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Acoustic and Physiologic Correlates of Vocal Effort in Individuals With and Without Primary Muscle Tension Dysphonia

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ABSTRACT

Objectives: The aims of this study were to determine relationships between vocal effort and (a) acoustic correlates of vocal output and (b) supraglottic compression in individuals with primary muscle tension dysphonia (pMTD) and without voice disorders (controls) in the context of a vocal load challenge.

Method: Twenty-six individuals with pMTD and 35 vocally healthy controls participated in a 30-min vocal load challenge. The pre- and postload relationships among self-ratings of vocal effort, various acoustic voice measures, and supraglottic compression (mediolateral and anteroposterior) were tested with multiple regression models and post hoc Pearson's correlations. Acoustic measures included cepstral peak prominence (CPP), low-to-high spectral ratio, difference in intensity between the first two harmonics, fundamental frequency, and sound pressure level (dB SPL).

Results: Regression models for CPP and mediolateral compression were statistically significant. Vocal effort, diagnosis of pMTD, and vocal demand were each significant variables influencing CPP measures. CPP was lower in the pMTD group across stages. There was no statistical change in CPP following the vocal load challenge within either group, but both groups had an increase in vocal effort postload. Vocal effort and diagnosis influenced the mediolateral compression model. Mediolateral compression was higher in the pMTD group across stages and had a negative relationship with vocal effort, but it did not differ after vocal loading.

Conclusions: CPP and mediolateral supraglottic compression were influenced by vocal effort and diagnosis of pMTD. Increased vocal effort was associated with lower CPP, particularly after vocal load, and decreased mediolateral supraglottic compression in the pMTD group.

Primary muscle tension dysphonia (pMTD) is a hyperfunctional voice disorder that occurs in the absence of structural or neurological laryngeal deficits (Oates & Winkworth, 2008; Verdolini et al., 2006). Commonly reported symptoms associated with pMTD include increased vocal effort and aberrant vocal quality, among others (Dworkin et al., 2000). Vocal effort is defined as the individual's perception of the physical exertion associated with phonation as measured by self-report (Hunter et al., 2020), and excessive vocal effort is one of the most frequently reported symptoms in individuals with vocal hyperfunction (Marks et al., 2021; Solomon, 2008). pMTD can also involve deterioration of voice quality, resulting in a breathy, rough, or strained voice (Patel et al., 2011). Voice quality severity in pMTD can be extremely variable, with some individuals experiencing aphonia and others experiencing mild or no changes in

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voice quality (i.e., excessive vocal effort being the primary complaint; Hillman et al., 2020). It is currently unclear how acoustic measures associated with voice quality correspond to self-reports of vocal effort in individuals who have pMTD.

Some studies have investigated the link between self-reported vocal effort and acoustic measures estimated from the voice signals, but, to date, no studies on this topic have been conducted specifically in the pMTD population. Previous studies have asked vocally healthy participants to rate their vocal effort when they intentionally produce voicing at varying levels of vocal effort (e.g., minimal, moderate, maximal effort; Bottalico et al., 2015; McKenna et al., 2019; McKenna & Stepp, 2018). Rating vocal effort in this fashion is potentially cyclical—if someone is told to change their level of effort from minimal to moderate, their vocal effort ratings might be biased based on that instruction. Studies that measure vocal effort during or after naturally occurring situations of increased vocal effort are needed, which can be achieved with vocal loading challenges. Studying the relationships between vocal effort and acoustic and physiological correlates of voice output following a vocal loading task has good construct validity because increased vocal demands are often cited as the precipitating event in patients with pMTD (Hillman et al., 2020; Kridgen et al., 2020).

Vocal Effort and Acoustic Correlates of Vocal Output

Intensity and Pitch Measures

Although there is a lack of studies that have directly compared vocal effort and acoustic output specific to the pMTD population, literature supports a relationship between elevated vocal effort and increased intensity of the speech signal in vocally healthy populations (e.g., softer voicing is less likely to result in excessive vocal effort; Bottalico et al., 2015; Hunter et al., 2020; Rosenthal et al., 2014). Time-based measures, such as fundamental frequency (f_o), have also been proposed to correlate with vocal effort (Rantala et al., 1998; Vilkman et al., 1999). Increases in f_o result from increased tension of the intrinsic laryngeal muscles and elevated pitch can require more physiological effort to vibrate the vocal folds (Kempster et al., 1988). On the other hand, lower f_o has also been associated with vocal fry, a commonly occurring feature in pMTD (Patel et al., 2011). Vocal fry typically involves increased vocal fold adduction and low phonatory airflow, which could also theoretically increase vocal effort. One weakness associated with using time-based measures is that calculations on aperiodic signals can be unreliable, especially in individuals with higher dysphonia severity (Awan & Roy, 2009). For this reason, acoustic measures that do not depend on time-based calculations may be better for aberrant vocal quality that may occur in patients with pMTD.

Spectral and Cepstral Measures

Measures estimated from the spectrum and cepstrum do not require time-based calculations, potentially making them more suitable for analysis of dysphonic voice signals. To compute the spectrum, a fast Fourier transform of the acoustic signal is conducted, which offers information on the magnitude of the frequency components within the signal. Low-to-high (L/H) ratio, which is the proportion of low-frequency (< 4 kHz) to high-frequency (> 4 kHz) spectral energy, is generally lower in the setting of dysphonia (Awan et al., 2010) and has been found to be an indicator of vocal effort in vocally healthy individuals (McKenna & Stepp, 2018).

The difference between the intensity of the first and second harmonics in the spectrum (H1–H2) has shown promise to estimate aspects of vocal physiology. Lower H1–H2 values are hypothesized to be the result of more adducted/pressed glottal configuration, whereas higher H1–H2 values are thought to represent less vocal fold adduction and increased breathiness (Klatt & Klatt, 1990). Recent ambulatory voice monitoring studies have found that measures of H1–H2 have been helpful to discriminate between individuals with and without vocal hyperfunction (Toles, Ortiz, et al., 2021; Van Stan et al., 2020, 2021). However, no work has yet sought to determine a connection between H1–H2 and vocal effort. Lower H1–H2 values might indicate altered vocal mechanics and align with increased self-reported vocal effort. Studies have found increased closing phase of the vocal fold vibratory cycle and circumferential vocal fold compression in individuals with pMTD (Chen et al., 2020; Patel et al., 2011). These patterns could potentially translate to lower H1–H2 values and might involve excessive engagement of intrinsic laryngeal muscles, theoretically leading to increased perceived vocal effort.

Cepstral peak prominence (CPP) is often used as an objective measure of overall dysphonia and breathiness and was recommended as a tool for measuring dysphonia by the American Speech-Language-Hearing Association (Patel et al., 2018). The cepstrum is calculated by performing a Fourier transform of the logarithm of the spectrum (Fraile & Godino-Llorente, 2014; Noll, 1964). CPP represents the level of the peak of the cepstrum and is reported in decibels (Murton et al., 2020). Its ability to be calculated without direct computation of the f_o lends itself to use in the pMTD population, in part due to its capability of being calculated on samples that have moderate-to-severe vocal aberrations. Previous research has found correlations between CPP and vocal effort in healthy individuals (McKenna & Stepp, 2018; Rosenthal et al., 2014). Generally, those studies have found elevated CPP in the setting of increased effort levels. However, the relationship between CPP and vocal effort in patients with pMTD is currently unclear. Based on the combined assumptions that increased vocal effort leads to vocal quality deterioration in individuals with pMTD and that CPP tends to decrease in the setting of increased dysphonia, lower CPP values could be a correlate of increased vocal effort in this group.

Vocal Effort and Supraglottic Compression

Degree of supraglottic activity is one recommended laryngeal parameter, among several, to be included in interpretation of laryngoscopic examinations of voice disorders (Poburka et al., 2017). Mediolateral and anteroposterior supraglottic compression identified on laryngoscopy are often thought to be diagnostic indicators of pMTD (Belisle & Morrison, 1983; Morrison et al., 1986; Morrison & Rammage, 1993). However, recent studies that have compared supraglottic compression patterns between patients with pMTD and vocally healthy individuals have found that these laryngeal configurations occurred in the individuals both with and without pMTD (McDowell et al., 2022; Shembel et al., 2023). Findings from previous literature have suggested that modification of supraglottic activity to achieve different types of phonation might not necessarily be pathologic but a tool to achieve more economic voice production under different circumstances (e.g., when singing rock music) while protecting the vocal folds from damage (Guzman et al., 2013, 2015) due to increased inertance of the vocal tract (Titze & Story, 1997). Only a few studies have investigated the connection between supraglottic compression and vocal effort, and all were conducted in populations without voice disorders (Guzman et al., 2013, 2015; McKenna et al., 2019). Furthermore, no studies have investigated the relationship between vocal effort and supraglottic compression following a vocal load challenge.

Theories of the etiology and pathophysiology of vocal hyperfunction suggest that supraglottic activity can be a normal compensation in the setting of increased vocal demands (Hillman et al., 2020), so it follows reason that vocal effort might increase with increased supraglottic compression in individuals with a healthy vocal mechanism. When vocal demands are lifted, vocal effort and supraglottic activity would theoretically decrease in vocally healthy individuals. However, individuals with pMTD might theoretically have more difficulty recovering back to typical physiological status when demands are lifted, leading to heightened perceptions of vocal effort at baseline and even greater increases in perceived vocal effort during heavy vocal demands. It is difficult to validate this theory due to insufficient literature investigating connections between vocal effort and vocal physiology in individuals with pMTD, particularly in the context of increased vocal demands.

The overarching objective of this study was to investigate relationships between vocal effort and objective measures of vocal output and physiology to better define the concept of vocal effort. To achieve this objective, we measured vocal effort, acoustic correlates of vocal output, and supraglottic compression patterns on laryngoscopy in a group of individuals with pMTD and a group of individuals with no voice disorders (controls). Measures were collected at baseline and following a 30-min vocal load challenge. The specific aims of the study were to determine the relationships between (a) vocal effort and acoustic voice output and (b) vocal effort and measures of supraglottic compression, both at baseline and following a vocal loading challenge in groups with and without pMTD.

Method

Participants

This study was approved by the institutional review board at The University of Texas Southwestern Medical Center (STU-2020-0720). Twenty-six patients diagnosed with pMTD (average age: 50.44 ± 16.98 years; 77% women) and 35 typical voice users (healthy controls; average age: 31.69 ± 11.53 years; 77% women) were recruited for the study. All participants with pMTD met criteria for the diagnosis based on the Classification Manual of Voice Disorders (Verdolini et al., 2006). The diagnosis was made by one of three board-certified laryngologists and two speech-language pathologists. Participants were recruited into the control group through a convenience sample (e.g., through distribution of flyers, social media posts, etc.). To be included in the control group, participants without voice disorders had to exhibit laryngeal anatomy and physiology that was within normal limits, based on visualization with laryngoscopy (e.g., absence of lesions, structural deficits, and vocal fold movement abnormalities). Participants in the control group also had to have no perceivable deviations in vocal quality as assessed by two voice-specialized clinicians, to score less than 7 on the Voice Handicap Index-10 (Rosen et al., 2004), and less than 22 on Part 1 of the Vocal Fatigue Index (Nanjundeswaran et al., 2015). Voice quality was assessed using the Overall Severity parameter from the Consensus Auditory-Perceptual Evaluation of Voice (Kempster et al., 2009), which is a 100-mm visual analog scale with higher scores indicating more severe dysphonia. At baseline, participants in the control group had an average (standard deviation) overall dysphonia severity of 11.62 (8.65), and participants in the pMTD group had an average score of 33.12 (24.48).

Protocol

Vocal load. Participants read a nonfiction novel (at an eighth-grade reading level [Harry Potter]) out loud for half an hour at a volume greater than 85 dB(A) at a distance of 30 cm from the mouth to the dB SPL meter microphone. DATQ DI-720 USB acquisition hardware and software were used to visualize and monitor decibel levels. Study staff monitored dB levels to confirm that target dB was maintained. This protocol has previously been described in detail and has shown to significantly increase self-perceptions of vocal effort in participants with and without pMTD (McDowell et al., 2022).

Vocal effort. All participants were asked to rate their level of vocal effort at pre- and postvocal load time points on a 100-mm visual analog scale, with 0 representing minimal effort and 100 representing maximal effort. Visual anchors were provided. Participants were asked to rate their vocal effort in relation to their sustained /i/ productions that were produced before and after finishing the reading task. Vocal effort was defined for participants as the level of physical exertion it took to produce voicing. Tick marks for each pre- and postload visual analog scale of vocal effort ratings were measured with a ruler and assigned a representative number based on the 100-mm scale.

Acoustic correlates. To obtain pre- and postvocal load voice samples for acoustic analysis, participants were first fitted with a head-mounted unidirectional condenser microphone (MicroMic C250) at a distance of 4 cm from the lips at a 45° angle and connected to a microphone preamplifier (M-Audio Air 192, 4 USB C Audio Interface) and laptop computer (Dell XPS). Participants were instructed to produce six utterances of /i/ at modal pitch and loudness, which were recorded in Praat (version 6.6.16) with a sampling rate of 44.1 kHz. Segments that were not steady-state vowel productions were removed from the voice sample so that only 10–15 s of vowel productions remained in each sample. A customized script in Praat (Phonanium CommV) was used in batch mode to obtain the following acoustic parameters: (a) CPP, (b) L/H ratio, (c) H1–H2, (d) dB SPL, and (e) f_o.

Supraglottic compression. Using previously established methods (Shembel et al., 2023), mediolateral and anteroposterior supraglottic compression was quantified and compared to vocal effort and acoustic vocal output. Laryngoscopic videos for six sustained /i/ vowels (3–5 s each) at modal pitch and loudness were first acquired using a standard flexible laryngoscope (Olympus distal chip, model ENF-VH). Digital still images were acquired during the steady state of each vowel production by two speech-language pathologists blinded to group and condition. The digital still images were captured in the middle of the steady-state vowel production, per previously validated methods (Shembel et al., 2023). To measure severity of supraglottic compression, endolaryngeal outlets for each image were first traced manually using the boundaries between the true vocal folds, ventricular folds, interarytenoid mucosa, and petiole of the epiglottis in ImageJ (Fiji for ImageJ version 1.63 t). The medial space between the anterior commissure or petiole of the epiglottis, anteriorly, and the interarytenoid mucosa posteriorly were used to normalize laryngeal exams. For mediolateral supraglottic compression measures, mean width of each endolaryngeal outlet was obtained and supraglottic compression severity was determined as (LO/W^2) × 100, where LO is the endolaryngeal outlet area and W is the average width of the outlet (in pixels). For anteroposterior supraglottic compression, the anteroposterior distance was determined based on the medial space between the anterior commissure or petiole of the epiglottis, anteriorly, and the interarytenoid mucosa posteriorly. Anteroposterior supraglottic compression was determined by (LO/AP^2) × 100, where LO is the endolaryngeal outlet area and AP is the anteroposterior outlet length (in pixels). Please see the work of Shembel et al. (2023) for details.

Statistical Analyses

All statistical analyses were completed using R statistical software (R Core Team, 2022) and the RStudio interface (RStudioTeam, 2022). The data were searched for outliers, defined as values > 3 *SD*s above or below the mean. Outliers were found in two participants in the pMTD group (one with high L/H ratio and one with low CPP). Sound files for each of these participants were reviewed for quality checking and found to be acceptable, and there were no issues found when processing these files through voice analysis software. Therefore, these values were kept in the data set for statistical analyses.

Multiple regression analyses were conducted to determine whether vocal effort, group (pMTD or control), or stage (pre- or postvocal load) was related to the acoustic measures or severity of supraglottic compression. Separate models were conducted for each acoustic measure and supraglottic compression parameter—(a) CPP, (b) L/H ratio, (c) H1–H2, (d) dB SPL, (e) f_o, (f) mediolateral supraglottic compression, and (g) anteroposterior supraglottic compression. The acoustic and supraglottic compression measures were the dependent variables for each model, and vocal effort, group, and stage were entered as independent variables in each model. Vocal effort values were meancentered to allow for ease of interpretation. All models met the assumptions for conducting multiple linear regression. Scatter plots were used to confirm linear relationships, and residual plots were used to confirm that the residuals were normally distributed. Multiple regression models were tested for multicollinearity using the Variance Inflation Factor (VIF) values, each of which rejected multicollinearity (all VIF values were < 2). To correct for multiple comparisons, a Bonferroni correction was applied, and the significance value was defined as $\leq .007$. For models that were statistically significant, post hoc analyses included (a) Pearson's correlations of acoustic and supraglottic compression variables with vocal effort scores within each group and stage and (b) paired *t* tests of acoustic variables and vocal effort scores within each group and stage to determine differences for each set of variables. Pearson's correlations were interpreted as small = |.10|–|.29|, medium = |.30|–|.49|, and large = |.50|–|1.00| (Cohen, 1988).

Results

Statistical results for multiple regression models are presented in Table 1. Results described below are organized by outcome variable.

CPP

The overall multiple regression model for CPP was statistically significant (Multiple $R^2 = .15$, $p < .001$), and all three predictor variables were statistically significant to the model. Controlling for group and stage, for every one-point increase in vocal effort, CPP decreased by 0.03 dB ($t = -2.41$, $p = .018$). Therefore, an increase of 32 points in vocal effort (which was the postload average across participants) would result in a 0.96 decrease in CPP when controlling for group and stage.

Post hoc paired *t* tests showed no statistically significant difference in CPP following vocal load in either group, whereas there was a statistically significant increase in vocal effort following vocal load in both groups (see Table 2). CPP values were also significantly lower in the pMTD group compared to the control group in both stages. Pearson's correlations (see Table 3) indicated a small negative relationship ($r = -.17$, $p = .391$) between CPP and vocal effort in participants with pMTD at baseline, which increased to a medium negative relationship ($r = -.34$, $p = .088$) following vocal load. Controls had no relationship between CPP and vocal effort at baseline ($r = -.04$, $p = .781$) and a small negative relationship ($r = -.26$, $p = .129$) following vocal load.

L/H Ratio and H1–H2

The overall multiple regression models for L/H ratio and H1–H2 were not statistically significant (see Table 1). Therefore, post hoc analyses were not formally conducted. Table 2 shows the means and standard deviations for L/H ratio values in each group for each stage. The pMTD group had higher average L/H ratio values compared to the control group, but results were not statistically significant. There were no postload changes in L/H ratio in either group. H1–H2 was not significantly different between groups or following vocal load.

SPL and f_o

The SPL multiple regression model was not statistically significant (see Table 1), and SPL was similar before and after vocal load within each group. The control group was approximately 2 dB louder than the pMTD group across stages (see descriptive statistics in Table 2). As reported in Table 1, the f_o multiple regression model was not statistically significant. f_o was higher in the control group across stages. In the pMTD group, f_o increased by 10 Hz following vocal load.

Supraglottic Compression

The overall regression model for mediolateral supraglottic compression was statistically significant ($R^2 = .13$, $p < .001$). Vocal effort and group were significant variables in the model (see Table 1). Mediolateral supraglottic compression was significantly greater in the pMTD group compared to the control group, across vocal loading conditions. There were no differences in mediolateral supraglottic compression following vocal load in either group. There were medium negative correlations between mediolateral compression and vocal effort in the baseline stage of the pMTD group ($r = -.23$, $p = .265$) and the control group ($r = -.24$, $p = .180$) as well as the postload stage of the pMTD group ($r = -.26$, $p = .194$). There were no meaningful correlations between mediolateral supraglottic compression and vocal effort following vocal load in the control group. The overall regression model for anteroposterior supraglottic compression was not statistically significant. Interested readers can refer to the Appendix for correlations between supraglottal compression measures and acoustic voice measures.

Discussion

Voice assessments capture both vocal function measures (acoustics and laryngeal patterns) and measures of patient experiences (vocal effort), and treatment goals are often based on these measures collected during the voice evaluation. Increased vocal effort is a hallmark symptom of pMTD, and patients with pMTD are often reported to exhibit aberrant vocal acoustics and increased supraglottic compression; increased vocal demands can exacerbate symptoms (Hillman et al., 2020; McDowell et al., 2022).

Table 1. Multiple regression model statistics using the acoustic-based voice output measures as the dependent variable for each model.

Acoustic variable	Model R^2	Model *p*	Intercept	Independent variables	*b*	β	*t*	*p*
CPP	.15	**< .001**	14.21					
				Effort	−0.03	−.28	−2.41	**.018**
				Group	−1.12	−.19	−2.05	**.042**
				Stage	1.38	.25	2.39	**.019**
L/H ratio	.02	.508	42.06					
				Effort	0.02	.09	0.75	.455
				Group	0.81	.06	0.58	.563
				Stage	−1.54	−.12	−1.04	.301
H1–H2	.02	.228	9.71					
				Effort	−0.06	−.17	−1.51	.134
				Group	2.00	.10	1.04	.299
				Stage	2.24	.11	1.10	.272
dB SPL	.08	.016	82.37					
				Effort	−0.02	−.04	−1.61	.111
				Group	−1.27	−.15	−1.63	.107
				Stage	1.12	.07	1.35	.180
f_o	.03	.300	204.61					
				Effort	−0.06	−.19	−0.30	.765
				Group	−13.62	−.17	−1.41	.161
				Stage	6.54	.15	0.64	.525
ML compression	.13	**< .001**	86.96					
				Effort	−0.46	−.24	−2.03	**.045**
				Group	48.02	.42	4.16	**< .001**
				Stage	17.04	.15	1.40	.164
AP compression	.04	.206	76.80					
				Effort	0.12	.10	0.78	.437
				Group	−16.92	−.22	−2.10	**.038**
				Stage	−6.22	−.08	−0.73	.465

Note. Bolded *p* values are considered statistically significant. *b* = unstandardized regression coefficient; β = standardized coefficient; CPP = cepstral peak prominence; L/H ratio = the ratio of low to high harmonic energy; H1–H2 = the difference between the first two harmonic magnitudes; SPL = sound pressure level; f_o = fundamental frequency; ML = mediolateral; AP = anteroposterior.

Table 2. Means (standard deviations) and significance notations of all continuous variables that were included in analyses, separated by group and stage.

Variable	pMTD group		Control group	
	Preload	Postload	Preload	Postload
Vocal effort	34.04 (23.91)*,§	67.08 (25.51)$^{*,\Delta}$	9.17 (12.03)*,§	40.74 (25.42)$^{*,\Delta}$
CPP (dB)	13.17 (3.20)§	13.65 (2.88)$^{\Delta}$	14.86 (2.52)§	15.49 (2.22)$^{\Delta}$
L/H ratio (dB)	42.77 (6.53)	42.01 (6.87)	41.54 (6.33)	40.58 (6.64)
H1–H2 (dB)	11.76 (7.47)	12.26 (9.35)	11.49 (9.03)	11.63 (10.49)
SPL (dB SPL)	81.19 (3.25)	81.42 (3.65)$^{\Delta}$	83.00 (4.08)	83.40 (3.71)$^{\Delta}$
f_o (Hz)	188.89 (41.29)*	198.57 (44.11)*	208.30 (49.12)	209.31 (45.66)
ML compression	135.13 (63.41)§	138.45 (76.39)$^{\Delta}$	99.76 (44.12)§	101.75 (33.73)$^{\Delta}$
AP compression	57.21 (31.84)	59.94 (38.87)	75.37 (37.77)*	69.18 (40.34)*

Note. pMTD = primary muscle tension dysphonia; CPP = cepstral peak prominence; L/H ratio = the ratio of low to high harmonic energy; H1–H2 = the difference between the first two harmonic magnitudes; SPL = sound pressure level; f_o = fundamental frequency; ML = mediolateral; AP = anteroposterior.

*Statistically significant difference ($p < .05$) following vocal load task within group on paired *t* tests. [§]Statistically significant difference ($p < .05$) between groups in the preload stage. [Δ]Statistically significant difference ($p < .05$) between groups in the postload stage.

Table 3. Pearson's correlations of vocal effort with cepstral peak prominence (CPP) and mediolateral (ML) compression within each group at baseline (preload) and following vocal load.

Parameter	pMTD group		Control group	
	Preload	Postload	Preload	Postload
CPP	−.18	−.34	−.05	−.26
ML compression	−.23	−.26	−.24	−.01

Note. pMTD = primary muscle tension dysphonia.

As such, relationships between vocal effort ratings and measures of acoustic output and laryngoscopic patterns in this population, especially in the context of vocal load, require elucidation. Thus, the objectives of this study were to determine whether voice acoustic and supraglottic compression measures were related to self-reported vocal effort in individuals with pMTD and controls and whether the relationships changed following a period of vocal loading. This study differed from other studies that have investigated relationships between vocal effort and acoustic measures in two primary ways. First, other studies have investigated vocal effort correlations with voice acoustics in individuals without voice disorders (Bottalico et al., 2015, 2016; McKenna et al., 2019; McKenna & Stepp, 2018; Rosenthal et al., 2014). Our goal was to investigate vocal effort in patients with pMTD, which will ultimately inform treatment practices and advance research related to etiological and pathophysiological factors associated with this hyperfunctional voice disorder. Second, many studies ask participants to alter their voice production by asking them to use a louder voice or simply to use a voice with increased effort (Bottalico et al., 2015; McKenna & Stepp, 2018; Rosenthal et al., 2014). The use of a vocal load challenge, although still somewhat artificial, may be more natural to the increased vocal demands patients with pMTD experience. Some studies have investigated acoustic output in relation to vocal fatigue after a vocal loading challenge (Whitling et al., 2017a, 2017b), which is a similar but distinct concept to vocal effort. For the purposes of the current study, vocal effort was defined as the amount of physical exertion perceived to phonate, whereas vocal fatigue can be defined as fatigue of the laryngeal tissue, muscle fatigue leading to laryngeal discomfort, or perception of being vocally tired (Hunter et al., 2020; Nanjundeswaran & Shembel, 2022; Shembel & Nanjundeswaran, 2022).

Significant Relationships Between Vocal Effort and CPP

The first primary finding in the current study was the significant relationship between vocal effort and CPP values in the pMTD group in the context of a vocal load challenge. The relationship between CPP and vocal effort at baseline in the pMTD group, but not in the control group, suggests that individuals with pMTD with lower CPP values may also report higher levels of vocal effort, especially at baseline (i.e., when they come to the voice clinic for a voice assessment). Furthermore, the relationship between vocal effort on CPP in both groups after a 30-min vocal load task suggests there may be similar underlying physiological constructs at play with increased vocal demands between self-reported measures of vocal effort and CPP measures, regardless of whether someone has a voice disorder or not. CPP is often associated with the "quality" or harmonic strength of the voice, in that lower values tend to sound more dysphonic (e.g., breathy, noisy, rough) while higher values have increased perceptual clarity (Awan et al., 2010; Murton et al., 2020). Similarly, increased vocal effort may result in reduced vocal quality, reflected by acoustic measures that are indicative of vocal quality.

Significant Relationships Between Vocal Effort and Supraglottic Compression

The second primary finding in our study was the significant relationship between vocal effort and mediolateral supraglottic compression. The higher mediolateral supraglottic compression in the pMTD group compared to the control group found in this study align with our previous study that demonstrated higher mediolateral supraglottic compression found in the pMTD group and increased anteroposterior supraglottic compression found in the control group (Shembel et al., 2023). Interestingly, increased mediolateral compression correlated with decreased vocal effort, which could point to a compensatory supraglottic inertance mechanism and not pathophysiology.

Nonsignificant Relationships Between Vocal Effort and Other Acoustic Metrics

Multiple regression models investigating the influence of vocal effort, group, and stage on the spectral-based measures of L/H ratio and H1–H2 were not statistically significant. This was somewhat surprising, as the work of McKenna and Stepp (2018) found that L/H ratio was a significant predictor of speaker ratings of vocal effort in vocally healthy individuals. In both groups, L/H ratio slightly decreased following vocal loading, which is the expected direction, but these changes were not statistically significant. It is possible that this disparity with the work of McKenna and Stepp (2018) is due to how vocal effort was measured (i.e., in context of heavy vocal load vs. when being asked to increase effort artificially). Lower L/H ratio values have been seen in individuals with dysphonia (Awan et al., 2010). The results from the current study, however, conflict with previous studies as they show no statistical difference between groups. One possible explanation for this discrepancy is that we did not have the power to detect a change. In the postload stage, there was a small effect size between groups (Cohen's d = .21). With a larger sample size, the difference between groups might be more apparent. Another explanation could be that a steady-state /i/ phoneme might not be optimal to determine differences between groups. Other studies have used different sustained vowels (İncebay et al., 2023), consonant–vowel–consonant stimuli (McKenna & Stepp, 2018), and continuous speech (Belsky et al., 2021; Gillespie et al., 2014).

H1–H2 was included as an outcome variable of interest because of its theoretical relationship with vocal physiology (Klatt & Klatt, 1990). H1–H2 has been a useful measurement in recent studies that have investigated phonotraumatic voice disorders, which are generally assumed to have a secondary muscle tension component (Toles, Ortiz, et al., 2021; Toles, Roy, et al., 2021; Van Stan et al., 2020). In those studies, patients with vocal hyperfunction tended to have lower H1–H2 values than the vocally healthy controls. Therefore, we suspected that it could be sensitive to altered laryngeal configurations present in the pMTD population and likely be associated with increased vocal effort. However, the H1–H2 model was not statistically significant in this study. H1–H2 did not change following vocal load in the control group. Large standard deviations for this measure are likely to explain the lack of significant differences. Finally, although some studies suggest that vocal effort increases in the setting of increased SPL and f_o (Jessen et al., 2005; Rosenthal et al., 2014), we found no significant differences on these parameters on vocal effort, group, or vocal load condition.

Limitations and Future Work

The first limitation in this study is that correlations were generally small to medium in strength. Though further investigation into these relationships is merited based on the results of this study, the small-to-medium effects imply that there may be other factors at play beyond these relationships. Furthermore, even though there was a stronger relationship between vocal effort and CPP values, especially after a vocal loading challenge, it is difficult to say whether these changes in CPP are clinically meaningful, as these data do not exist. Considering CPP is one of the primary measures that are recommended to collect in voice evaluations (Patel et al., 2018), future investigations into minimal detectable change and minimally clinically important differences in CPP values are warranted. The second main limitation is that voicing was only measured during sustained vowel productions, which may not be as functional of a measure as connected speech. CPP is known to be higher in sustained voicing compared to connected speech (Murton et al., 2020). It is certainly possible that connected speech would have shown stronger relationships between vocal effort and acoustic measures. The final limitation is that relationships between vocal effort and glottic laryngeal patterns or vibratory parameters were not studied. Future investigations into these relationships are warranted.

Conclusions

Vocal effort has a significant relationship with CPP values and mediolateral supraglottic compression and is influenced by presence of pMTD voice disorder and vocal demand. Correlations between vocal effort and CPP values were stronger following vocal load in both pMTD and control groups. Those who experienced increased vocal effort tended to have lower CPP values. Increased mediolateral supraglottic compression was associated with *lower* vocal effort in the pMTD group following vocal load, suggesting that mediolateral compression could be a resourceful, rather than maladaptive, compensatory strategy for individuals with pMTD in the setting of heavy vocal demands. Future work on other factors that play a role in vocal effort, acoustic parameters, and laryngeal patterns are needed.

Data Availability Statement

The data sets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Appendix

Pearson's Correlations of Mediolateral (ML) and Anteroposterior (AP) Compression With Acoustic Measures Within Each Group at Baseline (Preload) and Following Vocal Load

Acoustic variable	ML compression				AP compression			
	pMTD Group		Control group		pMTD group		Control group	
	Preload	Postload	Preload	Postload	Preload	Postload	Preload	Postload
CPP	−.18	.38	.25	.22	.08	−.10	.02	.04
L/H ratio	**−.42**	.10	−.24	−.12	.11	.12	.07	.12
H_1–H_2	**.55**	.03	−.10	.29	**−.47**	−.15	.06	−.24
dB SPL	−.37	.16	.26	.20	.21	−.01	−.08	−.08
f_o	−.32	.15	.08	.13	.18	−.11	−.17	−.27

Note. Bolded *r* values have a *p* value < .05. pMTD = primary muscle tension dysphonia; CPP = cepstral peak prominence; L/H ratio = the ratio of low to high harmonic energy; H_1–H_2 = the difference between the first two harmonic magnitudes; SPL = sound pressure level; f_o = fundamental frequency.