Examining the Effect of Volitionally Altering Fundamental Frequency on Measures Associated With Vocal Hyperfunction

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SUMMARY: Speech-language pathologists who work with transgender and nonbinary individuals are often concerned about introducing vocal hyperfunction (VH) while supporting the use of a more gender-congruent voice. The current study examined the effects of volitionally altering fundamental frequency (f_o) on measures associated with VH. Forty (20 female, 20 male) speakers with no vocal complaints and who did not identify as transgender were recruited. Speakers were recorded in two conditions: habitual f_o and altered f_o. In the altered f_o condition, speakers volitionally altered their f_o by two semitones in the stereotypical direction desired by transgender and nonbinary speakers with the same vocal anatomy: females lowered their f_o and males raised their f_o. A total of 13 acoustic, aerodynamic, videostroboscopic, and perceptual (self- and other) measures were assessed. Of the 13 measures, 7 were statistically affected by the two-way interaction between sex and f_o condition. Only three measures had medium or larger effect sizes. Compared to using a habitual f_o, females used longer vocal tract lengths, and higher smoothed cepstral peak prominences (CPPS) and low to high (L/H) ratios when lowering f_o and males used shorter vocal tract lengths and lower L/H ratios when raising f_o. In general, vocalizations produced with a volitionally altered f_o were more consistent with those in speakers with VH than vocalizations produced with a habitual f_o. In response to altering f_o, females had more measures that differed than males. This is counter to expectations given that males raised their f_o and using a higher f_o is associated with increased laryngeal tension. That being said, many of the changes reflected the physiological adjustments required to achieve an externally specified f_o target.

Keywords: Vocal hyperfunction–Fundamental frequency–Voice–Sex–Gender.

INTRODUCTION

Vocal hyperfunction (VH) has been a long-standing concern for speech-language pathologists (SLPs) who work with transgender and nonbinary people (sex-assigned at birth does not match gender identity). The concern is likely related to the desire of some transfeminine people to raise the pitch of their voice,[1] potentially disrupting typical patterns of phonation, and the theoretical understanding that phonating with a higher fundamental frequency (f_o) requires a greater degree of laryngeal tension[2] and a higher laryngeal position[3] when compared to a lower f_o. Taken together, one might assume that transfeminine people who desire a higher f_o would be predisposed to VH and transmasculine people who desire a lower f_o would not. Despite this, signs and symptoms associated with VH have been reported in both transfeminine[4,5] and transmasculine[6] people. An alternative hypothesis is that any long-term volitional alteration of f_o necessitates increased vocal effort to achieve and may lead to inefficiencies in voice production. In the current study, we seek to examine the relationship between altering f_o and behaviors associated with VH.

VH is an umbrella term describing voice symptoms that include excessive and/or uncoordinated laryngeal and perilaryngeal tension,[7] changes to voice quality,[8] vocal fatigue, and/or increases to vocal effort.[9–11] Other descriptions may include, but are not limited to, a high larynx position, supraglottic compression, and strained voice quality.[8,12,13] Symptoms of VH may contribute to up to 40% of referrals to multidisciplinary voice clinics.[14] It is unclear why speakers develop VH, but there are several hypotheses regarding the contribution of psychological and physical stressors to VH.[9] Transgender and nonbinary people experience unique psychological and physical stressors[15] and the physiological changes induced by altering f_o may affect the biomechanics of speech production. The current study aims to address the first step of disentangling the relationship between VH and gender identity by examining the effect of short-term alteration of f_o on measures associated with VH.

Measures associated with vocal hyperfunction

Vocal hyperfunction is described as a response to psychological and physical stressors. These stressors alter typical phonation. If typical phonation remains disrupted, a speaker may develop a voice disorder.[9] Volitionally altering a speaker's f_o may disrupt typical phonation, leading to inefficient voice production, and thus, increased signs and symptoms of VH. Given the associations between using a higher f_o and laryngeal tension[2] and laryngeal position,[3] raising f_o may result in a larger increase in signs and

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symptoms of VH as compared to lowering f_o. Because VH is not described by one specific metric, a multidimensional approach is necessary to evaluate whether typical patterns of phonation are disrupted when speakers alter their f_o.

Individuals with VH frequently report increased feelings of vocal effort[11] and are often described as having a strained vocal quality.[16,17] Identifying objective measures related to these perceptual measures has been difficult.[18,19] This may be partially explained by individual differences in the speaker's experience with increased vocal effort and a listener's perception of that voice.[20] Additionally, voices that are perceived to be primarily strained in voice quality often co-occur with some degree of breathiness or roughness.[17] Despite these difficulties, there have been considerable efforts to correlate these perceptions to objective measures to identify and track changes in VH.

Low to high ratio (L/H ratio) and cepstral peak prominence (CPP) are two acoustic correlates of vocal quality. Voices with more severe ratings of strain and higher self-ratings of vocal effort have higher CPP[20,21] and lower L/H ratio values.[17,19,20,22] However, vocal strain often co-occurs with breathy or rough vocal qualities.[17] Additionally, CPP and L/H ratio may be nonspecific to strained vocal qualities and have been linked to the overall severity of dysphonia,[22–25] breathiness,[23,24,26] and roughness.[24] Regardless of their specificity to vocal strain, these measures provide insight into changes in vocal quality in speakers with VH.

Relative fundamental frequency (RFF) is another acoustic measure associated with VH.[27,28] In general, RFF is lower in speakers with increased laryngeal tension.[28] Specifically, speakers with VH tend to have lower RFF values than speakers without VH.[16,29] RFF values are responsive to behavioral voice treatment,[30,31] but not surgical interventions,[29] indicating that RFF is a sensitive measure of functional rather than structural changes to the vocal folds. Further, voices with lower RFF values elicit greater listener ratings of vocal effort [20] and strain [32] than do voices with higher RFF values.

Aerodynamic measures are also useful indicators of VH. When compared to speakers without VH, speakers with VH phonate with greater subglottal air pressures.[9,33] This pattern has been identified in speakers with phonotraumatic VH (e.g., vocal nodules) [34] and becomes apparent in these speakers with non-phonotraumatic VH (e.g., muscle tension dysphonia) when subglottal air pressure is normalized to the sound pressure level of the vocalization (SPL).[33] Increases in subglottal air pressure suggest a greater degree of longitudinal and/or transverse vocal fold tension and increased collision forces in the voices of those with VH than in the voices of speakers without VH.[9] Indirect evidence for these changes is reported in studies of RFF,[16,35] which also suggest that speakers with VH use elevated laryngeal tension. Similarly, speakers without VH who phonate with a maximal vocal effort use greater subglottal air pressures and transglottal airflows than when phonating with minimal vocal effort.[21]

Supraglottic activity has long been associated with VH and increased muscle tension during phonation.[8,12,13] A higher percentage of individuals with VH disorders present with anterior-posterior (A-P) supraglottic compression [36,37] and medial-lateral (M-L; referred to as false vocal fold) supraglottic compression [36] than those without a voice disorder, although supraglottic activity may be identified in persons without voice complaints.[36,38,39] M-L supraglottal compression is also linked with laryngeal articulation (e.g., production of glottal stops) [36] and may be related to lower CPP values.[40] Thus, the presence and degree of supraglottic compression are associated with VH, but supraglottic compression is also present in speakers without VH.

Fundamental frequency and measures of VH

Altering f_o is a complex biomechanical process. It is often described as the result of adjustments to vocal fold tension and stiffness,[41–43] which are associated with the activation of the cricothyroid muscle resulting in longer or shorter vocal folds. When phonating, longer vocal folds have greater tension and stiffness, contributing to a faster rate of vibration and thus, fundamental frequency than shorter vocal folds. Additionally, thyroarytenoid muscle activation works to shorten the vocal folds thus lowering f_o. It may also stiffen or relax different layers of the vocal folds, which will also affect a speaker's f_o.[42,43] Other factors, such as subglottal pressure and duration of vocal fold contact also contribute to a speaker's f_o.[43] Given that these factors are interrelated, it makes sense that a speaker's f_o may be variable.

Social and cultural factors contribute to the variability of f_o. A speaker's f_o changes depending on the speaking task,[44–47] communication partner,[48] and the language that is spoken.[49] Additionally, the mean habitual f_o in English, particularly for females, has shifted over time.[47,50] Given this variability, it is unsurprising that there is conflicting evidence for group differences in the habitual f_o of speakers with and without VH.[17,51–54] However, habitual f_o often changes (increase or decrease) as a result of intervention in speakers with VH.[55–57] Changing habitual f_o is not the goal, but may be a byproduct of altering the tension within the vocal folds during phonation.[31]

Speakers with VH often have increased supralaryngeal tension during phonation.[58,59] This is evidenced by a higher laryngeal position during phonation than that found in speakers without VH.[51] Because laryngeal position alters vocal fold tension, a higher laryngeal position is also related to a higher f_o [3,60] and a lower laryngeal position is related to a lower f_o.[3,40,60] Therapeutic techniques, such as circumlaryngeal massage,[7,58] are used to decrease supralaryngeal tension, allowing speakers to phonate with a reduced laryngeal height.[61,62] As a result of intervention, speakers tend to have reduced supralaryngeal tension and phonate with lower laryngeal heights. Changes to f_o are not consistent across studies.[57,59,61,63]

Considering the relationships across f_o, vocal fold tension, and VH, it may be easy to theorize that an "optimal"

f_o exists that allows the speaker to phonate most efficiently.[64] Over the decades, this idea has received attention (e.g., Britto & Doyle, 1990),[45] but was not well-supported by treatment results, which did not result in consistent changes (in either direction and magnitude) in f_o.[57,59,61,63] Although no longer directly associated with f_o, the idea of optimizing vocal efficiency remains. In particular, altering f_o and optimizing vocal efficiency are frequently discussed in gender-affirming voice care.

Gender-affirming voice training primarily relies on therapeutic techniques (e.g., semi-occluded vocal tract exercises and vocal function exercises) that were originally designed to address VH in order to alter f_o and vocal tract resonances.[1] It also typically includes education on vocal hygiene to prevent the introduction of vocal inefficiency.[65] This historical precedent associates an altered f_o with vocal inefficiencies, and thus, increased signs of VH. It is critical to investigate these connotations to avoid applying unfounded assumptions to transgender and nonbinary speakers and gender-affirming voice training.

Current study

The current study investigated the effects of altering f_o on measures of VH. We limited our study to a single timepoint and speakers without a voice disorder who did not identify as transgender. Participants were asked to produce their habitual f_o and then to alter their f_o in one of two directions: females were asked to lower their f_o and males were asked to raise their f_o. Specific outcome measures were chosen for their theoretical relationship with VH. We hypothesized that, compared to speech produced with a habitual f_o, speech produced with an altered f_o would be more consistent with VH, regardless of the direction of f_o change. Further, because of the link between raising f_o and VH, we hypothesized that the differences from habitual speech in measures of VH would be larger for speech produced with a raised f_o than with a lowered f_o. This single-timepoint experimental design only examined short-term or acute changes in measures of VH. Any changes would reflect initial compensatory strategies to complete a novel vocalization task and thus, may be representative of the inefficiencies associated with the initial development of a motor speech plan, prior to consolidation and habituation of the new behavior. In other words, the results of the current study were not intended to represent long-term changes associated with habituating an altered f_o.

METHODS

Informed consent was obtained from all participants, in compliance with the Boston University's Institutional Review Board (IRB 2625). Recruitment of participants was completed via flyers, online postings within the university and community, and word of mouth. All participants were compensated for their time.

Participants

Forty speakers (20 male,[1] 20 female[2]) who did not identify as transgender[3] and were aged between 18 – 36 years (M = 22.7; SD = 3.6) completed this study. An additional 21 speakers were recruited, but were excluded from the analysis.[4] No speaker reported a history of speech, language, or hearing disorders, voice disorder, or acquired head injury. All speakers passed a pure-tone hearing screening of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz at 25 dB, and 8000 Hz at 35 dB while seated in a quiet room. Race and ethnicity information are reported in Supplementary Material 1.

A voice-specialized SLP who was aware of the study purpose and population provided a clinical assessment of vocal quality using the Consensus of Auditory-Perceptual Evaluation of Voice (CAPE-V).[66] Sixteen sound files were repeated to assess intra-rater reliability. Ratings of overall severity of dysphonia, roughness, breathiness, and strain ranged from 0 to 10. Using two-way intraclass correlations (ICC [2,1]) for agreement, intra-rater reliability ranged from 0.62 to 0.84 which was consistent with the published reliability of the CAPE-V.[67] Pitch and loudness ratings were 0 for all speakers, indicating that these dimensions were appropriate for the speaker's assumed age, sex, and cultural expectations. Overall, the speakers presented with perceptually healthy vocal quality.

Sixteen inexperienced listeners aged between 18 – 34 years (M = 22.4; SD = 4.3) were recruited to rate vocal strain. Eight listeners identified as cisgender women, four as cisgender men, two as transgender women, one as genderfluid, and one as nonbinary. No listener identified as intersex. No listeners reported a history of speech, language, or hearing disorders, voice disorder, or acquired head injury. All listeners passed a pure-tone hearing screening of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz at 25 dB, and 8000 Hz at 35 dB. Two additional listeners were recruited, but were excluded from the analysis due to failed hearing screenings.

Data collection and analysis

Speaker data were collected in a single session lasting approximately 1.5 h. Acoustic and aerodynamic data collection occurred in a sound-attenuated booth. Each session consisted of four experimental blocks. In the first block, speakers were asked to produce speech using their habitual f_o. In the second block, speakers practiced using a target f_o. The target f_o was defined as a 2 semitone (ST) change from

[1] All males were assigned-male at birth and identified as cisgender, except for one person who identified as nonbinary, but did not identify as transgender.

[2] All females were assigned-female at birth and identified as cisgender, except for one person who identified as a woman with multiple genders who did not identify as transgender.

[3] Persons who identified as transgender were referred to a separate experiment that ran concurrent to this study.

[4] Speakers were excluded for a technical issue (1 male), a failed hearing screening (1 female, 2 male), unable to match the altered f_o target (7 female, 2 male), or unable to tolerate endoscopy (1 female, 7 male).

their habitual f_o measured from a reading task in one of two directions: females lowered their f_o and males raised their f_o. The direction was determined by the stereotypical direction of change often desired by persons who identify as transgender and conform to binary gender norms (e.g., transmasculine persons assigned female at birth may desire to lower their f_o). A single target was chosen to experimentally control the degree of change that all participants were asked to produce, regardless of their habitual f_o. A 2 ST change was chosen based on the feasibility for female pilot participants to lower their f_o. Although male pilot participants were able to alter their f_o to a greater extent than females, a case study of involving ambulatory monitoring of f_o in a transgender woman supported that a 2 ST may be more representative of the degree of change that can be habituated in everyday communication after four weeks of gender-affirming voice training.[68] During practice, speakers were instructed that, "The target pitch [was] intended to be an average," and that they could, "vary [their] pitch around this target, like [they] would when speaking naturally." They heard a synthetic voice producing /ɑ/ at the target f_o generated with a free-software synthesizer (Madde, Tolvan Data) and used visual biofeedback via a customized real-time pitch tracker to facilitate matching the target f_o. In the third block, speakers repeated the speech tasks from the first block while matching the target f_o. The visual biofeedback was removed. To support the use of the target f_o, speakers heard the synthetic voice before each speech task. Tasks were repeated if the speaker did not accurately match the target f_o (on average). In the fourth block, the speakers underwent stroboscopy via nasal endoscopy. Speakers produced /i/ at a comfortable f_o and two f_o matching conditions: the habitual f_o measured from their reading passage and the target f_o. The synthetic voice was presented during the f_o matching conditions. A comfortable f_o condition was included to account for potential supraglottic constriction related to discomfort during the exam and/or f_o matching rather than altering f_o. Block order was consistent across speakers to optimize the likelihood that speech produced with a habitual f_o was representative of the speaker's everyday speech production.

Acoustic

Speakers wore an omnidirectional microphone (MX153, Shure Niles, IL) positioned 7 cm from the mouth at a 45-degree angle.[69] Sound pressure level was calibrated. Acoustic signals were recorded using a microphone preamplifier (QuadMic II, RME, Germany) and digitized using a soundcard (Fireface UCX, RME, Germany) before being recorded in Sonar Artist (Cakewalk) and sampled at 44.1 kHz. Speakers produced sustained vowels (/ɑ/, /i/, /u/, and /ɛ/), /VfV/ stimuli (/ɑfɑ/, /ifi/, /ufu/), and a reading passage.[70] Data analysis involved using a set of customized scripts in Praat Version 6.2.04[71] and MATLAB (MathWorks, 2016). See Table 1 for all outcome measures.

TABLE 1.
Outcome Measures of Speech Production

Instrumentation	Outcome measures
Acoustic	Fundamental frequency (f_o) Intensity (dB SPL) Estimated vocal tract length (VTL) Smoothed cepstral peak prominence (CPPS) Low to high ratio (L/H ratio) Relative fundamental frequency (RFF)
Aerodynamic	Oral air pressure normalized SPL Oral airflow normalized SPL
Stroboscopy	Voice Vibratory Assessment for Laryngeal Imaging (VALI):[76] supraglottic activity
Perceptual	Vocal effort (speaker) Strain (listener)

The middle 50% duration of each sustained vowel was automatically extracted and analyzed for the following measures: f_o, intensity, the first four formant frequencies (F1- F4), smoothed cepstral peak prominence (CPPS), and L/H ratio. Based on the mean of the third and fourth formant frequencies of /ɛ/, vocal tract length (VTL) was estimated using Eq. 1,[61,72] where n is the formant number, c is the speed of sound in air (34,300 cm/s), and F_n is the formant frequency in Hertz. CPPS was extracted using a Praat script.[73] The L/H ratio was measured from the spectrum with a cut-off ratio of 4 kHz.[74] All f_o and formant parameters were manually adjusted by the first author.

$$\textit{Vocal tract length} = \frac{(2n-1)c}{4F_n} \tag{1}$$

The relative fundamental frequency (RFF) was extracted from /VfV/ utterances using a semi-automated MATLAB algorithm.[75] A trained researcher confirmed the position of the /f/; the algorithm calculated the frequency of the ten boundary cycles closest to voicing offset and onset. These frequencies were then converted to ST, in reference to offset cycle 1 and onset cycle 10. For the current study, we reported the average RFF for the two cycles closest to phonation offset and onset, *RFF Offset 10* and *RFF Onset 1*, respectively. A minimum of two utterances within each condition were required, consistent with previous work.[75]

Four measures were extracted from the reading passage: f_o, intensity, CPPS, and L/H ratio. Although each measure was also collected from vowels, connected speech required additional processing. Using a publicly available voice detection algorithm,[73] voiced segments (i.e., no silences or voiceless phonemes) were extracted and CPPS was automatically calculated. To calculate f_o, these voiced segments were manually inspected for modal phonation (e.g., no creaky phonation) and accurate f_o tracking (i.e., removed frequency halving or doubling). A customized MATLAB script was used to remove pauses, but retain voiceless phonemes prior to automatically extracting L/H ratio with a cut-off value of 4 kHz.

Aerodynamic

Aerodynamic data were collected using a circumferentially vented pneumotach mask with a catheter placed between the lips (Glottal Enterprises, Syracuse, NY). The mask and catheter were connected to a transducer and analog computer interface. Speakers produced /pʌ:/ strings at comfortable and loud volumes. All air pressure and airflow signals were low pass filtered at 50 Hz and were calibrated. Air pressure signals were visually inspected to confirm that pressure equalization occurred during the /p/. The first syllable was always omitted from analysis to reduce onset effects. Air pressure was calculated as the average of two adjacent air pressure peaks. Airflow was measured from the middle 50% of the vowel, excluding the first and last syllables in the /pʌ:/ string to reduce onset and offset effects.

Stroboscopic

Visualization of the vocal folds was conducted via nasal endoscopy. Digital video (via a distal imaging chip; EPK-1000; Pentax, Tokyo, Japan) and acoustic signals were recorded with the Digital Stroboscopy System (Kay Electronics, Lincoln Park, NJ) with a strobe light source. Video was digitized at 30 frames per second with a frame size of 480 x 360 pixels. A nasal decongestant and lubricating jelly were used to improve comfort. A numbing agent was not provided.

Speakers produced at least three repetitions of /i/ in three different conditions: a) comfortable f_o, b) habitual f_o, and c) altered f_o. Productions that accurately matched the target f_o (habitual f_o and altered f_o conditions only) were extracted by the first author into video clips ranged from 5 – 13 s in duration. Using a customized MATLAB script to pseudo-randomize and blind raters to speaker and f_o condition, a voice-specialized SLP rated each clip for supraglottic activity using the Voice Vibratory Assessment for Laryngeal Imaging Form for stroboscopy (VALI).[76] Forty-eight (20%) video clips were repeated to assess intra-rater reliability, resulting in a total of 288 ratings (2 videos X 3 conditions X 40 participants + 48). The first author (also a SLP) rated 48 videos (20%) to assess interrater reliability. Cohen's weighted Kappa was used to assess intra- and inter- rater reliability.[77] Intra-rater reliability for A-P and M-L supraglottic activity was 0.79 and 0.69, respectively, and interpreted as moderate agreement. Interrater reliability values for A-P and M-L supraglottic activity were 0.71 and 0.75, respectively, and interpreted as moderate agreement.

Self-perceptual

Speakers were asked to rate their vocal effort in the first and third blocks, after the sustained vowels and a reading passage, resulting in four ratings per speaker (2 tasks X 2 f_o conditions). Vocal effort was defined as described in Abur, Perkell and Stepp,[70] "Vocal effort is how easy or difficult it is to talk in terms of how much effort, strain, discomfort, and/or fatigue you perceive when using your voice. Think only of the vocal effort [pointed to larynx], not mental effort or concentration it takes to produce an effortless voice." The speakers were then asked to use to the Borg CR100 scale of vocal effort [78] when making their vocal effort ratings using the following directions, "When you are rating your vocal effort, I want you to use this scale. It ranges from 0 to 100. You can tell me a number with a decimal point if you want. Think of minimal vocal effort as a voice that is easy to produce and free of any strain or discomfort. In contrast, when you use maximum vocal effort, you can think of when you have laryngitis and can barely get a sound out."

Listener perception

Listeners completed a self-paced auditory-perceptual experiment designed in MATLAB. Listeners wore headphones, adjusted the volume to a comfortable listening level, and completed the task in a sound attenuated booth. For each stimulus, listeners made four ratings, but only ratings of strain will be reported. All ratings were made along a 100-point visual analog scale. Sixteen (20%) stimuli were repeated to assess intra-rater reliability, resulting in 96 (2 conditions X 40 participants + 16) experimental stimuli. Using ICCs, the average intra-rater reliability was 0.32, indicating poor reliability. When we examined the range of values, the average absolute differences for each participant ranged from 0.13 to 12.07 (out of 100) which indicates that listeners tended to rate participants similarly across repetitions. Inter-rater reliability two-way ICCs with random effects over the mean of 16 raters was 0.71, interpreted as adequate interrater reliability. The rating task took approximately 1 h.

The auditory-perceptual experiment consisted of a familiarization phase and an experimental phase. During the familiarization phase, listeners read the definition of the strain, the "perception of excessive [speaker] vocal effort",[66] and practiced rating three non-experimental stimuli. Ratings were made on a visual analog scale with labels "Typical" and "Severely atypical" at approximately 0% and 100% of the scale length, respectively. Familiarization stimuli were chosen from the Perceptual Voice Qualities Database [79] to represent "mild," "moderate," and "severe" strain. After each rating, listeners saw the rating of an experienced listener rating. During the experimental phase, listeners could access the definition for strain via a help button, but did not receive any feedback. Experimental stimuli consisted of the second and third sentence of the reading passage (~10–15 s) and were root-mean-square amplitude normalized. Experimental stimuli could be replayed one time. Once satisfied with their rating, listeners pressed "Continue" to progress to the next stimulus.

Stimuli were pseudo randomly presented so listeners did not make consecutive ratings of the same speaker.

Statistical analysis

Linear mixed-effects models were used to examine the effects of sex and f_o condition on measures associated with VH, excluding stroboscopic measures, using the lme4[80] package in R.[81] Because the acoustic measures were derived from different speech stimuli, separate models were constructed for each independent variable. All models included fixed effects for sex (*female, male*), f_o condition (*habitual, altered*), and their two-way interactions. A fixed effect for task was included for vowel acoustics (/a/, /i/, /u/, /ε/), RFF (/afa/, /ifi/, /ufu/), and aerodynamic (*comfortable, loud*) measures. A fixed effect of intensity was included for spectral [82] and cepstral measures.[82] Consistent with Espinoza, Zañartu, Van Stan, Mehta and Hillman,[33] aerodynamic measures were normalized by their associated SPL by dividing SPL by each outcome measure resulting in ratios. Prior to normalization, airflow and air pressure were converted into a logarithmic scale (20 times the logarithm of both measures). Normalizing to SPL may improve sensitivity to group differences related to variations in sound pressure level [52] and higher ratios as indicative of greater vocal efficiency.[33] By-speaker slopes and intercepts were included for acoustic, aerodynamic, and vocal effort measures. For listener ratings of strain only, by-speaker and by-listener slopes and intercepts were included. All categorical fixed effects were sum-coded. Significant interactions were investigated using the function *emmeans*[83] and Holm post-hoc adjustments were made to *p*-values (denoted *P**). An alpha level of.05 was used for all statistical tests and for all significant fixed effects, partial eta[2] effect sizes are reported. Partial eta[2] effect sizes were calculated using the function *eta_squared* within the effectsize package.[84] Partial eta[2] (η^2_p) effect sizes of 0.01, 0.06, 0.14 are interpreted as small, medium, and large effects, respectively.[84]

Because the stroboscopic analysis resulted in ordinal data, nonparametric testing was conducted to examine the effect of sex and f_o condition on A-P and M-L supraglottic activity. Kruskal Wallis rank sum tests were conducted to examine the effect of condition by sex and eta[2] effect sizes were calculated using the *kruskal_test* and *kruskal_effsize* functions in the rstatix package.[85] Significant effects were analyzed using Wilcox rank sum tests with Holm post-hoc *p*-value adjustments using the *pairwise.wilcox.test* function in the stats package.[86] Eta[2] (η^2) effect sizes of 0.02, 0.13, 0.26 were interpreted as small, medium, and large effects, respectively.[87]

RESULTS

Descriptive data for continuous outcome measures by sex and f_o condition and all statistical model outputs are presented in Supplementary Material 2. Graphical representation of the data is provided in Figure 1. The *p*-values and effect sizes for all continuous outcome variables are provided in Table 2 and those for supraglottic activity are provided in Table 3. Post hoc analyses for significant effects will be described in the text below.

Acoustic

Vowels: Vocal tract length differed by sex, f_o condition, and their interaction. The post hoc analysis of the fixed effects indicated that as expected, males had longer VTLs than females. In comparison to using a habitual f_o, speakers altered the length of their vocal tracts when altering f_o. Post hoc analysis of the interaction indicated that compared to vocalizations with a habitual f_o, females increased their VTL by an average of 0.70 cm when decreasing their f_o and males decreased their VTL by an average of 0.20 cm when raising their f_o. CPPS and L/H ratio values differed by sex, f_o condition, task, intensity, and the interaction between sex and f_o condition. Males had higher CPPS and L/H ratio values than females. On average, CPPS and L/H ratio values were higher when altering f_o than when using a habitual f_o. Post hoc analysis of the interaction indicated that for females, CPPS and L/H ratio values increased when lowering their f_o (both $P^* < .001$), but for males, CPPS values did not differ between conditions ($P^* = .874$) and L/H ratio values decreased when raising f_o ($P^* = .025$). Post hoc analysis of task for CPPS revealed stepwise differences where /ε/ had higher CPPS values than /ɑ/ and /i/ (both $P^* < .001$), which did not differ from each other ($P^* = .351$), and were, in turn, higher than /u/ (both $P^* < .011$). Post hoc analysis of L/H ratio values also revealed stepwise differences where /u/ had a higher L/H ratio than /ɑ/ ($P^* < .001$), which was higher than /ε/ ($P^* < .001$), which was higher than /i/ ($P^* < .035$). CPPS and L/H ratio values were higher for vocalizations with greater intensity.

RFF

RFF Offset Cycle 10 differed by f_o condition, task, and the interaction between sex and f_o condition. RFF Offset Cycle 10 values were higher (less negative) when speakers used their habitual f_o as compared to an altered f_o. Post hoc analysis of the interaction between sex and f_o condition indicated that RFF Offset Cycle 10 differences were driven by female speakers whose habitual f_o productions had higher RFF Offset Cycle 10 values than their lowered f_o productions ($P^* < .001$). Male RFF Offset Cycle 10 values did not differ between f_o conditions ($P^* = .147$). Post hoc analysis of task indicated that /ɑfɑ/ had higher RFF Offset Cycle 10 values than /ufu/ and /ifi/ (both $P^* < .001$), which did not differ from each other ($P^* = .623$). RFF Onset Cycle 1 differed by sex, f_o condition, task, and the interaction between sex and f_o condition. On average, RFF Onset Cycle 1 values were lower for females than males and were greater for altered f_o productions than a habitual f_o productions ($P^* < .001$). Post hoc analysis of the interaction revealed that this was only true for females who lowered their f_o ($P^* < .001$). For males, RFF Onset Cycle 1 values decreased when raising their f_o ($P^* = .001$). Post hoc

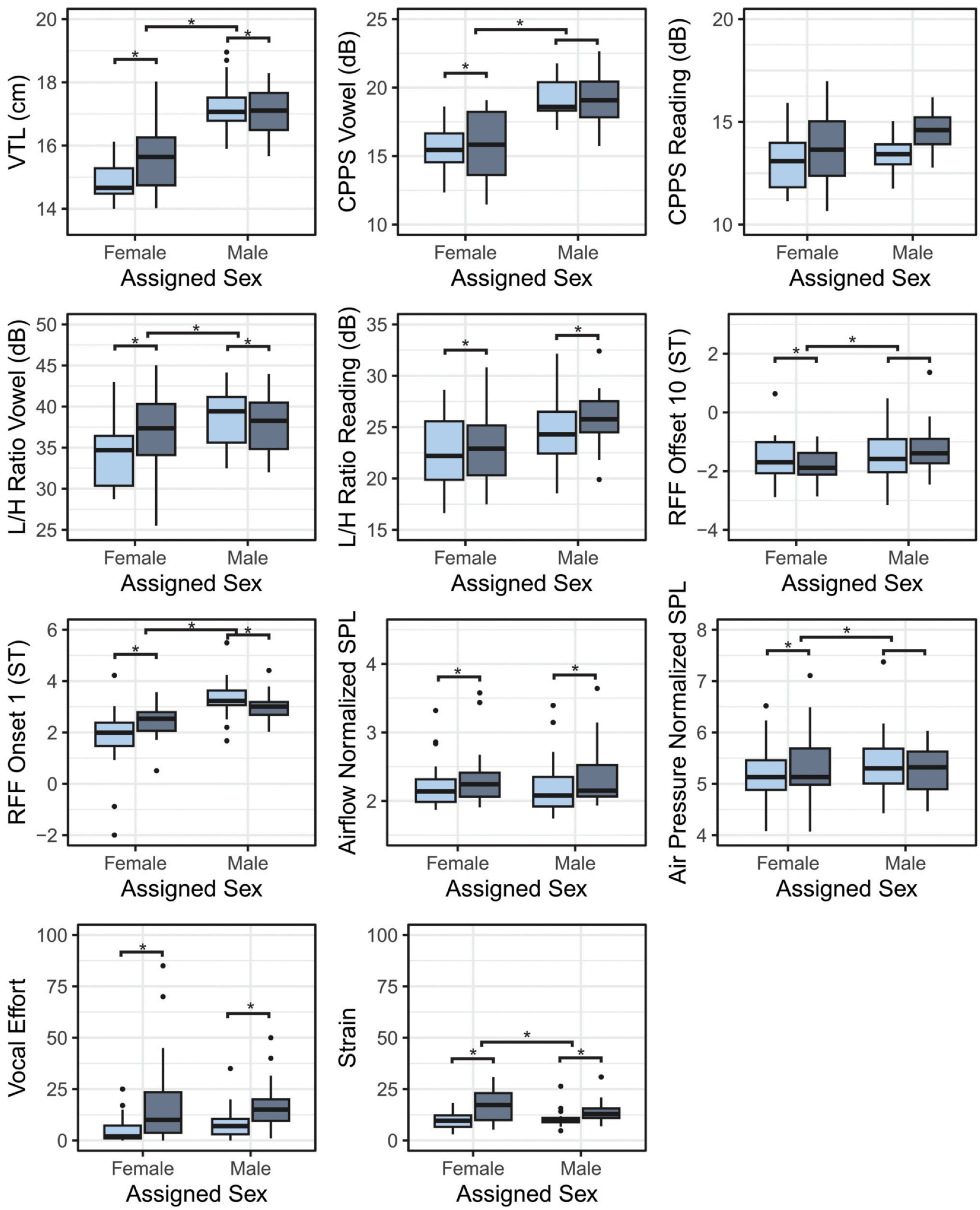

FIGURE 1. Boxplots for female and male data for the 11 continuous outcome variables. Habitual f_o is depicted in light blue and altered f_o is depicted in dark gray. Aerodynamic measures only depict comfortable loudness. Airflow normalized SPL is measured in dB/log transformed mL. Air pressure normalized SPL is measured in dB/log transformed cm H_2O. Significant differences ($P^* < 0.05$) are indicated with a bracket and asterisk. SPL, sound pressure level.

TABLE 2.
Summary Table of Fixed Effect *P*-Values and Eta Squared Effect Sizes

Measure	Sex	f_o condition	Sex*f_o condition	Task	Intensity
VTL	**< 0.001 (.63)**	**< 0.001 (0.11)**	**< 0.001 (0.33)**	-	-
$CPPS_{vowel}$	**< 0.001 (.45)**	**< 0.001 (0.06)**	**< 0.001 (0.06)**	**< 0.001 (0.31)**	**< 0.001 (0.19)**
$CPPS_{reading}$	0.314	**< 0.001 (0.35)**	0.316	-	**< 0.001 (0.43)**
L/H $ratio_{vowel}$	**0.021 (0.12)**	**< 0.001 (0.03)**	**< 0.001 (0.07)**	**< 0.001 (0.52)**	**0.019 (0.00)**
L/H $ratio_{reading}$	0.096	**0.001 (0.23)**	0.984	-	**0.011 (0.10)**
RFF *Offset10*	0.096	**0.040 (0.00)**	**< 0.001 (0.00)**	**< 0.001 (0.02)**	-
RFF *Onset1*	**< 0.001 (0.32)**	**< 0.001 (0.00)**	**< 0.001 (0.04)**	**< 0.001 (0.04)**	-
Airflow normalized SPL	0.561	**< 0.001 (0.04)**	0.581	**< 0.001 (0.07)**	-
Air pressure normalized SPL	0.881	**< 0.001 (0.02)**	**< 0.001 (0.03)**	**< 0.001 (0.38)**	-
Vocal effort	0.753	**< 0.001 (0.33)**	0.161	0.766	-
Strain	0.446	**< 0.001 (0.04)**	**0.016 (0.00)**	-	-

Abbreviations: CPPS, cepstral peak prominences; L/H, low to high; RFF, relative fundamental frequency; SPL, sound pressure level; VTL, vocal tract length. Note: P values significant at the < 0.05 are bolded and partial eta^2 effect sizes are provided in parentheses. Dashes indicate that the model did not include a fixed effect for task or intensity.

TABLE 3.
Mean (Standard Deviation) and Statistical Significance for Stroboscopic Data for Females and Males by f_o Condition

		f_o condition			
Sex	Measure	Comfortable	Habitual	Altered	*P* value
Female	Anterior-posterior	1.38 (0.84)	1.43 (0.90)	2.05 (1.15)	0.012 (0.06)
	Medial-lateral	0.45 (0.50)	0.52 (0.78)	0.68 (0.83)	0.540
Male	Anterior-posterior	1.18 (0.98)	1.38 (1.08)	1.40 (1.06)	0.593
	Medial-lateral	0.75 (0.74)	0.85 (0.80)	0.78 (0.73)	0.888

Note: *P* values significant at the < 0.05 are bolded and eta^2 effect sizes are provided in parentheses. Medium effect sizes (η^2 ≥0.13) and larger are highlighted in light green.

analysis of task indicated that RFF Onset Cycle 1 values for /ɑfɑ/ were higher than those for /ifi/, which was higher than those for /ufu/ (all $P^* < .001$).

Reading: For CPPS and L/H ratio, there were significant effects of f_o condition and intensity. On average, CPPS and L/H ratio values were higher when speakers used an altered f_o as compared to a habitual f_o. CPPS and L/H ratio values increased as intensity increased.

Aerodynamic

Airflow normalized SPL differed by f_o condition and task. On average, airflow normalized SPL increased when using an altered f_o (interpreted as more efficient) as compared to a habitual f_o. Airflow normalized SPL also increased when using a loud loudness as compared to a comfortable loudness. Air pressure normalized SPL differed by f_o condition, task, and the interaction between sex and f_o condition. On average, air pressure normalized SPL decreased (interpreted as less efficient) when using an altered f_o as compared to a habitual f_o, but post hoc analysis of the interaction revealed that this was driven by female speakers ($P^* < .001$). Male air pressure normalized SPL did not differ between f_o conditions ($P^* = .312$). The task effect indicated that when averaged across f_o condition and sex, air pressure normalized SPL was greater (more efficient) when vocalizing at a comfortable loudness than a loud loudness.

Stroboscopic

Only female A-P supraglottic activity differed by f_o condition ($P = .012$, $\eta^2 = 0.06$). Post-hoc analysis indicated that A-P supraglottic activity was similar when females vocalized with a comfortable and habitual f_o ($P^* = .810$), but increased significantly when females volitionally lowered their f_o to 2 ST below their habitual f_o (both $P^* < .032$).

Perceptual

Vocal effort ratings differed by f_o condition only. On average, speakers reported that vocal effort increased when using an altered f_o as compared with a habitual f_o. Listener ratings of strain differed by f_o condition and the interaction between sex and f_o condition. On average, listeners reported that speech produced with an altered f_o was more atypically strained than speech produced with a habitual f_o. Post hoc analysis of the interaction confirmed that this pattern was true for female and male speakers, but the ratings increased by an average of 6 points for female speakers whereas they increased by 3 points for male speakers (both $P^* < .001$).

DISCUSSION

Speech-language pathologists are concerned about introducing vocal hyperfunction when working with transgender and nonbinary individuals who seek to use a more gender congruent voice. One of the most commonly altered acoustic cues is f_o.[1] The current study aimed to examine whether volitionally altering f_o was a physiological stressor that disrupted typical phonation, leading to increased signs of VH. Because VH is not described by one specific metric, we used a multidimensional approach inclusive of acoustic, aerodynamic, stroboscopic, and perceptual (self- and other) measures. Any statistically significant changes to measures of VH may reflect initial compensatory strategies associated with a new vocal behavior, either raising or lowering f_o, but it is incorrect to interpret changes in measures as predictive of VH.

Although there are baseline differences in adult acoustic and aerodynamic measures related to differences in vocal anatomy and physiology,[88] the study paradigm confounded sex and the direction of f_o change. Thus, the following paragraphs will focus on the effects of females lowering their f_o and males raising their f_o on measures of VH.

Lowering f_o

Females were asked to lower their f_o by 2 ST, which resulted in an average decrease of 22 Hz from the speaker's mean habitual f_o based on a reading passage. Using a lower f_o was associated with a longer VTL, higher CPPS and L/H ratio values, lower airflow normalized SPL and air pressure normalized SPL, and greater vocal effort, strain, and A-P supraglottic compression than when using a habitual f_o. The changes to CPPS, airflow normalized SPL, vocal effort, strain, and supraglottic compression were in the direction associated with VH, thus supporting our original hypothesis that lowering f_o may be a physiological stressor that may contribute to the development of a vocal hyperfunctional response.

Although we hypothesized that only a decrease in VTL was consistent with VH, females most likely increased their extrinsic laryngeal muscle activation to increase their VTL. A longer VTL was consistent with a lower f_o[3,40,60] and the current study supported observable differences in VTL related to a small decrease in f_o of 2 ST. Physiologically, we assume that speakers activated their infrahyoid extrinsic laryngeal muscles to achieve a lower laryngeal position; thus, there was increased muscle activation. Considering that speakers with muscle tension dysphonia tend to have increased perilaryngeal muscle tension, both supra- and infra- laryngeal muscle tension, and a decreased ability to vary their VTL,[7] we might consider a lack of change in VTL when altering f_o as a more appropriate indicator of VH than a general increase in perilaryngeal muscle tension. In other words, changes in muscle activation without subsequent changes in VTL are more appropriate indicators of VH than changes in muscle tension with a subsequent change in VTL. Given that f_o often changes in response to vocal demands,[10] future studies should investigate changes in VTL in speakers with VH disorders.

The differences in CPPS, L/H ratio, airflow normalized SPL, and air pressure normalized SPL may be related to typical physiological changes related to lowering f_o rather than indicative of VH. When compared to a higher f_o, a lower f_o is often associated with a greater closed quotient, less subglottal pressure, and lower airflow.[42,89] This is also associated with reduced aperiodic energy in the acoustic signal[42] which contributes to higher CPPS and L/H ratio values. Our findings are consistent with this pattern.

Interestingly, only lowering f_o by 2 ST resulted in increased A-P supraglottic activity. A-P supraglottic compression has been observed in speakers without vocal complaints,[36,38,39] but is more frequently reported in speakers with VH disorders.[36,37] Thus, this finding also supports that females who lowered their f_o altered their biomechanics when phonating.

Raising f_o

Males were asked to raise their f_o by 2 ST, which resulted in an average increase of 12 Hz in the speaker's mean f_o based on a reading passage. Using a higher f_o was associated with a shorter VTL, higher CPPS and L/H ratio, lower airflow normalized SPL and air pressure normalized values, and greater vocal effort and strain than when using a habitual f_o. The changes to VTL, CPPS, airflow normalized SPL, air pressure normalized SPL, vocal effort, and strain were in the direction associated with VH, thus supporting our hypothesis that raising f_o may be a physiological stressor that may contribute to the development of a vocal hyperfunctional response.

Several of these changes may reflect physiological adjustments to increasing f_o. Speakers can adjust VTL as a secondary mechanism to alter f_o where a shorter VTL is associated with a higher f_o.[3,60] Additionally, a higher f_o requires a greater amount of subglottal air pressure to initiate vocal fold vibration than a lower f_o.[2] As a result, a shorter VTL and high air pressure are not immediately indicative of VH.

Similarly, increasing f_o is associated with a more open glottal configuration [90] and a greater rate of airflow.[89] These changes may result in an increase in the aperiodic energy in the acoustic signal, contributing to lower CPPS and L/H ratio values. Our results did not reflect this, potentially because the increase in f_o was too small to indicate a change in glottal configuration. Rather, speakers may adjust their vocal fold tension. A small increase in A-P vocal fold stiffness is associated with an increased f_o and a slight reduction in aperiodic energy.[42] The reduction in aperiodic energy, particularly if centered in the mid to high frequencies, would explain the increase in $CPPS_{reading}$ and L/H $ratio_{reading}$ values.

Experimental task effects

We hypothesized that raising f_o would result in larger differences in measures of VH than lowering f_o. Instead, lowering f_o tended to drive interaction effects. This is likely related to the decision to use a Semitone scale rather than the Hertz scale when defining the magnitude of change for the altered f_o condition. The Semitone scale was chosen because it better accounts for perceptual differences across frequencies. By asking speakers to change their voice by 2 ST, we prioritized the perceived change in pitch rather than the acoustic change in frequency. When measured acoustically, females lowered their f_o by an average of 22 Hz and males raised their f_o by 12 Hz. Based on the average change measured in Hertz, females were required to alter their f_o by a greater magnitude, which may explain why there were more significant differences in the female speech than in the male speech.

Another contributing factor is the direction of change. Potentially, it is more difficult to lower f_o than to raise f_o by 2 ST because a speaker's habitual f_o tends to sit in the lower half of their maximum phonational frequency range.[45] Thus, lowering f_o was more likely to approximate a phonational frequency boundary than raising f_o. Despite this, we did not find sex differences in vocal effort ratings. In other disciplines, sex differences in effort ratings are relative to the fitness of the participant (e.g., running).[91,92] There may be a difference in the "vocal fitness" of the speakers who were able to successfully complete the experiment; eleven females, but only two males were singers. Assuming that female and male participants had different levels of vocal "fitness," we may infer that volitionally lowering f_o required greater vocal control than raising f_o by 2 ST. Because speakers were only asked to alter their f_o in one of two directions, this remains speculation and would benefit from further research. Rather, the current study supports that volitionally altering f_o may increase signs of VH, but these changes may also reflect the physiological adjustments required to match a f_o target or the acoustic influence of f_o on the harmonic structure. Additionally, asking males to raise f_o by 2 ST is not inherently more harmful than asking females to lower f_o by 2 ST. In sum, the changes in measures associated with VH were reflective of inefficiencies in phonation (and potentially maladaptive compensatory strategies) and the typical physiological adjustment required to produce a specific vocal target.

The changes to perceptual measures of voice were potentially the most intuitive: speakers reported that altering their f_o was more effortful than using a habitual f_o and listeners rated speech produced with an altered f_o as more strained than habitual f_o. These results are consistent with previous research supporting that more effortful speech tends to be rated as more strained.[20] Considering that speakers were only provided with three minutes to practice using an altered f_o without any instruction, these changes only reflect short-term effects that are unrelated to training. Habituation of an altered f_o in transgender speakers is associated with decreases in the vocal effort.[93] Thus, our perceptual findings may be interpreted as a sign of VH, but also reflect the experimental constraints inherent to our experimental, single-session study.

Similar to previous research,[94] RFF was sensitive to changes in f_o which supports that RFF is sensitive to intrinsic laryngeal tension. That being said, the significant differences had only small or negligible effect sizes. We concluded that while RFF was sensitive to changes in f_o, these changes were insufficient to indicate VH.

Although it was not the primary purpose of this study, we noticed that most speakers reduced the f_o range of their reading passage when altering their f_o. Despite explicit direction to vary their pitch, females in particular decreased their f_o variability, evidenced by the decrease in f_o SD. Decreasing the extent to which and the amount of variation within their f_o range was likely a strategy to ensure accuracy when completing the vocal demand: to produce a mean f_o consistent with the target f_o. Considering that half of the speakers in the experiment had a lower maximum f_o and higher minimum f_o when altering their f_o, this seems likely. The other strategies that contributed to a smaller f_o range aligned with the direction of f_o change: females shifted both their maximum and minimum f_o lower whereas males shifted both their maximum and minimum f_o lower. In other words, avoiding using frequencies in the opposite direction of the f_o change contributed to the decrease in f_o range and f_o SD. Together, these changes likely reflect the increased attention and vocal control required to complete the vocal demand: volitionally altering f_o to match an external target.

CLINICAL IMPLICATIONS

Many transgender and nonbinary individuals seek to alter their f_o as part of affirming their gender. SLPs who work with these individuals are often concerned about the potential detrimental effects of altering typical phonation and the risk of developing VH which has been addressed through instruction in vocal hygiene.[94] Considering a recent chart review found that only 3 out of 61 transgender women (5%) had a vocal fold pathology,[95] which is consistent with the prevalence of voice disorders in the general population,[96] and the potential to pathologize vocal-gender incongruence in transgender people,[97] it is critical to question whether altering f_o is associated with increased signs of VH. Although many of the results of the current study can be interpreted as consistent with VH, these changes also reflect normal biomechanical adjustments and their acoustic consequences. Clinicians should be aware of these changes, incorporate them into their interpretations of clinical assessment, and in addition to education in vocal hygiene, instruct clients on typical changes to phonation associated with altering f_o. Instruction will provide a common vocabulary which may be useful to prevent the introduction of inefficient patterns of phonation. Because this study involved a non-transgender identifying sample of speakers, future research should examine the effects of altering f_o in transgender speakers on measures associated with VH. Additionally, future research should examine the long-term effects of volitionally altering f_o on measures associated with VH to determine whether habituating a new f_o will decrease inefficiencies in voice production.

LIMITATIONS

The primary limitation for this study was the exclusion of persons who identify as transgender within this study. Because transgender persons experience unique psychological and physical stressors [15] from cisgender persons, they were excluded to examine the role of altering f_o primarily as a physiological stressor contributing to the development of VH. Instead, transgender persons were referred to a separate, but related study.

A second limitation is that participants were only asked to alter their f_o in one of two directions. This confound limited our ability to more broadly interpret the physiological adjustments inherent to both raising and f_o and signs of VH. That being said, this was outside the scope of the current study. Directional effects were examined based on the desired application of study results to the transgender and nonbinary population. Additionally, the experimental task was difficult. In addition to the 40 participants who successfully completed this study, nine were unable to volitionally alter their f_o by 2 ST, indicating that the task was more difficult than anticipated. We speculate that attrition would have increased if speakers were required to both raise and lower their f_o by 2 ST.

A third limitation was the use of a single f_o target for all speech tasks. A single f_o target was chosen to prioritize individualizing the target f_o and control the magnitude of change, despite previously reported task effects on f_o.[44] Our results replicated this task effect: speakers tended to use a higher habitual f_o during vowels than connected speech. Despite this, inclusion of the vowels and RFF tokens provided less cognitively demanding tasks for speakers to practice altering their f_o prior to the reading passage. Additionally, identifying multiple f_o targets unique to each speech task would have increased the experimental complexity and decreased feasibility. Further, by focusing on the magnitude of change and not a single f_o target (e.g., above 150 Hz for a gender ambiguous range),[98] the study had greater experimental control, which supported the interpretations of the physiological adjustments to raise or lower f_o across the speaker groups.

CONCLUSION

The current study examined the role of altering f_o on measures associated with VH in a non-transgender identifying sample. Speakers were asked to either lower or raise their f_o by 2 ST based on their sex assigned at birth. Acoustic, aerodynamic, stroboscopic, and perceptual measures related to VH were collected and analyzed. The results indicated that 12 of the 13 measures differed by f_o condition. Compared to vocalizations with a habitual f_o, measures taken when speakers altered their f_o were more consistent with VH. A subset of these measures also depended on the direction of f_o change required, suggesting that a more nuanced interpretation is required. The changes in measures of VH may reflect both short-term changes in the efficiency of voice production and the typical physiological adjustments required to raise or lower f_o.

Data availability

The datasets generated during this study are not publicly available due to the inability to fully deidentify voice recordings.

Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jvoice.2026.02.012.

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