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Effects of Voice Therapy on Relative Fundamental Frequency During Voicing Offset and Onset in Patients With Vocal Hyperfunction

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Purpose: The purpose of this study was to determine whether the relative fundamental frequency (RFF) surrounding a voiceless consonant in patients with hyperfunctionally related voice disorders would normalize after a successful course of voice therapy.
Method: Pre- and posttherapy measurements of RFF were compared in 16 subjects undergoing voice therapy for voice disorders associated with vocal hyperfunction.
Results: A 2-way analysis of variance showed a statistically significant effect of both cycle of vibration near the consonant and therapy phase (pre- vs. post-), with $p < .001$. A post hoc paired Student's *t* test showed that posttherapy RFF measurements were significantly higher (more typical; $p < .0001$) than pretherapy measurements.

Conclusions: Prior to therapy, participants exhibited lowered RFF values, similar to those found previously (Stepp, Hillman, & Heaton, 2010). After successful completion of voice therapy, RFF values increased toward patterns seen previously in individuals with healthy typical voice. The goal of voice therapy in these patients was to reduce laryngeal muscle tension; therefore, the increase of RFF toward more typical values may be indicative of decreased baseline laryngeal muscle tension resulting from therapy. Results are discussed further in terms of necessary research to incorporate RFF as a clinical measure of vocal hyperfunction.

Key Words: vocal hyperfunction, muscle tension dysphonia, vocal nodules, fundamental frequency

Vocal hyperfunction, which has been defined as "conditions of abuse and/or misuse of the vocal mechanism due to excessive and/or 'imbalanced' muscular forces" (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989, p. 373), characterized by excessive laryngeal and paralaryngeal tension (e.g., Aronson, 1980; Dworkin, Meleca, & Abkarian, 2000; Koufman & Blalock, 1991; Morrison, Rammage, Belisle, Pullan, & Nichol, 1983; Roy, 2008), is a common cause of and accompaniment to voice disorder. Vocal hyperfunction may lead to organic changes on the surface of the vocal fold, such as vocal fold nodules. Individuals with vocal hyperfunction and without another known cause of voice disorder (e.g., nodules or polyps) are diagnosed with *muscle tension dysphonia* (MTD).

Although estimates of the prevalence of vocal hyperfunction indicate that the condition may account for 10%–40% of cases referred to multidisciplinary voice clinics (Roy, 2003), current assessment of vocal hyperfunction in clinical practice still relies primarily upon the subjective interpretation of patient history and physical examination. There is currently a lack of objective measures for detecting the presence or severity of vocal hyperfunction. Primary attempts to develop such measures have included investigation of acoustic, aerodynamic, and electromyographic (EMG) parameters. Strain is the most common auditory–perceptual quality attributed to vocal hyperfunction, but there is no known good acoustic correlate (e.g., Colton, Casper, & Leonard, 2006, p. 19). Aerodynamic–acoustic measures have

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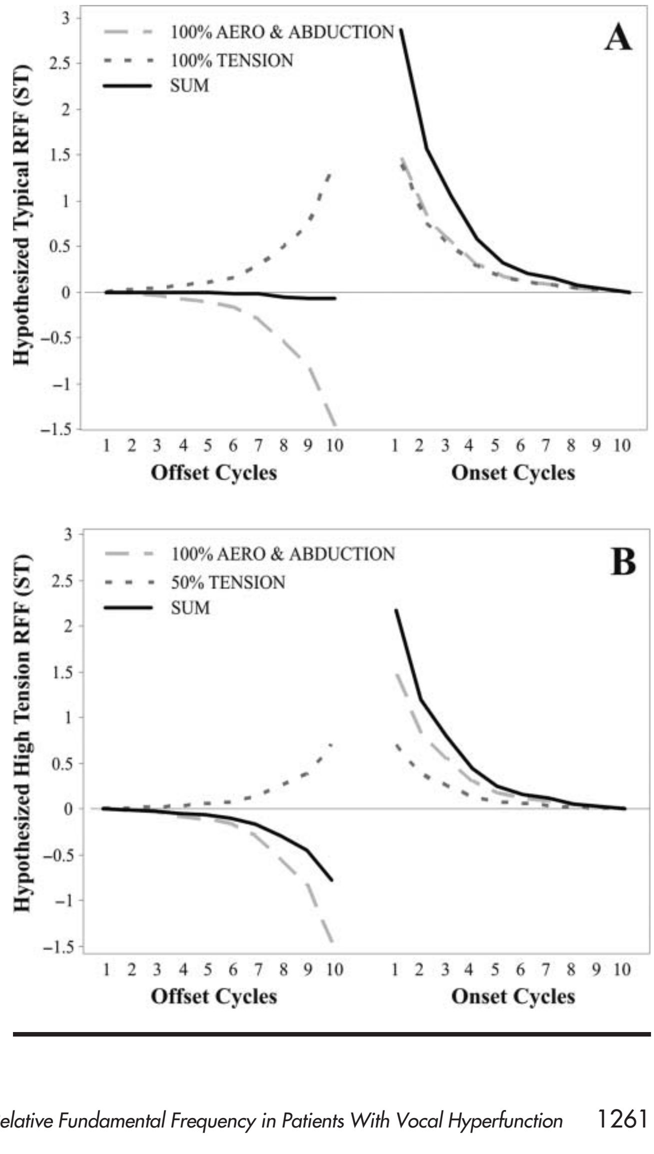
shown promise for differentiating voice produced with vocal hyperfunction from healthy typical voice (Grillo & Verdolini, 2008; Hillman et al., 1989). However, the presence of laryngeal pathology in patients (e.g., vocal fold nodules) causes glottal insufficiency that can impact aerodynamic measures, regardless of the presence of vocal hyperfunction, making it difficult to differentiate such effects from the separate influence of vocal hyperfunction. Several attempts have been made to correlate surface EMG with vocal hyperfunction, but these have yielded conflicting results (Hocevar-Boltezar, Janko, & Zargi, 1998; Redenbaugh & Reich, 1989; Stepp et al., in press). Lack of objective measures for vocal hyperfunction creates an obstacle to effective evaluation of the effectiveness of voice therapy for the treatment of vocal hyperfunction, as the voice therapist has limited ability to reliably detect changes in the degree of vocal hyperfunction present during voice production. Objective clinical assays of vocal hyperfunction are needed to aid in the assessment of patients with hyperfunctionally related voice disorders. Recent work suggests potential for the use of relative fundamental frequency (RFF) changes surrounding voiceless consonant production as an assay of vocal hyperfunction (Stepp, Hillman, & Heaton, 2010).

RFF is operationally defined as the fundamental frequency of the cycles immediately before and after production of a voiceless consonant, normalized by "steady-state" fundamental frequencies of the voicing preceding and subsequent to the consonant. This normalization is often in the form of semitones (ST) relative to the steady-state instantaneous fundamental frequency, and it allows changes in fundamental frequency to be compared across individuals with very different resting fundamental frequencies. It is now well established that for healthy typical speakers, the vocal cycles immediately after voiceless consonant production (vowel onset) show an increased RFF (Goberman & Blomgren, 2008; Ohde, 1984; Robb & Smith, 2002; Watson, 1998). The RFF immediately prior to voiceless consonant production (vowel offset) also shows characteristic patterns. Watson (1998) found that younger speakers had relatively stable RFF across the 10 cycles prior to devoicing, whereas older speakers showed a decrease in RFF. More recently, Robb and Smith (2002) examined RFF during vowel offset in individuals at 4, 8, and 21 years of age. They found no significant differences among age groups and observed a slight decrease in RFF across the 10 cycles prior to devoicing. The production of vowels before and after production of a voiceless consonant is associated with characteristic physiological behaviors that have been hypothesized by many to underlie the acoustic phenomenon: (a) tension is thought to be increased preceding, during, and immediately after voiceless consonant production (Löfqvist, Baer, McGarr, & Story, 1989; Stevens, 1977); (b) abduction occurs during the vowel prior to voiceless consonant production and the cessation of voicing (Fukui & Hirose, 1983); and (c) peak and minimum airflow values increase during vowel offset and onset surrounding a voiceless consonant (Löfqvist, Koenig, & McGowan, 1995; Löfqvist & McGowan, 1992). An increase in tension during voiceless consonant production may be used to inhibit voicing (+stiff), and this increase may also carry over into surrounding vowels, resulting in an increase in both offset and onset RFF (Halle & Stevens, 1971; Stevens, 1977). This hypothesized effect is shown as a schematic in the dark gray dotted line in Figure 1A.

The effects of abduction prior to devoicing and aerodynamics are less clear. Watson (1998) proposed that

Figure 1. A: Schematic of the hypothesized mechanisms for relative fundamental frequency (RFF) production in the "typical" case. B: Schematic of the hypothesized mechanisms for RFF production in the "high tension" case, in which the proposed RFF effects of tension have been reduced by 50%. ST = semitones; AERO = aerodynamics.



abduction during the vowel prior to devoicing would contribute to decreases in offset RFF, whereas Ladefoged (1967, p. 33) hypothesized that the high rate of airflow at the release of the voiceless consonant may create a large Bernoulli force causing rapid adduction of the vocal folds and thus higher RFF at onset. The hypothesized combination of the effects of abduction and aerodynamics are shown as a schematic in the light gray dashed line of Figure 1A. In summary, the combination of laryngeal tension mechanisms with abduction and aerodynamics would lead to relatively constant RFF prior to the voiceless consonant, followed by higher RFF at the onset of voicing after the consonant. Figure 1A shows a schematic of the hypothesized mechanisms for RFF production in which RFF is the result of the linear superposition of the effects of the tension with the effects of abduction and aerodynamics. In the "typical" case (Panel A), nearly equivalent but opposite offset RFF effects sum to produce a stable RFF pattern, whereas the sum of onset RFF effects is additive (solid black line).

The combination of these effects is compatible with the finding that individuals with Parkinson's disease (PD) have lowered RFF during both vocal offset and vocal onset when compared with age-matched controls (Goberman & Blomgren, 2008), especially given that laryngeal rigidity is thought to be a symptom of PD and that increased thyroarytenoid muscle activation has been correlated with perceptual measures of impairment in voice onset and offset in individuals with PD (Gallena, Smith, Zeffiro, & Ludlow, 2001). A possible interpretation of these results is that the baseline laryngeal muscle tension of individuals with PD is already increased, impeding their ability to use tension as a devoicing strategy. This might effectively lower RFF values relative to individuals with healthy typical voice, both prior to and after voiceless consonant production. Figure 1B shows a case in which the proposed RFF effects of tension have been reduced by 50%. Here, the summed effects of RFF are predominated by abduction and aerodynamic effects, causing an overall decrease in both offset and onset RFF, similar to the decrease in offset and onset RFF shown previously in individuals with PD (Goberman & Blomgren, 2008).

This interpretation of Goberman and Blomgren's (2008) findings is supported by a recent study by Stepp, Hillman, and Heaton (2010). This retrospective study found that three groups of individuals diagnosed with a voice disorder and thought to display vocal hyperfunction (i.e., diagnosed with MTD, vocal fold nodules, or vocal fold polyps) prior to treatment showed a statistically significant lowering of RFF when compared with typical controls. The authors interpreted this finding as a by-product of heightened baseline levels of laryngeal muscle tension in the individuals with vocal hyperfunction, which restricted their ability to vary laryngeal muscle tension levels at the phonemic level. Although average speaking fundamental frequencies do vary considerably among typical speakers and throughout utterances of individuals due to intentional prosodic changes (Atkinson, 1976), relative changes on smaller time scales (such as RFF) could correlate with the background level of laryngeal muscle tension. RFF has shown promise for detecting the presence of vocal hyperfunction, but it has yet to be studied in relation to changes in vocal hyperfunction, such as those changes experienced by individuals participating in voice therapy. The purpose of this study was to determine whether the RFF in patients with hyperfunctionally related voice disorders would normalize after a successful course of voice therapy, the goal of which was to reduce laryngeal muscle tension. We hypothesized that participants with hyperfunctionally related voice disorders would show increased RFF values after completion of voice therapy, relative to their RFF values prior to therapy.

Method

Participants

Participants were 16 women between the ages of 18 and 59 (*M* = 32, *SD* = 14) who had been clinically diagnosed with either bilateral vocal fold nodules or MTD and who had voice recordings before and after a course of successful voice therapy (see Table 1 for participant diagnoses). Participants had an average overall severity as rated on the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V; Kempster, Gerratt, Verdolini Abbott, Barkmeier-Kraemer, & Hillman, 2009) of 27.1 (*SD* = 18.8; mild to moderate). Individual participants had overall severity ratings in the mild (n = 8), mild to moderate (n = 6), moderate (n = 1), and moderate to severe (n = 1) ranges (see Table 1). We obtained de-identified data from an archival database of voice samples collected during routine clinical examinations at the Massachusetts General Hospital Center for Laryngeal Surgery and Voice Rehabilitation between 2005 and 2009. A team composed of a laryngologist and one or more certified speech-language pathologists (SLPs) made diagnoses based on comprehensive voice evaluation procedures that included endoscopic and perceptual assessments. Participants consented to the use of their voice samples for research purposes during their initial visit. The 16 participants included all patients who had been given voice therapy between 2005 and 2009 for MTD or nodules; had no other known speech, language, or hearing disorder; and had completed voice evaluations both prior to any voice therapy and after successful completion of voice therapy.

Experimental Design

Voice samples from each individual were collected at two time points: at the initial voice evaluation prior to any voice therapy (pre-) and at the postevaluation following the successful completion of a course of voice therapy (post-). The duration of the course of therapy varied for each individual participant and ranged from 3 to 21 sessions (M = 10.4, SD = 5.0). Participants typically attended one voice therapy session per week, but some variation occurred due to individual scheduling preferences. Table 1 outlines the number of therapy visits for each participant. Participants were included only if their voice therapy treatment was determined to be successful based on a comprehensive postevaluation consisting of acoustic and aerodynamic measurements and perceptual ratings made by the SLP as well as subjective interpretations of progress and improvement made by both the patient and the SLP.

Data Recording and Analysis

All acoustic recordings were completed in a sound-treated room using the Computerized Speech Lab (CSL; KayPentax, Lincoln Park, NJ) and a head-mounted condenser microphone (Sennheiser MK E2) with a sampling rate of 32 kHz. Participants read the first paragraph of “The Rainbow Passage” (Fairbanks, 1960) and two sentences from the CAPE-V: “Peter will keep at the peak” and “My mamma makes lemon muffins.” These texts were part of the current clinical voice evaluation protocol. Six voiced–voiceless–voiced combinations were selected from these texts for analysis. The combinations selected for analysis in “The Rainbow Passage” were “ever finds” (/ər/–/f/–/aɪ/) and two combinations from “looking for” (/ʊ/–/k/–/ɪŋ/ and /ɪŋ/–/f/–/ɔr/). The combinations in the CAPE-V sentences were “muffins” (/ʌ/–/f/–/ɪ/), “keep at” (/i/–/p/–/æ/), and “the peak” (/ɘ/–/p/–/i/).

Table 1. Participant diagnoses and therapy schedule.

Participant	Diagnosis	Therapy sessions	Therapy period (weeks)	RFF productions (pre- | post-)	Pre-CAPE-V overall severity
P1	MTD	4	4	4.5 | 4.5	14
P2	Nodules	11	9	4 | 4.5	57
P3	MTD	3	4	3.5 | 4.5	79
P4	Nodules	15	31	4 | 2.5	7
P5	Nodules	6	8	5 | 5	21
P6	MTD	14	16	2.5 | 2	15
P7	MTD	10	15	2.5 | 2.5	17
P8	MTD	11	18	3.5 | 3.5	40
P9	MTD	12	12	4.5 | 3.5	35
P10	MTD	9	17	4 | 4.5	12
P11	MTD	8	8	4 | 5.5	14
P12	MTD	17	26	3 | 3	18
P13	MTD	8	21	4 | 5	24
P14	MTD	13	7	4 | 4.5	34
P15	MTD	4	4	3 | 2.5	29
P16	MTD	21	29	4 | 4.5	18

Note. RFF = relative fundamental frequency; MTD = muscle tension dysphonia; CAPE-V = Consensus Auditory–Perceptual Evaluation of Voice.

A single investigator (the second author) performed acoustic analysis by displaying the time wave forms of the samples in Praat acoustic analysis software. The investigator measured the 10 periods of vibration prior to (offset) and after (onset) the voiceless consonant by using the pulse function in Praat. The instantaneous fundamental frequency was calculated as the inverse of each period, and all frequencies were then converted to ST relative to the points in the voicing farthest from the voiceless consonant (the first cycle in the 10 cycles prior to voicing offset and the final cycle in the 10 cycles following voicing onset). Stepp et al. (2010) did not find statistically significant differences between the RFF across three different voiceless consonant productions within individual participants; therefore, the RFF was averaged across all six voiceless consonant productions studied. In some cases, glottalization or a lack of periodicity prior to or following the voiceless consonant production made it impossible to reliably determine the RFF for that production. When this occurred, RFF values from that production were excluded, and only the remaining productions were utilized for the average. The mean number of productions used was 4.2 (SD = 0.9) for each participant’s offset averages and 3.4 (SD = 1.2) for each participant’s onset averages. Table 1 details the number of productions used for each participant.

The second author reevaluated approximately 10% of samples 2 months after the initial evaluation to assess intrarater reliability (Pearson’s r = .96); the average difference for all RFF values in this sample was –.022. Likewise, the first author analyzed approximately 10% of samples to assess interrater reliability (Pearson’s r = .93); the average difference for all RFF values between the two raters in this sample was –.031.

Statistical Analysis

The effects of therapy (pre- vs. post-) and cycle were assessed with a two-factor analysis of variance (ANOVA), followed by a post hoc paired Student’s t test (one-sided) to further assess the difference between pre- and posttherapy values. We chose the one-sided test given the a priori hypothesis that posttherapy values would show increased values of RFF. Analyses were completed using Minitab Statistical Software (Minitab Inc., State College, PA).

Results

A two-way ANOVA showed a statistically significant effect on the pre- and posttherapy RFF of the 16 participants of both cycle, $F(19) = 53.1$, $p < .001$, and therapy phase (pre- vs. post-), $F(1) = 14.1$, $p < .001$, but no effect of the interaction between cycle and therapy phase, $F(19) = 1.44$, $p = .10$. A post hoc one-sided paired Student's t test showed that posttherapy RFF measurements were significantly higher, $t(319) = 4.5$, $p < .0001$, than pretherapy measurements. Figure 2 shows mean pre- and posttherapy measurements of RFF in ST across all 20 cycles (Panel A) as well as the mean differences (post- minus pre-) between pretherapy and posttherapy recordings (Panel B). Post- and pre- values are shown in Table 2. Differences between pre- and posttherapy recordings were largest for Offset Cycles 4–10 and for Onset Cycle 1.

Figure 2. A: Mean values of RFF for participants ($N = 16$) pre- and posttherapy. Error bars indicate the standard error. B: Mean differences (post- minus pre-) of the RFF change. Error bars indicate the standard error.

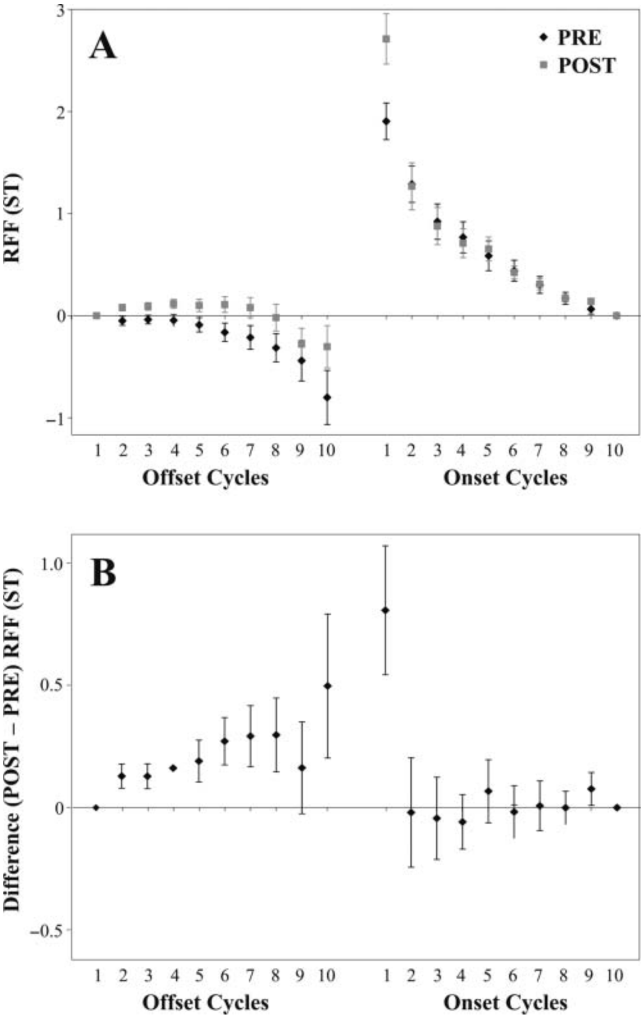


Table 2. Pre- and post-RFF.

Cycle	Pre-RFF (*M* ± *SE*)	Post-RFF (*M* ± *SE*)
Offset 1	0	0
Offset 2	–0.05 ± 0.05	0.08 ± 0.03
Offset 3	–0.04 ± 0.04	0.09 ± 0.04
Offset 4	–0.05 ± 0.06	0.12 ± 0.04
Offset 5	–0.09 ± 0.07	0.10 ± 0.06
Offset 6	–0.16 ± 0.09	0.11 ± 0.08
Offset 7	–0.21 ± 0.12	0.08 ± 0.10
Offset 8	–0.32 ± 0.14	–0.02 ± 0.13
Offset 9	–0.44 ± 0.20	–0.28 ± 0.15
Offset 10	–0.80 ± 0.26	–0.30 ± 0.21
Onset 1	1.90 ± 0.18	2.71 ± 0.25
Onset 2	1.29 ± 0.18	1.27 ± 0.23
Onset 3	0.92 ± 0.17	0.88 ± 0.18
Onset 4	0.77 ± 0.15	0.71 ± 0.14
Onset 5	0.59 ± 0.14	0.65 ± 0.12
Onset 6	0.44 ± 0.10	0.42 ± 0.06
Onset 7	0.30 ± 0.08	0.31 ± 0.05
Onset 8	0.17 ± 0.06	0.17 ± 0.04
Onset 9	0.06 ± 0.05	0.14 ± 0.03
Onset 10	0	0

Discussion

Comparison With the Literature

Stepp et al. (2010) reported average offset RFF values in individuals with voice disorders ranging from –1.017 ST to –1.61 ST at Cycle 10 and average onset RFF values ranging from 2.12 ST to 2.48 ST at Cycle 1. Conversely, individuals with healthy typical voice showed average offset RFF at Cycle 10 of –0.33 ST and average onset RFF at Cycle 1 of 3.82 ST. Prior to therapy, our participants showed average offset RFF at Cycle 10 of –0.80 ST and average onset RFF at Cycle 1 of 1.90 ST. These values are similar to those seen previously in the individuals with hyperfunctional voice disorders prior to intervention. Posttherapy, the average offset RFF at Cycle 10 increased to –0.30 ST, and the average onset RFF at Cycle 1 also increased to 2.71 ST. These values are statistically significant increases relative to pretherapy RFF values. However, although posttherapy offset values seem to completely normalize by reaching –0.30 ST in Cycle 10, onset values at Cycle 1 are still markedly reduced when compared with the healthy controls studied previously (2.71 relative to 3.82; Stepp et al., 2010). This difference could be the result of variance in the measure of RFF or lack of specificity in RFF for detecting vocal hyperfunction. It is also possible that individuals with hyperfunctional voice disorders after successful therapy still display some vocal hyperfunction relative to healthy controls, which is being detected by this measure. This discrepancy may be elucidated by additional normative data as well as future work comparing RFF and other measures of vocal hyperfunction over the rehabilitation process.

Relationship of RFF to Baseline Laryngeal Tension

Participants with hyperfunctionally related voice disorders prior to therapy showed lowered RFF, and after successful voice therapy, RFF increased toward patterns seen in individuals with healthy typical voice. Given that the goal of voice therapy in these patients was to reduce laryngeal muscle tension, this finding supports the theory asserted by Stepp et al. (2010) that decreased RFF may be indicative of increased baseline laryngeal muscle tension.

However, Hanson (2009) recently noted that the raw fundamental frequency following voiceless obstruents is increased in high-pitch environments to a greater extent than in low-pitch environments. Although this work did not calculate RFF, the results suggest that if baseline laryngeal muscle tension is increased in a high-pitch environment, this finding may conflict with the supposition that RFF is lowered by such baseline tension. Hanson argues that the difference between high- and low-pitch environments is due to conflicts between the segmental feature of stiff vocal folds and intonational changes. The relationship between laryngeal tension in patients with PD or hyperfunctional voice disorders and typical speakers producing speech in a high-pitch environment is not currently known; thus, this topic requires further exploration. In particular, future studies collecting RFF and simultaneous electromyography of intrinsic and extrinsic laryngeal muscles under differing vocal conditions are necessary, in both healthy individuals and individuals with vocal hyperfunction.

Clinical Potential for Adoption of RFF Measures

Participants' RFF values increased toward patterns seen previously in individuals with healthy typical voice after successful completion of voice therapy, which is a promising finding for the use of RFF as an objective measure of vocal hyperfunction. Looking specifically at the total sum of RFF values across all cycles, the value of Offset Cycle 10, and the value of Onset Cycle 1, there is promise for a diagnostic marker. An increase (post- minus pre-) in the RFF sum and an increase in RFF of Offset Cycle 10 was seen in 81% of these successful patients, and an increase in RFF of Onset Cycle 1 was seen in 94% of the patients included. Future prospective studies incorporating RFF values before and after both successful and unsuccessful courses of therapy will allow us to determine the utility of changes in RFF relative to absolute RFF values as a clinical tool.

One limitation of the application of RFF as a clinical tool is the need for periodicity in the measured voice sample. As noted in the Method section, some voiced–voiceless–voiced tokens were not measured because of inadequate periodicity, and this limitation would likely be a substantial impediment to adoption of RFF-based measures in severe vocal hyperfunction because individuals with the greatest voice dysfunction are also the most likely to display such nonperiodicity. For acoustic signals without clear periodicity, the standard acoustic measures used clinically are also of limited utility, and perceptual ratings are currently the best measurements for clinical assessment (Titze, 1995). As an acoustic measure, RFF is also susceptible to this failing and will need to be secondary to perceptual ratings in extremely disordered cases.

Conclusions

Prior to therapy, participants with hyperfunctionally related voice disorders exhibited lowered RFF values similar to those found previously (Stepp et al., 2010). After successful completion of voice therapy, RFF values increased toward patterns seen in individuals with healthy typical voice. Given that the goal of voice therapy in these patients was to reduce laryngeal muscle tension, this finding supports the theory asserted by Stepp et al. (2010) that decreased RFF may be indicative of increased baseline laryngeal muscle tension. Results indicate promise for future clinical adoption of RFF measures for repeated assessment throughout treatment to identify progress while also suggesting that future prospective study is warranted.

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