	Music	7	Voicing	20.6% (3.3%)	5.2% (0.3%)	12.6% (1.8%)	9.8% (1.5%)	1.8% (0.5%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	13.9% (1.2%)	9.3% (1.0%)	11.4% (0.2%)	8.0% (0.6%)	5.4% (1.0%)	1.6% (0.6%)	0.3% (0.2%)	<0.01% (<0.01%)	<0.01% (<0.01%)
MM1	Music	7	Voicing	23.4% (3.0%)	6.1% (0.8%)	12.3% (1.5%)	7.2% (1.9%)	1.1% (0.4%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	14.1% (1.2%)	8.1% (0.3%)	12.7% (0.5%)	8.9% (0.6%)	4.9% (0.8%)	1.0% (0.3%)	0.2% (0.1%)	<0.01% (<0.01%)	<0.01% (<0.01%)
MM2	Music	8	Voicing	17.2% (1.1%)	5.6% (0.3%)	14.9% (0.9%)	10.2% (0.6%)	2.0% (0.3%)	0.1% (0.0%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
			Silence	15.9% (0.9%)	9.7% (0.2%)	13.0% (0.6%)	6.9% (0.4%)	3.7% (0.5%)	0.8% (0.2%)	0.1% (0.0%)	<0.01% (<0.01%)	<0.01% (<0.01%)

The interval data for each participant is provided in the above tables. The APM data for each participant was averaged over the number of data collection days. The intervals of voicing and silence were divided into bins according to duration of the interval in seconds. The data are presented as the average percentage of the total intervals that fell into that particular bin in the format of Mean % (SD). Due to the antagonistic relationship between voicing and silence and the sampling rate of the APM, the voicing and silence percentages should collectively sum to approximately 100%. For all participants, the majority of the intervals were no longer than 3.15 seconds in duration.

[Table 3]

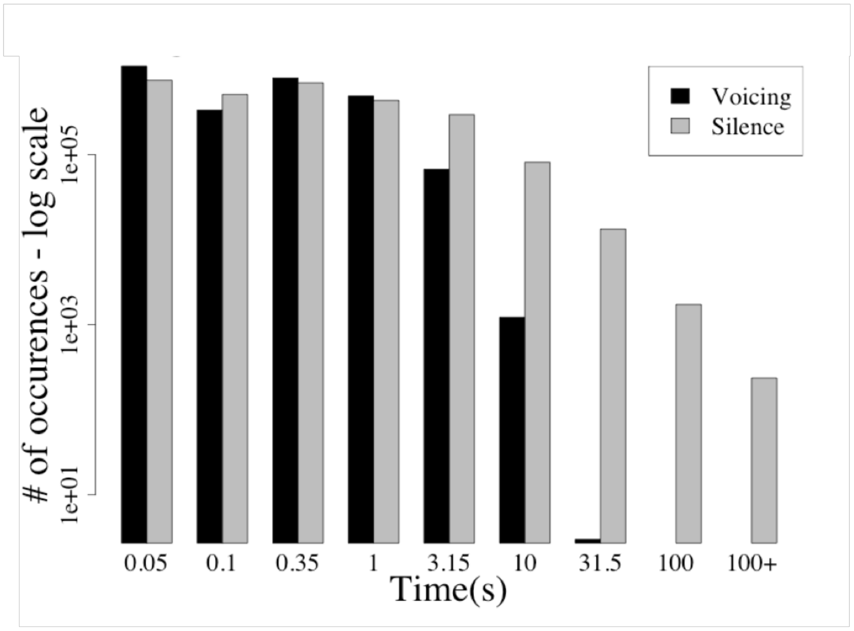
Table 3: Classroom and Music Teacher Group Means and Standard Deviations

Group	Voicing/ Silence	0.05	0.1	0.36	1.0	3.15	10.0	31.5	100.0	100.0+
Classroom	Voicing	19.7% (5.6%)	6.5% (0.7%)	14.3% (4.1%)	8.5% (1.4%)	1.0% (0.3%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
Classroom	Silence	11.9% (3.8%)	8.8% (0.6%)	13.4% (3.6%)	7.8% (0.9%)	6.0% (1.3%)	1.7% (0.8%)	0.3% (0.3%)	0.1% (0.1%)	<0.01% (<0.01%)
Music	Voicing	19.1% (3.5%)	5.8% (0.6%)	14.7% (2.2%)	9.0% (1.6%)	1.2% (0.5%)	<0.01% (<0.01%)	<0.01% (<0.01%)	0.0% (0.0%)	0.0% (0.0%)
Music	Silence	13.3% (2.4%)	9.3% (0.9%)	12.5% (2.1%)	7.7% (0.8%)	5.2% (1.0%)	1.5% (0.6%)	0.3% (0.2%)	<0.01% (<0.01%)	<0.01% (<0.01%)

The APM data for each group was averaged over the number of data collection days for each participant in each group. The intervals of voicing and silence were divided into bins according to duration of the interval in seconds. The data are presented as the average percentage of the total intervals that fell into that particular bin in the format of Mean % (SD). Due to the antagonistic relationship between voicing and silence and the sampling rate of the APM, the voicing and silence percentages should collectively sum to approximately 100%. For both groups, the majority of the intervals were no longer than 3.15 seconds in duration. The music teachers had a greater percent of voicing in the 1.0 second and 3.15 second bins. This is consistent with the physiologic differences between singing and speaking, such as sustaining continuous phonation in singing while holding out a note.

[Figure 5]

Figure 5: Voicing and Silence Interval Profile for All Data



The number of occurrences of the voicing and silence intervals for all of the data for each teacher are shown logarithmically in the above histogram. Each occurrence is binned according to the duration of voicing or silence interval. While some occurrences of voice use exceeded 3.15 seconds, the vast majority are shorter than 3.15 seconds, which implies an overwhelming reliance on the immediate energy system.

A significant multivariate effect for the between group analyses of voicing and silence intervals was identified: F(85, 6) = 11.43, *p* < .001 for voicing and F(82, 9) = 6.33, *p* < .004 for silence. The music teachers had larger percentages of voicing than the classroom teachers in the 1.0 and 3.15 second bins.

Results from the MANOVA demonstrated a significant multivariate effect for both of the within classroom teacher group analyses: F(68, 24) = 6.25, *p* < .001 for voicing and F(56, 36) = 4.69, *p* < .001 for silence.

Results from the MANOVA demonstrated a significant multivariate effect for both of the within music teacher group analyses: F(36, 366) = 6.18, $p < .001$ for voicing and F(54, 348) = 5.99, $p < .001$ for silence.

Discussion

Given the constraints of articulation and pulmonary volumes, it was hypothesized that the voicing intervals determined from the APM data would be short and indicate a reliance on anaerobic metabolism. The bioenergetic profile for each teacher, particularly the classroom teachers, suggests overwhelming reliance on anaerobic energy pathways (i.e. most vocalizations were 3.5 seconds or less), particularly the immediate energy system for muscle fuel, thus providing support for the initial hypothesis.

The inferred bioenergetic pathways in this study are consistent with the ILSM muscle fiber type found in the literature review. Two cadaver studies conducted by Shiotani et al. (1999) and Rosenfield et al. (1982) reported high percentages of Type II fibers across ILSMs with the exception of the PCA, which had high percentages of Type I fibers relative to other ILSMs. This high proportion of Type II muscle fibers is consistent with the hypothsis that teachers use their ILSMs in short bouts of repeated engagement. One caveat to the description of laryngeal muscle engagement and disengagement is the antagonistic role of vocal fold adductors (lateral cricoarytenoids, cricothyroids, interarytenoids, and thyroarytenoids) and vocal fold abductors (posterior cricoarytenoid). While the adductors are engaged to approximate the vocal folds to produce phonation, the abductors are disengaged, and likewise, the abductors engage during breathing and silence periods and the adductors are relatively disengaged. The description of muscle engagement and disengagement in terms of phonation, therefore, more accurately depicts the vocal fold adductors. The PCA would likely be the inverse, meaning it is engaged for longer extended periods of time, e.g. during sleep or when not talking for several minutes or hours, than the adductors. This indicates that the bioenergetic profile for the PCA may be quite different than any other intrinsic laryngeal muscles.

Another aspect for application of muscle bioenergetic physiology to this investigation is that ILSMs are typically used in a submaximal fashion, unlike sport comparisons where the athlete is working at a higher percentage of total power output. Although maximal power vocal tasks have not yet been defined, it is intuitive that phonation does not typically occur at the maximum output possible over the course of a teacher's work day. An example of a potential maximal voice task for a teacher, could be using his/her voice at a high SPL to tell them recess is over, or to gain the attention of his/her students attention in a noisy lunchroom. Because typical conversation does not require a maximal SPL, voice use is not typically a maximal power task.

Oxygen was likely used in small amounts for muscle recovery of bioenergetic systems, but not as a primary muscle fuel substrate for voicing intervals. The findings of this investigation should be considered in the context of research conducted by Tellis, Rosen, Carroll, Fierro, and Sciote (2011) who investigated oxygen uptake during a non-continuous 60 second phonation task with Visible Light Spectroscopy (VLS). Oxygen levels were found to decrease during the phonation task; therefore, Tellis et al. (2011) may have identified oxygen as a component of recovery, rather than as a substrate for energy production, unless the bioenergetic pathways within the ILSMs are unique.

Due to the highly specialized role of the ILSMs, these muscles have unique demands, and in turn, may have a novel bioenergetic profile. Unlike limb skeletal muscles, ILSMs work in rapid successions of engagement and disengagement over an extended period of time. This is similar to patterns of activity for power athletes, such as soccer players, who have rapid changes in acceleration. While a soccer game lasts for a few hours, the ILSMs are engaged and disengaged throughout the entire day. This hypothesis is in part supported in the work by Han et al. (1999), which described the presense of slow tonic muscle fibers (STF) in the thyroarytenoid muscles of 9 human cadavers. This type of muscle fiber is characterized by its fatigue-resistance and appears unique for human TAs as it has not yet been identified in other mammals (Han et al., 1999). Additionally, Shiotani et al. (1999) described the presense of superfast muscle fibers (IIL) in all of the human intrinsic laryngeal muscles including the cricothyroid muscle. Given the unique muscle fiber profile that has been identified, the bioenergetic profile, therefore, could also be unique, as it relies primarily on anaerobic energy systems over extended periods of time.

Previous research has attributed voice disorders in high risk populations, such as teachers, to differences in voice use or extended voice use. Van Stan et al. (2015) found there to be no differences in voicing patterns in teachers with vocal pathology than matched controls. As far as extended voice use is concerned, the patterns of voicing and silence, described in these findings as well as those shown by Titze et al. (2003), suggest voicing is not “engaged” for extended periods of time. Rather, it is engaging and disengaging in rapid successive high acceleration movements, much like that of a soccer or basketball player.

Given the proposed reliance on the immediate energy system for ILSM metabolism, a closer inspection of the production of ATP via the immediate energy system may yield new perspectives for voice building and recovery. An aspect of performance recovery that has been studied in athletes is the use of creatine supplementation to support faster recovery of the immediate energy system (Brooks, et al., 2004). Because the teacher voice bioenergetic profiles indicate a great reliance on the immediate energy system, creatine supplementation may be beneficial for teachers to recover laryngeal muscle function faster in times of extensive voice use or when the ILSMs bioenergetic systems have not yet been sufficiently upregulated to meet the voicing demands of the occupation.

Differences were identified in the voicing and silence profiles of classroom and music teachers. Music teachers had a larger percentage of continuous voicing intervals in the 0.36, 1.0 and 3.15 second bins than the classroom teachers. While it is difficult to determine why these differences exist, it is likely due to the difference in physiologic requirements of singing and speaking. In singing, it is a common occurrence to hold out a note for several seconds, but this type of continuous phonation does not frequently occur in speaking. It should also be noted that while the voicing and silence interval data appear somewhat similar in Table 1, the music teachers total vocal dose for the day was almost double that of the classroom teachers (Morrow and Connor, 2011).

Differences were also identified within classroom teachers and music teachers for voicing and silence profiles. These differences could be attributed to individual teaching styles; however, specific aspects of teacher style cannot be determined from this data set alone. For example, one teacher may be very verbal throughout an entire lecture, while another teacher may verbally introduce the information, provide students with independent work, and then review the assignment together. The voice use patterns of these two teachers could potentially be different, even though they are both constrained by articulation and repiration. Audio recordings synchronized with APM data could help identify aspects of teaching style that may account for the between teacher differences. Physiological differences, such as pulmonary volumes, could also account for differences in voice use between teachers, as an individual with a larger pulmonary volume could phonate for a longer period of time than an individual with a smaller pulmonary volume before requiring an additional breath. Teachers are likely a heterogeneous group, and additional research needs to be done to discern what stylistic differences may impact voice production effectiveness.

The minimal occurence of silence periods longer than 10 seconds was an unexpected finding. This may indicate that these participants used their voices in short bursts throughout the day with short durations of silence between the bursts of phonation. This may also be attributed to a small number of silence intervals that were lengthy, during preparatory period for example, but too few in number compared to the short intervals to register as a significant percentage. As shown in Tables 1, 2 and 3, silence intervals of duration longer than 10 seconds are typically less than .01%, indicating than longer pauses occur, but not very frequently throughout the day. It is plausibale that the higher incidence of voice disorders in teachers could be attributed to a lack of recovery time during the day to sufficiently restore bioenergetic substrate for the immediate energy system. Insufficient recovery from mechanical stress may also occur with an absence of longer silence intervals. Additional research into the recovery period required to adequately replenish the immediate energy system substrate is needed. Idenficiation of optimal recovery periods throughout the workday for elementary school teachers may mitigate bioenergetic and mechanical stress and subsequently reduce the possibly for development of voice disorders.

An aspect of voice use to be considered is the synergistic relationship between bioenergetic stress and mechanical tissue stress. Prior research on voice fatigue has developed a model of vocal fold tissue stress based on a mechanical stress hypothesis (Titze, et al., 2007). Mechanical stress may be triggered in part by bioenergetic stress. Muscle bioenergetics works efficiently when muscle metabolism has been upregulated to meet the demands of the voice load imposed. In the absence of metabolic upregulation, the lack of locally available muscle fuel substrate to produce ATP may be a component of muscle fatigue, resulting in bioenergetic stress.

When bioenergetic stress occurs and muscle activity continues, the individual may be more prone to injury. Performance adaptations that alter muscle biomechanics because the muscle tissue is bioenergetically stressed, may lead to maladaptive compensatory behavior, behavior that is often attributed to the development of voice disorder.

Strengths of this investigation include the use of ecologically valid data versus the task-specific acoustic assessments that are typically completed within the voice laboratory. Use of the APM for data collection allowed for a longer data collection period that would be difficult to replicate in the laboratory. The interdisciplinary merger of the application of bioenergetics to occupational voice disorders is another strength of this investigation. Given the technical and physiological challenges of *in vivo* assessment of muscle cell metabolism, bioenergetic pathways were inferred using time-based analyses of probable metabolic profile. This method is aligned, in part, with performance assessments used in exercise physiology assessments of aerobic and anaerobic performance.

Limitations of this investigation included a relatively small sample size and inclusion of only elementary classroom and music teachers. In keeping with the exercise physiology paradigm for muscle performance, it is helpful to identify occupation-specific features of voice use for future comparison with the voice requirements of other occupations. From a bioenergetic perspective, the time-based inference of muscle fuel utilization is incomplete given that maximum power generated is also part of the calculation for tests of anaerobic ability. Power generation could not be included in this investigation as we lack an agreed upon performance indicator of vocal power. Further, most voicing tasks are submaximal, unlike maximal tasks required for physical performance assessments in exercise physiology.

A future direction would be to define and develop a measure of maximal voicing power to evaluate vocal fitness. Another aspect to investigate further is habilitation and rehabilitation programs designed specifically based on the occupational voice use requirements. For example, because elementary school teachers' voice use parallel a power athlete's physical requirements, formulating training programs for vocal power athletes could provide better specificity and therefore better outcomes for vocal efficiency and performance. If a teacher is able to train, or upregulate, the ILSMs to meet the demands of their occupation through task specific exercises, the risk of developing vocal disorders could potentially be mitigated. Additionally, because of summer break, teachers' vocal workload would be different during the school year than during the summer. Vocal exercise programs may be beneficial during the summer months to prevent detraining of the vocal mechanism when the voice is not being used to the same degree as it was trained up to and is used to working.

Conclusion

Based on the constraints of articulatory features of voiced/voiceless phonemes and the limitations of pulmonary capacity, it was hypothesized that the voicing durations of elementary school teachers would be 3 seconds or less on average with a difference observed when classroom teachers and music teachers were compared. These hypotheses were evidence-supported. The voice use of both groups of teachers was primarily reliant on anaerobic energy systems, with classroom teachers overwhelmingly reliant on the immediate energy system and music teachers relying primarily on immediate energy system but also having some bouts of voice use relying on the glycolytic energy system. Although the large vocal doses of teachers may imply they are vocal distance athletes, the way in which they use their voice for short bursts throughout the day indicates they are more similar to a mixed athlete, with a greater reliance on anaerobic metabolism for intrinsic laryngeal muscle work. Characterization of occupation-specific voice demands from a muscle performance perspective allows for a more realistic understanding of voice use requirements. Similar profiling of the voice use of other high risk occupations, such as call center operators, actors, and singers would be beneficial. The findings from this novel interdisciplinary perspective could inform new methods for voice habilitation and rehabilitation, i.e., voice techniques or approaches designed to meet the specific demands of the occupation.

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