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High-Density Surface Electromyography: A Visualization Method of Laryngeal Muscle Activity

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Objectives/Hypothesis: Laryngeal muscle activation is a complex and dynamic process. Current evaluation methods include needle and surface electromyography (sEMG). Limitations of needle electromyography include patient discomfort, interpretive complexity, and limited duration of recording. sEMG demonstrates interpretive challenges given loss of spatial selectivity. Application of high-density sEMG (HD sEMG) arrays were evaluated for potential to compensate for spatial selectivity loss while retaining benefits of noninvasive monitoring.

Study Design: Basic science.

Methods: Ten adults performed phonatory tasks while a 20-channel array recorded spatiotemporal data of the anterior neck. Data were processed to provide average spectral power of each electrode. Comparison was made between rest, low-, and high-pitch phonation. Two-dimensional (2D) spectral energy maps were created to evaluate use in gross identification of muscle location.

Results: Three phonatory tasks yielded spectral power measures across the HD sEMG array. Each electrode within the array demonstrated unique power values across all subjects ($P < .001$). Comparison of each electrode to itself across phonatory tasks yielded differences in all subjects during rest versus low versus high, rest versus low, and rest versus high and in 9/10 subjects ($P < .001$) for low versus high phonation. Symmetry of HD sEMG signal was noted. Review of 2D coronal energy maps allowed for gross identification of cricothyroid muscle amidst anterior strap musculature.

Conclusions: HD sEMG can be used to identify differences in anterior neck muscle activity between rest, low-, and high-pitch phonation. HD sEMG of the anterior neck holds potential to enhance diagnostic and therapeutic monitoring for pathologies of laryngeal function.

Key Words: Surface electromyography, electrophysiology, high-density surface electromyography, laryngeal electromyography, electromyography, cricothyroid muscle.

Level of Evidence: NA

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INTRODUCTION

Laryngeal electromyography (EMG) is a well-established means to evaluate the neuromuscular activity of both intrinsic and extrinsic laryngeal musculature.[1–14] Two modalities of EMG have emerged over decades of electrophysiologic inquiry: invasive needle-based electromyography (nEMG) and surface electromyography (sEMG).

nEMG is an invasive test, potentially uncomfortable for patients, and requires technical skill for placement of electrodes and interpretation of tracings. In most cases, the duration of inquiry is also limited due to the necessity of clinical and/or lab settings for needles or hook wires to collect electrophysiologic signal.[4,15] It is, however, an excellent test for identifying morphological characteristics of the motor unit signal and has applicability in numerous clinical scenarios.[3,5–11,14,16–19] The placement of needle electrodes directly into target tissues by experienced operators affords confidence that the signal obtained is reflective of the interrogated target muscle. Practical concordance between nEMG signals of the same laryngeal muscle have been found to be 95% in experienced hands.[4] Although extremely informative, it is not practical for widespread use due to the aforementioned limitations.

sEMG within the field of laryngology has been used for evaluation of laryngeal hyperfunction and swallow with inconsistent results.[20–25] Surface EMG has a number of limitations that impair signal detection: (1) impedance of the skin-electrode interface, (2) distance between the myoelectric source and surface electrode, (3) lack of specificity due to interposed or neighboring active muscles resulting in cross talk, and (4) limitations in the ability to describe wave morphology.[26] Its appeal, however, is ease of use, patient comfort, and ability to collect data over extended periods of time.

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High-density sEMG (HD sEMG) has the potential to compensate for the previously described spatial selectivity limitations by application of a large number of electrodes within defined area. Each electrode results in a discrete detection volume defined by interelectrode distance and electrode surface area. A multielectrode array that spans the anterior neck can ensure a high number of electrodes concurrently capture the signal of interest during phonation. Additionally, as detection volume decreases, the summative contents of the electromyographic signal become more individualized. Although issues of impedance and identification of wave morphology remain, high-density arrays potentially provide a means for differentiation of muscle activation through electrode comparison. High-density arrays allow for evaluation of each point in comparison to the other across phonatory tasks. Additionally, gross visualization of activity can be intuitively displayed as power-density energy maps.[25,27,28] Task-specific muscle activation is used to highlight differences between adjacent musculature. In this article, we propose that we can differentiate cricothyroid (CT) muscle activity from rest, and that we can identify different muscle activity patterns between low- and high-pitch phonation. Additionally, we believe there to be a wide variety of diagnostic and therapeutic applications of this technology should the modality be adequately validated.

MATERIALS AND METHODS

Ten healthy adults (four females, six males, ages 22–51 years, median age = 33.4 years) were enrolled. Inclusion criteria was greater than 18 years of age. Exclusion criteria included a history of laryngeal pathology, a Voice Handicap Index (VHI-10) score of >10, subjective dysphonia at the time of recording, previous neck surgery, or neurologic illness.

Ethical approval was granted for this study by the Institutional review board at University of California, San Diego. All participants were seated in a ~80° slightly reclined position with the neck in slight extension to minimize strap muscle activity at rest. Surface landmarks, specifically the cricothyroid space and sternal notch, were identified with digital palpation and marked for reference. Skin preparation for all electrode sites included standard alcohol wipes and exfoliating impedance-reduction gel (NuPrep Skin Prep Gel; Weaver and Company, Aurora, CO). Standard electrocardio monitoring electrodes (3 M Red Dot [REF: 2670-5]; 3 M, St. Paul, MN) composed of silver/silver chloride were modified through circumferential removal of the adhesive patch. Electrodes were organized to create a high-density, 20-channel array (five rows by four columns) at 1.5 cm from each electrode center (electrode diameter = 5 mm). An occlusive transparent dressing (Tegaderm; 3 M) was modified with a punch and template. The array was centered on the CT space to ensure electrodes 10 and 11 were overlying the cricothyroid muscles (Fig. 1).

Signal Acquisition

A differential amplifier (Brain Vision Device; BrainVision, LLC, Morrisville, NC) was connected to the array, reference and ground electrode were placed overlying the volar surface of the right forearm and left mastoid process respectively, and impedance values were recorded. An audio prompt was played over a 5-minute period for each recorded task. Tasks included the following: (1) rest, (2) low-pitch phonation, (3) high-pitch phonation. Subjects were able to demonstrate adequate difference between low and high pitch as confirmed by the authors with frequency analysis (Audio Frequency Counter; Keuwlsoft, London, United Kingdom). Each task was paced to afford 5 seconds of phonation, on an /i/ vowel, followed by 10 seconds of rest. This was repeated for a total of 5 minutes, resulting in 20 recorded intervals of each phonatory task for each participant. EMG data were recorded at a sampling frequency of 500 samples per second using standard EMG recording software (Brain Vision Recorder; BrainVision, LLC). Data were then transferred using EMG analysis software (Brain Vision Analyzer, v. 2.1; BrainVision, LLC) to custom software written in Python programming language (Python Software Foundation, Python Language Reference, v. 3.6.3, https://www.python.org/).

Signal Processing

Raw data were processed over a four-step workflow (Fig. 2). The average of all the recordings for each dataset was used as a reference and subtracted from the original signals to reduce ambient sources of noise common in all electrode sites.[29] During initial review of data it was noted that in both low- and high-pitch recordings, periodic repetitions of 5-second phonation followed by 10 seconds of rest manifested in oscillatory patterns. Signal analysis sought to characterize EMG contraction only

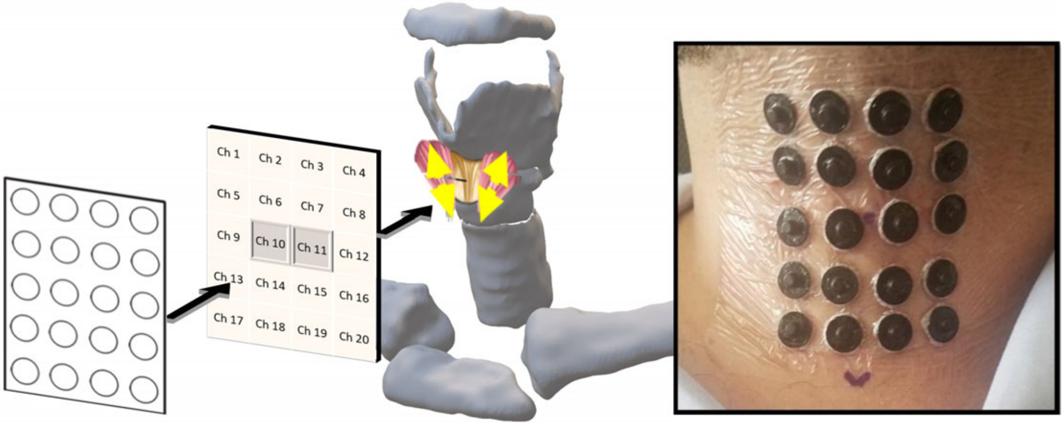

Fig. 1. High-density surface electromyography array positioned on anterior surface of neck. Central dot (between electrodes 10 and 11) indicates cricothyroid space. Inverted V inferior to array indicates sternal notch. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

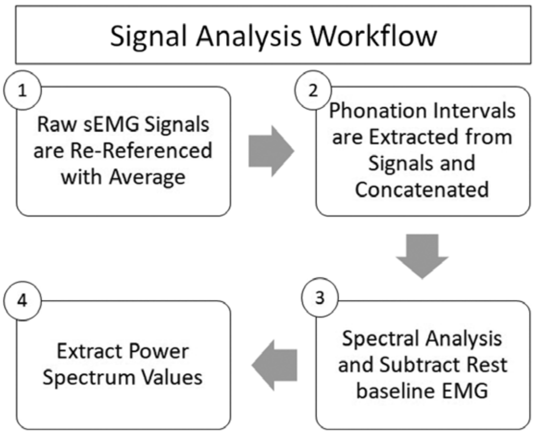

Fig. 2. Signal analysis method organized by key steps. EMG = electromyography; sEMG = surface electromyography.

during phonation. Hence, only the segments of each task for the rest, low pitch, and high pitch were considered. In addition, during the onset and offset of phonation, muscles prepare to contract or relax, potentially producing large voltage alterations. Therefore, only the central 3 seconds of each phonatory epoch were extracted. (Fig. 3). Subtraction of rest data from low- and high-pitch data removed the spectral components due to 60 Hz noise (created by the surrounding electrical environment), removed low-frequency drift from electrode motion, and corrected for variability in noise between electrodes. From this, we extracted the average power-density values across all frequency bands. After analysis, separate energy animations of rest, low-pitch, and high-pitch phonatory tasks were created, representing the entire recorded task (Fig. 4).

Statistical analysis of power-density data from each electrode were compared by four methods through one-factor analysis of variance (ANOVA) utilizing Fisher statistics and Pearson coefficients of correlation. Statistical analysis was performed using Microsoft Office Excel (Microsoft Corp., Redmond, WA). Graphical display utilized GraphPad Prism version 7.04 (GraphPad, San Diego, CA,). The first compared each electrode to every other electrode within the same array within the same phonatory task. The second compared the same electrode to itself between phonatory tasks. The third compared the two left and two right columns by ANOVA analysis. The fourth method compared the two left and two right columns for symmetry by Pearson (*r*) correlation.

RESULTS

Enrollment VHI-10 scores ranged from 0 to 2, and 80% of subjects scored 0 of 40 reflecting healthy phonatory states. Three phonatory tasks (rest, low pitch, high pitch) resulted in spatiotemporal matrices of average spectral power densities across the array. The values for each electrode within the array were subsequently compared to evaluate for significant variance.

Each electrode was numbered and compared to every other electrode within the array for the tasks of rest, low-pitch, and high-pitch tasking per subjects. Each electrode exhibited unique power values despite the same task in 10/10 (100%) subjects ($P < .001$–.04), suggesting each electrode is recording a unique underlying signal, despite the uniform task being performed by the subject. Further evaluation compared each electrode to itself between phonatory tasks as follows: rest to low, rest to high, and low to high, yielding rest versus low pitch (10/10, 100%, $P < .001$),

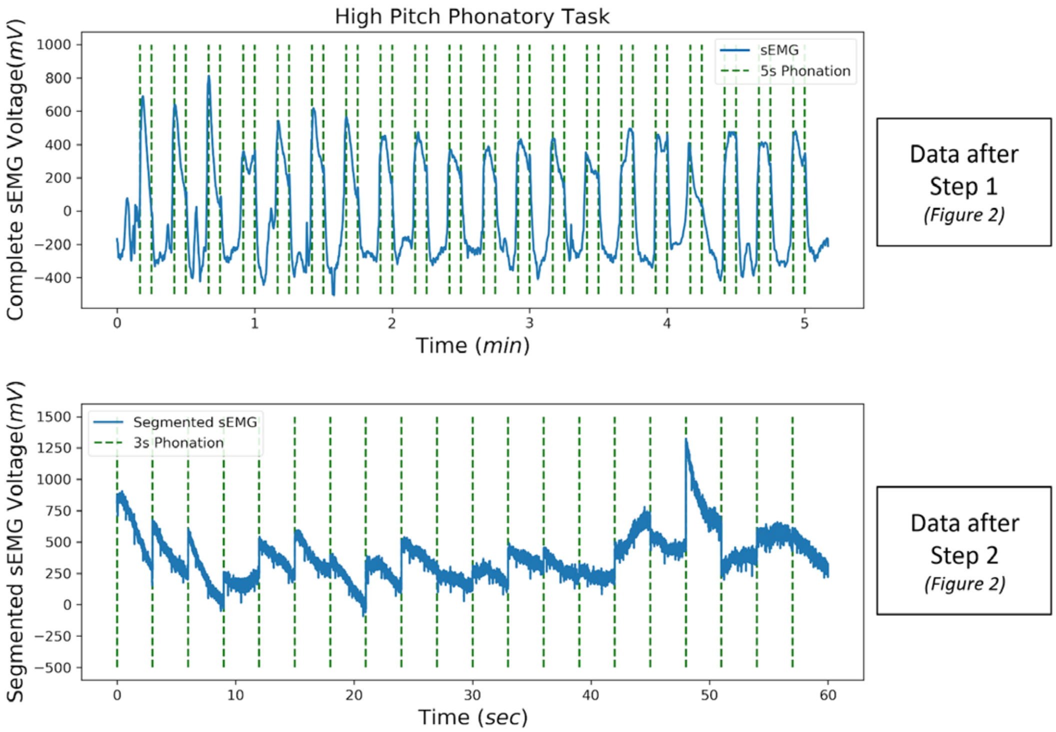

Fig. 3. Time series plot of signal from electrode 10 of subject 6. (Top) Tracing of a high-pitch task over full 5-minute recording. Vertical dotted lines indicate 5-second phonatory interval. (Bottom) Concatenated segments during high-pitch task. Three-second central intervals over 20 repetitions. sEMG = surface electromyography. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

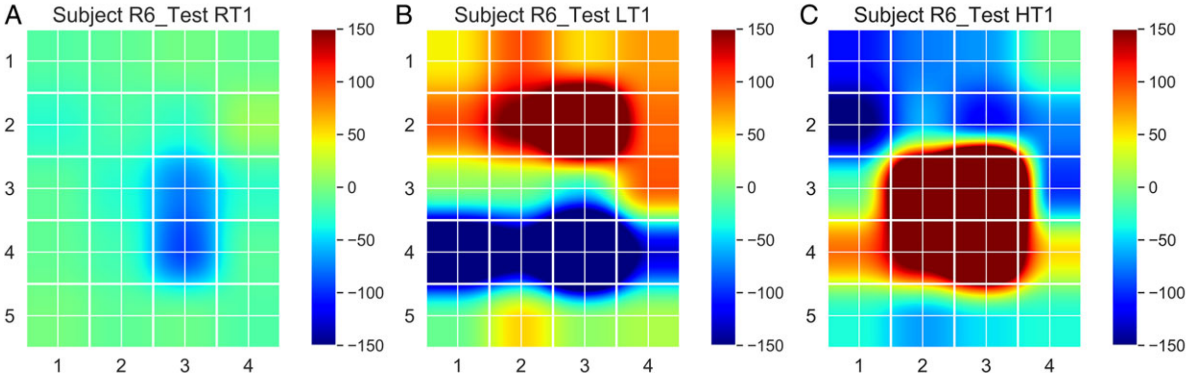

Fig. 4. Voltage amplitude (mV) energy maps demonstrate the relative intensity of muscle activation within the coronally oriented spatial field. Red indicates increased muscle activation. Blue indicates decreased muscle activation. These maps are representative samples from a single moment in time during each task for subject 6. (A) Rest. (B) Low-pitch phonation. (C) High-pitch phonation. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

rest versus high pitch (10/10, 100%, $P < .001$), and low pitch versus high pitch (9/10, 90%, $P < .001$–.085). Laterality of each array was then analyzed, anticipating symmetry in the context of healthy participants. When the two left and two right columns of the array were considered, there were no statistically significant variances in 9/10 (90%, $P = .02$–.94) of subjects during rest, 8/10 (80%, $P = .03$–.64)) during low-pitch phonation, and 10/10 (100%, $P = .07$–.91) during high-pitch phonation. Pearson (r test) correlation additionally confirmed symmetry between the left and right side at rest ($r = 0.92$, $P < .001$), low pitch ($r = 0.89$, $P < .001$), and at high pitch ($r = 0.74$, $P = .015$) (Fig. 5). Finally, most subjects, 8/10 (80%), demonstrated a pattern of high-pitch phonation as the highest measured average power spectra compared to both rest and low-pitch phonation (Fig. 6).

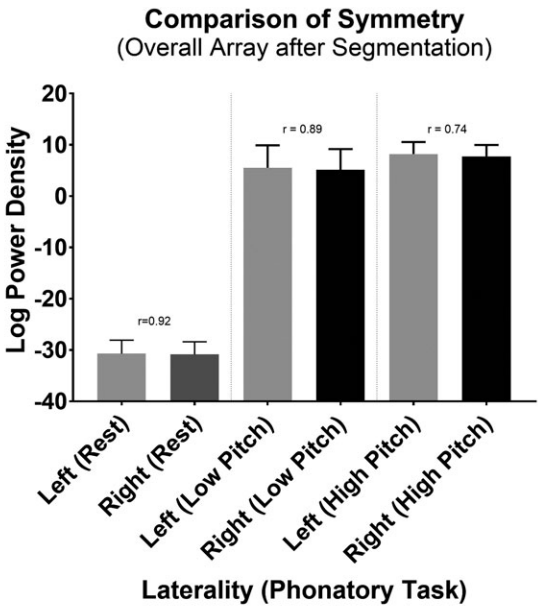

Fig. 5. Pearson (r) correlation of averaged data of all subjects by task and laterality demonstrating symmetry across the overall array for all subjects. An r approaching 1.0 indicates strong correlation.

DISCUSSION

Laryngeal muscle function within the anterior neck is a complex and dynamic process, summative of the interplay between both intrinsic and extrinsic laryngeal muscle activity.[9] During phonation, these muscles may contract in isolation or in concert, depending on the task and extent of recruitment in habitual, hyperfunctional, or hypofunctional states.[8,12,20,22]

sEMG has been explored in numerous medical applications (e.g., electrocardiography, electroencephalography). Applications in laryngology have been varied and previously focused on hyperfunctional disorders, dysphagia, and use as a biofeedback tool.[6,30–32] Prior studies for laryngeal or anterior neck application have seen limited success with conflicting data.[6,21,30,32–36] One of the challenges of sEMG interpretation, especially when only one or a few electrodes are used across a discrete surface area, is the dynamic relationship of skin to underlying structures that occur with movement. This limits interpretation due to uncertainties of muscle position. In other words, is the signal an accurate reflection of activity or has the muscle of interest moved relative to the skin? An HD sEMG array enables comparison of multiple sites and allows for improved spatial resolution. Further visual representation of muscle activity within the anterior neck is possible through power-density energy maps.[25,27,36,37]

The CT muscle has been highlighted in this project due to its anterior position in relation to the laryngotracheal apparatus and absence of overlying cartilage. Additionally, its increased recruitment during high-pitch phonation allows for isolation during specific phonatory tasks. As such, in this study, subjects were asked to maintain a target pitch above 300 Hz for males, and 400 Hz females to ensure reliable CT activation.[38,39] Contamination of signal by muscles associated with swallowing was minimized, because concurrent swallowing would not be expected within each central 3-second phonatory segment. Gross neck movement was limited by volitional control and cervical support provided by the examination chair. Signal-to-noise ratio (SNR) was reduced by subtracting the power spectral density of the rest task from that of the corresponding low and high phonatory tasks.

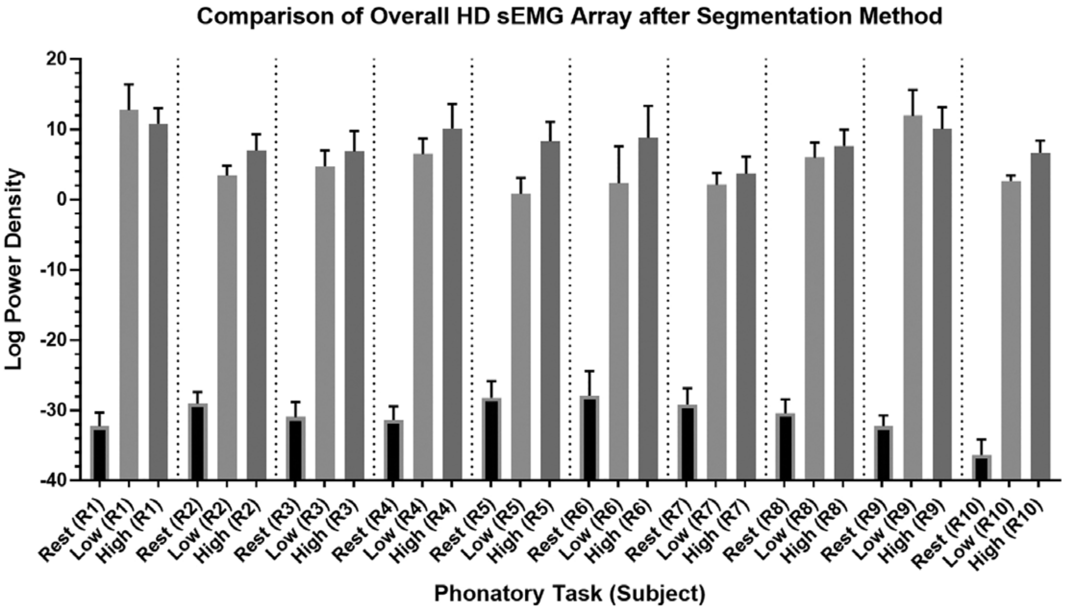

Fig. 6. Average power spectra for all subjects after isolation of phonatory data. Eight of 10 (overall) demonstrate a pattern in which high-pitch phonation resulted in the highest measured amplitudes. HD sEMG = high-density surface electromyography.

It is well established in signal detection theory that that SNRs can be improved through evaluation of a repetition paradigm. Comparison of repeated signal allows for noise variance reduction.[40]

When electrodes were initially compared to one another within the array during the same task, each electrode demonstrated unique power output. This indicated that each site was different from its counterparts within each task when comparing for difference in location alone during the specific task. When each electrode was then compared to itself between tasks, controlling for spatial location while changing the activity of underlying musculature, a significant difference in power output was noted between rest versus low and rest versus high in all subjects. When comparing low versus high, the majority still met statistical significance for variance, demonstrating some loss in differentiation between low and high alone. This would be expected compared to the stark contrast of rest and phonation, but demonstrated an ability to begin to discriminate a difference between low and high phonation in comparison of power alone.

In this study, HD sEMG and power maps were used to identify CT muscle activation preferentially during high-pitch phonation as compared to low pitch in nine of 10 subjects. It is possible that in the remaining patient, the CT muscle was not adequately activated due to subject compliance, or that the CT muscle in some individuals is just no more active in high-pitch versus low-pitch voicing. We were also unable to account for potential contribution from the intralaryngeal musculature during phonatory tasks as a result of the shielding provided by of the thyroid cartilage.

Prior HD sEMG use on the anterior neck has been limited. The first publication of its use focused on assessment of pharyngeal function during swallow of substances of different viscosity.[25,28] More recently, the same group, in a series of four patients, utilized high-density arrays to evaluate energy distribution during vocal tasks. That study demonstrated identification of muscle activity through evaluation of phonation at contrasting levels of loudness and pitch glides.[27] In all of these studies, there remain several limitations of HD sEMG that are inherent to all forms of sEMG.

Impedance of the skin-electrode interface is a known limitation that negatively impacts all forms of sEMG. Close adherence of the electrode grid to the contours of the anterior neck can reduce interference. Even with high-level skin prep and careful electrode placement, this can be a persistent problem. Specificity of muscle location and associated signal acquisition is also of concern. In this study, this issue is overcome by the broad acquisition area of the array and preferential CT activation during high-pitched phonation. Strap muscle activation was reduced as much as possible, with neutral supported head position during testing paradigms.

The next iteration of this study will include concurrent, fine-wire signal acquisition to further support proof of concept. We also expect that acquiring data on individuals with vagal lesions or high cervical plexus injury may allow for "knockout" conditions to allow for visualization of discrete muscle function and dysfunction. We would emphasize that with the current technology, specifics about wave morphology is not the goal of HD sEMG. Rather, its use is intended to be complementary to the finite morphological inquiry of nEMG. The primary goal of this study's utilization of HD sEMG is gross identification of muscle activity. Analysis was focused on less-granular aspects of signal such as average power density and energy map generation, but did not include a more detailed analysis of whether signal morphology is identifiable within the tracings. The authors believe that morphological description may be possible through future iterations of array design and enhanced signal processing, but is beyond current technologic capability of this device version.

Additional limitations of this study include a small sample size (n = 10). Due to technical limitations, concurrent acoustic data were not captured with this subject series. Also, in their current form, the electrode array profile and recording equipment are somewhat cumbersome and would not be practical for extended durations. Future work could exploit recent developments in flexible and stretchable skin-mounted electronics,[41] along with advances in scalable fabrication procedures,[42,43] to produce high-density, high-fidelity, and minimally obtrusive electrophysiologic monitoring systems.

Finally, we are excited by the ever-advancing field of machine learning. EMG tracings have prominent potential as a medium of input given their characteristics.[40] We believe it likely that subtle nuances that may be imperceptible to gross visualization within energy maps and/or tracings could be used as a means to train a computer to recognize clinically meaningful data such as difference between recurrent laryngeal nerve, superior laryngeal nerve, or proximal vagal nerve palsies.

Despite these limitations, HD sEMG represents an exciting new variant of surface electromyography. Its promise lies in the improvement on existing sEMG modalities to compensate for spatial selectivity loss and to globally monitor the anterior neck function through a dense electrode configuration. Potential application includes diagnostic utility to identify laryngeal nerve injury in the absence of endoscopic capabilities, to compare hyperfunctional states, or as a visual biofeedback tool during rehabilitative efforts.

CONCLUSION

We demonstrate an ability to identify differences of power spectra within an HD sEMG array during rest, low-pitch phonation, and high-pitch phonation across all subjects. Regions of increased power density during high-pitch phonation correspond to those electrodes most likely to be overlying or adjacent to the cricothyroid muscle. Furthermore, review of energy maps generated for each subject afford gross recognition of the cricothyroid activity within the anterior neck. HD sEMG and derived 2D coronal energy map interpretation demonstrates exciting potential for clinical application as a diagnostic tool, therapeutic monitoring device, and visual biofeedback medium of the activity of infrahyoid and cricothyroid muscles.

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