A comprehensive assessment of genioglossus electromyographic activity in healthy adults

Jennifer R. Vranish and E. Fiona Bailey
Department of Physiology, College of Medicine, University of Arizona, Tucson, Arizona

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Vranish JR, Bailey EF. A comprehensive assessment of genioglossus electromyographic activity in healthy adults. J Neurophysiol 113: 2692–2699, 2015. First published February 18, 2015; doi:10.1152/jn.00975.2014.—The genioglossus (GG) is an extrinsic muscle of the human tongue that plays a critical role in preserving airway patency. In the last quarter century, >50 studies have reported on respiratory-related GG electromyographic (EMG) activity in human subjects. Remarkably, of the studies performed, none have duplicated subject body position, electrode recording locations, and/or breathing task(s), making interpretation and integration of the results across studies extremely challenging. In addition, more recent research assessing lingual anatomy and muscle contractile properties has identified regional differences in muscle fiber type and myosin heavy chain expression, giving rise to the possibility that the anterior and posterior regions of the muscle fulfill distinct functions. Here, we assessed EMG activity in anterior and posterior regions of the GG, across upright and supine, in rest breathing and in volitionally modulated breathing tasks. We tested the hypotheses that GG EMG is greater in the posterior region and in supine, except when breathing is subject to volitional modulation. Our results show differences in the magnitude of EMG (%regional maximum) between anterior and posterior muscle regions (7.95 ± 0.57 vs. 11.10 ± 0.99, respectively; \(P < 0.001\)), and between upright and supine (8.63 ± 0.73 vs. 10.42 ± 0.90, respectively; \(P = 0.008\)). Although the nature of a task affects the magnitude of EMG (\(P < 0.001\)), the effect is similar for anterior and posterior muscle regions and across upright and supine (\(P > 0.2\)).

THE GENIOGLOSSUS (GG) muscle of the human tongue is involved in functions critical to survival, including swallowing, speech, and breathing. In view of the muscle’s role as an airway dilator, the preponderance of research has focused on electromyographic (EMG) activity during sleep and wakefulness when subjects are in the supine or side-lying position (Eastwood et al. 2003; Malhotra et al. 2004; Fogel et al. 2005; Bailey et al. 2007; Eckert et al. 2009; Wilkinson et al. 2010; Jordan et al. 2010; Richardson and Bailey 2010; Saboisky et al. 2010; Laine and Bailey 2011; Trinder et al. 2013). Numerous other studies have incorporated manipulations that impact upon respiratory-related GG activity, including head/body position (i.e., head up vs. head back; upright vs. supine) (Douglas et al. 1993; Wasicko et al. 1993; Ono et al. 1996; Otsuka et al. 2000; Tsukii et al. 2000; Williams et al. 2000; Pae et al. 2002 2004; Takahashi et al. 2002; Walsh et al. 2008), assessment of EMG activity in multiple muscle regions (Eastwood et al. 2003; Wilkinson et al. 2008 2010; Nicholas et al. 2010; Richardson and Bailey 2010; McSharry et al. 2013; Trinder et al. 2013), and in different tasks (i.e., rest breathing, voluntary hyperventilation, maximal inspiratory effort, or exercise) (Mezzanotte et al. 1992; Williams et al. 2000; Eastwood et al. 2003; Walls et al. 2013). In addition, studies of human tongue muscle tissue highlight regional differences in GG muscle fiber type, myosin heavy chain composition, cross-sectional area, innervation, and motor end-plate banding (Sanguineti and Laboissi 1997; Saigusa et al. 2001; Zur et al. 2004; Buchaillard et al. 2009; Mu and Sanders 2010; Daugherity et al. 2012; Sanders et al. 2013), which suggest different regions of the muscle may fulfill different functions (Saigusa et al. 2001; Daugherity et al. 2012).

In this case, we sought to integrate across the breadth of approaches reported in the literature and recorded multiunit EMG activity in rest breathing, deep breathing, voluntary hyperventilation, and Mueller maneuvers. Given the suggestion that different regions of the muscle are driven preferentially by certain inputs (Eastwood et al. 2003), or that different regions of the muscle may have different mechanical effectiveness in dilation of the airway (Bilston and Gandevia 2014), we recorded activity in the most anterior and most posterior regions of the muscle. In view of gravitational effects on the upper airway (Pae et al. 1994) and recently reported evidence that the posterior region of the GG muscle exhibits greater respiratory-related activation (Cheng et al. 2008), we predicted that EMG activity would be greatest in the posterior region and in supine. Second, given indications that (motor) cortical input may be a more potent driver of the anterior tongue (Laine and Bailey 2011) and anatomical evidence that the anterior GG may be more important for volitional activities (Saigusa et al. 2001), we predicted that anterior EMG would exceed posterior EMG activity in the context of volitionally modulated breathing.

METHODS

We recruited 14 healthy young adults (11 women and 3 men, age 20.6 ± 2.1 yr; height 167.7 ± 9.0 cm; weight 62.0 ± 11.2 kg; body mass index 21.9 ± 2.8). Subjects were nonsmokers, without history of sleep disorders, respiratory, neuromuscular, or cardiovascular disease, and a forced expiratory volume (1.0 s) to forced vital capacity ratio >80% predicted value based on height, weight, age, and sex (Miller et al. 2005). Experimental procedures were approved by The University of Arizona Human Subjects Protection Program, and subjects gave their written informed consent before participation.

General procedures. Subjects were fitted with an oronasal facemask that allowed for oral and nasal breathing (series 8900; Hans Rudolph). The mask was held in place with a head cap (series 7450; Hans Rudolph) and self-sealed to the face. The seal was verified by a vacuum leak test. Inspiratory and expiratory airflows were measured using a pneumotachometer attached in series to the mask (Fig. 1) and connected to an amplifier (model 1110; Hans Rudolph) that transmit-
We recorded multiunit EMG activity in the GG using two electrode types (see below). In the anterior region, EMG activities were recorded via bipolar intramuscular hook-wire electrodes (50 μm; California Finewire, Grover Beach, CA) inserted via the mouth, as described previously (Sauerland and Harper 1976; Williams et al. 2000; Pittman and Bailey 2009; Richardson and Bailey 2010). Each hook wire was bared of ~2–3 mm insulation at the tip, threaded through a 30-gauge needle (0.3 × 13 mm; Becton-Dickinson, Franklin Lakes, NJ), and inserted bilaterally, immediately posterior to the lingual sulcus at points equidistant from the lingual frenulum to a depth ~12 mm from the mucosal surface (Sauerland and Harper 1976; Eastwood et al. 2003). The needle subsequently was removed, leaving the hook wire in the muscle belly. Hook wires were taped to the chin and anchored by the breathing mask. This recording area corresponds well with the region identified previously as GG-A comprising anterior and superior muscle fibers before entry into the tongue (Daugherty et al. 2012).

Multiunit EMG activity in the posterior GG was recorded via bipolar intramuscular tungsten microelectrodes (1–5 μm tip diameter, 250 μm shaft diameter; Frederick Haer, Bowdoin, ME). Electrodes were inserted bilaterally into the skin underlying the jaw, ~2.0 cm posterior to the mandible, ~0.5–1.0 cm from the midline, and 1.0–2.0 cm from the other electrode. Based on our calculations and depending on subject size, electrodes were inserted ~15–18 mm posterior to the mandible at an angle ~120–130 degrees to the horizontal when seated upright. This recording area is in the most posterior region of the muscle and corresponds well with the area GG-P identified previously as comprising inferior oblique and horizontal muscle fibers (Daugherty et al. 2012). For these recordings, the distance to the GG in each subject was determined via ultrasonography (Aloka Pro Sound 3500, Tokyo, Japan) (Eastwood et al. 2003), and this information was used to place a mark on the electrode to indicate the distance to the middle of the muscle. This mark served as an indicator of the target depth and was used to ensure that the electrode placement was preserved throughout. Subjects were grounded with a gold cup electrode ear clip (Grass Technologies, Warwick, RI).

Tungsten microelectrodes were manufactured without insulation on the last 5.0 mm (Frederick Haer). Similarly, we prepared hook-wire electrodes baring ~2–3 mm insulation at the terminal tip to match the impedance of the tungsten electrodes. Both electrode types subsequently were assessed and found to have equivalent negligible impedances at 1,000 Hz (Electrode Impedance Tester; Bak Electronics, Sanford, FL) and thus equivalent recording surface areas. EMG signals were sampled at 5 kHz and preamplified (3X), amplified (1,000X), and band-pass filtered from 30 to 3,000 Hz using CED 1902 amplifiers and head stages (Cambridge Electronic Design, Cambridge, UK). The signals were digitized and stored using a Cambridge Electronic Design 1401 interface and Spike2 software (Cambridge Electronic Design).

Experimental protocol. Subjects were assigned randomly to begin the experiment in supine or seated upright. Head placement was kept in the Frankfort plane throughout the experiment (Johnson 1950).

GG EMG activity, inspiratory and expiratory airflow, and mask pressure were subsequently recorded for 2 min in rest breathing via the mouth and rest breathing via the nose. Subjects next performed deep breathing, maximal voluntary hyperventilation, and Mueller maneuvers. For deep breathing, subjects were instructed to inspire to approximately two times their normal breath (Fox et al. 1986). For maximal voluntary hyperventilation, subjects were instructed to breathe as fast and as deeply as they could. In view of the high airflows associated with these tasks and to minimize airway resistance, subjects were directed to breathe through the mouth (Fregosi and Lansing 1995; Williams et al. 2000). For Mueller maneuvers, subjects made an inspiratory effort at end-expiration against the occluded intake port on the pneumotachometer. For purposes of EMG normalization, subjects were asked to perform sharp sniffs, unimpeded tongue protrusions out of the mouth, and swallows at end-expiration to determine maximal GG activation. The maneuver in which the maximum EMG amplitude was observed served as the maneuver against which EMG in all other maneuvers or tasks were normalized. Note that subjects rested for 1–2 min between maneuvers/tasks to ensure that EMG and breathing frequency returned to baseline before proceeding. The entire protocol, including maximum maneuvers, was repeated for the seated upright or supine body position, whichever body position had yet to be completed.

Data analysis. All data were analyzed offline using Spike2 software and customized scripts. EMG signals were rectified and integrated at a time constant of 100 ms. Breathing frequency (breaths/min) was determined for each task. Measures of inspiratory flow were integrated to obtain inspiratory tidal volume (VT) and ventilation. Mean inspiratory flow (VT/TI, ml/s) was calculated as an accepted index of ventilatory drive (Milic-Emili and Grunstein 1976; Boggs and Tenney 1984) in each breathing task. Average multiunit EMG activity was determined for the phasic (i.e., inspiratory) and tonic (i.e., expiratory) portions of each breath cycle. Because breathing frequencies varied between tasks, EMG measures at each electrode location were subsequently assessed and found to have equivalent negligible impedances at 1,000 Hz (Electrode Impedance Tester; Bak Electronics, Sanford, FL) and thus equivalent recording surface areas. EMG signals were sampled at 5 kHz and preamplified (3X), amplified (1,000X), and band-pass filtered from 30 to 3,000 Hz using CED 1902 amplifiers and head stages (Cambridge Electronic Design, Cambridge, UK). The signals were digitized and stored using a Cambridge Electronic Design 1401 interface and Spike2 software (Cambridge Electronic Design).
raw voltage, EMG values were normalized with regard to the regional maximal EMG activity (%maximum) and averaged across breaths. The maximum EMG for both the anterior (range: 0.5–1.6 mV) and posterior (range: 0.2–1.3 mV) muscle regions occurred during unimpeded tongue protrusion in all subjects (Pittman and Bailey 2009).

EMG averages were not normally distributed and were converted into logarithms for statistical purposes (Douglas et al. 1993). Statistical evaluation was by general linear model ANOVA (2 × 2 × 2 × 5), testing for significant differences in EMG, airflow ($V_\text{T}/T_\text{T}$), and breathing frequency as a function of muscle region (anterior vs. posterior), body position (upright vs. supine), and task (rest breathing via nose, rest breathing via mouth, deep breathing, voluntary hyperinflation, Mueller maneuver). Significance was set at $P < 0.05$. Post hoc comparisons were performed using paired $t$-tests, with significance adjusted according to the Bonferroni correction.

**RESULTS**

Means and SEs for ventilation parameters in upright and supine and for each task are reported in Table 1. There were no differences in inspiratory time ($T_\text{E}$), expiratory time ($T_\text{I}$), and tidal volume ($V_\text{T}$) between the two conditions ($P > 0.3$). breaths/min rate ($f_\text{b}$) and minute ventilation ($V_\text{E}$) in each task and as a function of body position (i.e., upright and supine).

### Table 1. $T_\text{E}$, $T_\text{I}$, $f_\text{b}$, $V_\text{T}$, $V_\text{T}/T_\text{T}$, and $V_\text{E}$ in each task and as a function of body position

<table>
<thead>
<tr>
<th>Task</th>
<th>Body position</th>
<th>Nasal Breathing</th>
<th>Oral Breathing</th>
<th>Deep Breathing</th>
<th>Hyperventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upright</td>
<td>Supine</td>
<td>Upright</td>
<td>Supine</td>
<td>Upright</td>
</tr>
<tr>
<td>$T_\text{E}$, s</td>
<td>1.62 ± 0.16</td>
<td>1.73 ± 0.20</td>
<td>1.60 ± 0.19</td>
<td>1.71 ± 0.17</td>
<td>2.37 ± 0.43</td>
</tr>
<tr>
<td>$T_\text{I}$, s</td>
<td>2.82 ± 0.24</td>
<td>2.64 ± 0.22</td>
<td>2.75 ± 0.25</td>
<td>2.66 ± 0.27</td>
<td>3.79 ± 0.36</td>
</tr>
<tr>
<td>$f_\text{b}$, breaths/min</td>
<td>13.82 ± 1.12</td>
<td>14.08 ± 1.30</td>
<td>14.04 ± 1.19</td>
<td>14.19 ± 1.30</td>
<td>9.96 ± 0.75</td>
</tr>
<tr>
<td>$V_\text{T}$, ml</td>
<td>306.01 ± 39.21</td>
<td>312.62 ± 38.36</td>
<td>345.29 ± 47.65</td>
<td>391.83 ± 47.83</td>
<td>726.25 ± 91.13</td>
</tr>
<tr>
<td>$V_\text{T}/T_\text{T}$, ml/s</td>
<td>189.19 ± 24.41</td>
<td>181.0 ± 22.16</td>
<td>215.27 ± 27.63</td>
<td>229.76 ± 26.73</td>
<td>306.21 ± 34.22</td>
</tr>
<tr>
<td>$V_\text{E}$, l breaths $^{-1}$ min$^{-1}$</td>
<td>4.23 ± 0.55</td>
<td>4.40 ± 0.57</td>
<td>4.85 ± 0.60</td>
<td>5.56 ± 0.59</td>
<td>7.23 ± 0.94</td>
</tr>
</tbody>
</table>

Values are means ± SE for inspiratory time ($T_\text{E}$), expiratory time ($T_\text{I}$), breathing frequency ($f_\text{b}$), tidal volume ($V_\text{T}$), inspiratory flow ($V_\text{T}/T_\text{T}$), and minute ventilation ($V_\text{E}$) in each task and as a function of body position (i.e., upright and supine).

In summary, body position and breathing task are key determinants of the magnitude of GG EMG activity in both the anterior and posterior regions of the GG. These healthy young adults exhibited tonic activation in the anterior and posterior regions of the muscle across upright and supine that shifted to phasic activity in voluntarily modulated deep...
breathing and hyperventilation. The increase in the magnitude of tonic and phasic components of the EMG from rest breathing to volitionally modulated breathing is consistent with the recruitment of increasing numbers of GG motor units (Richardson and Bailey 2010; Bailey 2011; Walls et al. 2013). We found no evidence of differential activation of the anterior vs. posterior GG, rather the magnitude of EMG activities in each region was similarly impacted by the requirements of the particular task.

Fig. 2. Representative recordings obtained from one subject during rest breathing via the mouth (A), deep breathing (B), and voluntary hyperventilation (C). Airflow (l/min) where inspiration is negative (trace on top), anterior multiunit muscle GG electromyographic (EMG) (trace in middle), and posterior multiunit muscle GG EMG (trace on bottom). Broken lines demonstrate inspiratory (I) and expiratory (E) breath phase information to illustrate which portions of the electromyogram were used during analysis. [Note for this individual, average EMG (mV) recorded in the maximum maneuver was 1.3 mV in the anterior region and 1.1 mV in the posterior region].

Critique of method. We studied 14 healthy young adults reportedly free of sleep-disordered breathing. Although we did not perform overnight sleep studies, subjects were interviewed and health history was provided by self-report, which in low-risk subjects is known to be effective in ruling out individuals with sleep apnea (Mezzanotte et al. 1992; Young et al. 1993). Second, the population comprised a majority of women, whereas previous studies recruited exclusively male subjects.
between breathing tasks.

Equivalently, impedance and EMG activity was normalized to the equivalent negligible impedance measured at.

Finally, the signal detection properties of the two types of electrodes are virtually identical and depend primarily on the subject. In our experience, tungsten electrodes cause less discomfort upon percutaneous insertion than hook-wire electrodes inserted per orally into the floor of the mouth, ~5.0 mm from the internal aspect of the mandible close to the muscle’s origin on the mandible (Sauerland and Mitchell 1975; Sauerland and Harper 1976). This approach is well documented, well tolerated by subjects, and yielded excellent recordings in these 14 subjects.

To access the posterior region of the GG we used tungsten microelectrodes inserted via the skin under the chin, using ultrasound to establish distance to the GG muscle in each subject. In our experience, tungsten electrodes cause less discomfort upon percutaneous insertion than hook-wire electrodes (which require a hypodermic needle) and permit the monitoring of electrode position and depth throughout the experiment. Tungsten electrodes also yield remarkably stable recordings across diverse behaviors and protocols, as has been demonstrated previously (Pittman and Bailey 2009; Richardson and Bailey 2010; Laine and Bailey 2011; Walls et al. 2013).

The averages reported here are consistent with prior results also demonstrating predominantly tonic activation during rest breathing (Mezzanotte et al. 1992; Mateika et al. 1999; Laine et al. 2012; Walls et al. 2013) and underscore the role of GG as a pharyngeal airway dilator active in both the inspiratory and expiratory phases of the respiratory cycle in the healthy adult (Bailey 2011). Phasic activity has been observed previously in deep breathing associated with moderate exercise (Williams et al. 2000; Parreira et al. 2013). Divergent outcomes are to be expected if the conditions and/or tasks performed by the subjects also differ. For example, Wasicko et al. (1993) manipulated vestibular input and/or blood pressure secondary to passive tilt, whereas Williams et al. (2000) assessed GG EMG upright and supine within the context of cycling exercise. Thus, the stimulus may exert a unique and/or combinatorial effect on the GG electromyogram that renders meaningful comparison difficult.

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study are somewhat more anterior and further posterior than those reported by Eastwood et al. (2003).

Volitionally modulated breathing vs. rest breathing. Relative to rest breathing, the various volitionally modulated breathing tasks were associated with significantly greater magnitude of EMG overall as well as differences in the phasic and tonic EMG components. These effects held true across recording location and body positions. As noted above, the progression from rest breathing to deep breathing, hyperventilation, and Mueller maneuver was characterized by successive increases in the magnitude of the GG electromyogram (% maximum) in each subject (see Fig. 5). This increase in the magnitude of the EMG activity may be related to the source(s) of neural drives converging onto hypoglossal motoneurons. For example, rest breathing presumably is driven primarily by the respiratory central pattern generator and by mechanoreceptor and chemoreceptor inputs. For volitionally modulated breathing, however, additional inputs arise in motor cortex but may also include inputs arising in pontine, parabrachial nuclei that control respiratory phase switching and permit adjustment of the respiratory cycle to fit the particular behavioral requirements (Sawczuk and Mosier 2001; Martelli et al. 2013; Dutschmann and Dick 2014). Although reflex activation secondary to negative pressure pulse application was not attempted in this protocol, voluntary hyperventilation and Mueller maneuvers, large negative (inspiratory) pressures, also may have contributed to GG activation via stimulation of upper airway receptors, resulting in reflex augmentation of the EMG activity in a manner distinct from cortical drive (Horner et al. 1991; Eastwood et al. 2003).

Finally, studies in other respiratory motoneuron pools, including intercostal and abdominal muscles, have documented greater EMG activity in the context of volitionally modulated breathing (McKenzie et al. 1988; Gandevia et al. 1990); however, none assessed the magnitude of EMG activity across the number of tasks attempted here. The present data obtained across a range of behaviors may be of use in assaying regional muscle activation and in gauging the proportion of the motoneuron pool that can be recruited into activity in healthy adults.

In summary, we selected for use the traditional per oral hook-wire electrodes and lesser-known tungsten microelectrodes inserted percutaneously. Importantly, both electrodes were constructed to equivalent impedance specifications and yielded excellent recordings from their respective muscle locations. We conducted a comprehensive assessment of upper airway EMG in healthy adults across a range of breathing behaviors, in two body positions and two recording locations. Respiratory behaviors were selected for inclusion as tasks that reasonably might be encountered in the course of daily life and, in the case of the Mueller maneuvers, to approximate the response of the muscle to airway obstruction (Hanly et al. 1989; Andreas et al. 1992; Morgan et al. 1993; Somers et al. 1993; Koshino et al. 2010; Camen et al. 2013). Given evidence that individuals with sleep apnea exhibit augmented GG activity in wakefulness (Mezzanotte et al. 1992; Saboisky et al. 2007 and 2012), findings obtained from healthy individuals will serve as a valuable dataset against which to compare anterior and posterior GG activity in this population.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Author contributions: J.R.V. and E.F.B. conception and design of research; J.R.V. performed experiments; J.R.V. analyzed data; J.R.V. and E.F.B. interpreted results of experiments; J.R.V. prepared figures; J.R.V. and E.F.B. drafted manuscript; J.R.V. and E.F.B. edited and revised manuscript; J.R.V. and E.F.B. approved final version of manuscript.

REFERENCES


