Genioglossus and Intrinsic Electromyographic Activities in Impeded and Unimpeded Protrusion Tasks

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Pittman LJ, Bailey EF. Genioglossus and intrinsic electromyographic activities in impeded and unimpeded protrusion tasks. J Neurophysiol 101: 276–282, 2009. First published November 5, 2008; doi:10.1152/jn.91065.2008. Eight muscles invest the human tongue: four extrinsic muscles have external origins and insert into the tongue body and four intrinsic muscles originate and terminate within the tongue. Previously, we noted minimal activation of the genioglossus tongue muscle during impeded protrusion tasks (i.e., having subjects push the tongue against a force transducer), suggesting that other muscles play a role in the production of tongue force. Accordingly, we sought to characterize genioglossus tongue muscle activities during impeded and unimpeded protrusion tasks (i.e., having subjects slowly and smoothly move the tongue out of their mouth). Electromyographic (EMG) and single motor-unit potentials of the extrinsic genioglossus muscle were recorded with tungsten microelectrodes and EMG activities of intrinsic tongue muscles were recorded with hookwire electrodes inserted into the anterior tongue body. Tongue position was detected by an isotonic transducer coupled to the tongue tip. Protrusive force was detected by a force transducer attached to a rigid bar. Genioglossus and intrinsic tongue muscles were simultaneously active in both impeded and unimpeded protrusion tasks. Genioglossus whole muscle EMG and single motor-unit activities changed faithfully as a function of tongue position, with increased discharge associated with protrusion and decreased discharge associated with retraction back to the rest position. In contrast, during the impeded protrusion task drive the genioglossus muscle remained constant as protrusion force increased. Conversely, intrinsic tongue muscle activities appropriately followed changes in both tongue position and force. Importantly, we observed significantly higher levels of intrinsic muscle activity in the impeded protrusion task. These observations suggest that protrusion of the human tongue requires activation of the genioglossus and intrinsic protruder muscles, with the former more important for establishing anterior–posterior tongue location and the latter playing a greater role in the generation of protrusive force. A biomechanical model of these actions is provided and discussed.

INTRODUCTION

Our understanding of the principles governing the nervous system control of movement in large part comes from studies conducted in muscles of the limbs that have clearly defined origins and insertions and that produce force across a joint. In some instances, however, animals use structures composed primarily of muscle both to move and to apply force, examples of which include the elephant trunk, the tentacles of a squid, and the mammalian tongue. These structures, known as “hydrostats,” are capable of remarkably complex movements accomplished without the aid of a solid skeleton. That is, muscles modulate the internal pressure and stiffness of the structure to constitute a hydrostatic “skeleton” (Kier and Smith 1985; Skierczynski et al. 1996; Smith and Kier 1989) and provide the reaction forces needed for tongue movement. In this respect, tongues, trunks, and tentacles offer a novel framework within which to consider the nervous system control of movement because cooperative contraction of muscles underpins movement and provides the structural platform necessary for delivery of external force.

The human tongue comprises orthogonally related intrinsic muscles (verticalis, transversus, superior and inferior longitudinal) that originate and terminate within the tongue and so-called extrinsic muscles (genioglossus, hyoglossus, styloglossus, and palatoglossus) that have external bone origins and insert into the tongue body. The muscular hydrostat theory (Kier and Smith 1985) postulates a constant interaction of extrinsic and intrinsic muscles in all tongue functions.

To begin studying the highly complex muscular interactions that underlie tongue movements, relatively simple movements must be studied first. Accordingly, this study focuses on the muscular actions leading to tongue protrusion under conditions where protrusion is either impeded (i.e., quasi-isometric contractions) or unimpeded (simple displacement). According to the muscular hydrostat theory (Smith and Kier 1989), protrusion does not result from the activation of a single muscle but rather is a consequence of expansion in the long axis (via contraction of intrinsic tongue muscles verticalis and transversus) and forward movement in space (via contraction of genioglossus). Importantly, the multivectorial actions of the intrinsic tongue muscles are thought to stiffen the tongue, making the development of protrusive force possible (Kier and Smith 1985). Although this theory appears to hold in various animal species (Abd-El-Malek 1938; Bennett and Hutchinson 1946; Smith 1984), to date there is no evidence that protrusion of the human tongue requires activation of intrinsic and extrinsic tongue muscles. Accordingly, in the present study we recorded electromyographic (EMG) and single motor-unit activities from the extrinsic protruder muscle, the genioglossus, as well as the EMG of intrinsic protruder muscles in healthy human subjects that performed impeded or unimpeded protrusion tasks. Our main hypothesis is that tongue protrusion in human subjects requires activation of intrinsic and extrinsic tongue muscles. Our secondary hypothesis is that impeded and unimpeded protrusion tasks are associated with distinct muscle activation patterns, attributed to the presence or absence of a reaction force.
METHODS

We performed experiments in 10 healthy human volunteers (6 women and 4 men; ages 20–54 yr). All experimental procedures were approved by the Human Subjects Committee at the University of Arizona. Subjects gave their informed consent before participation in the study.

EMG recordings

EMG activities were recorded from the genioglossus (GG) muscle and from the intrinsic tongue muscles. The GG muscle arises from the medial aspect of the mandibular symphysis and fans out dorsoventrally to insert into the central mass of the tongue (Takemoto 2001). The protocol for electrode insertion has been reported previously (Bailey et al. 2007a,b). Briefly, we determined the distance from the skin surface to the inferior border of the GG muscle via ultrasonography (Pro Sound 3500; Aloka, Tokyo, Japan) (Eastwood et al. 2003). For whole muscle GG EMG activities, a tungsten needle electrode (1- to 5-μm tip diameter, 250-μm shaft diameter; FHC, Bowdoinham, ME) with insulation removed from the terminal tip (~2 mm) was inserted transcutaneously into the floor of the mouth, with the entry point about 1.5 cm from the midline and about 2–4 cm posterior to the mandible. A second high-impedance tungsten microelectrode (10 MΩ at 1 kHz, 1- to 5-μm tip diameter, 250-μm shaft diameter; FHC) was inserted to the same depth for purposes of recording GG muscle single motor-unit action potentials (SMUAPs).

We recorded intrinsic whole muscle EMG activities from the anterior tongue body with an intramuscular fine-wire electrode (50 μm; California Finewire, Grover Beach, CA) with insulation removed from the terminal tip (~2 mm). The wire was threaded through a 27-gauge needle and inserted through the dorsum of the tongue, posterior to the tongue tip at the first premolar, at a point equidistant from the terminal tip (~2 mm). The wire was threaded through a 27-gauge needle and inserted through the dorsum of the tongue, posterior to the tongue tip at the first premolar, at a point equidistant from the terminal tip (~2 mm). The wire was threaded through a 27-gauge needle and inserted through the dorsum of the tongue, posterior to the tongue tip at the first premolar, at a point equidistant from the terminal tip (~2 mm). The wire was threaded through a 27-gauge needle and inserted through the dorsum of the tongue, posterior to the tongue tip at the first premolar, at a point equidistant from the terminal tip (~2 mm).

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Surface electrodes (4-mm-diameter Ag/AgCl) attached to the skin overlying each mastoid process served as indifferent electrodes for tungsten and fine-wire EMG recordings. A ground strap was placed around the upper arm. EMG signals were amplified (~1,000, Model 15; Grass Instruments, West Warwick, RI) and band-pass filtered (0.3–3 kHz). Intrinsic and extrinsic whole muscle EMG activities were sampled at 10 kHz and GG SMUAPs were sampled at 20 kHz and recorded on the Spike2 data acquisition and analysis system (CED, Cambridge, UK). The amplified and filtered whole muscle EMG signals were subsequently rectified and moving-time averaged with a time constant of 200 ms.

Experimental protocol

Subjects were seated upright in a dental chair with their head supported. Respiratory movements of the chest were monitored by a respiratory effort transducer (Pro-Tech, Mukilteo, WA) positioned around the rib cage at the level of the axilla and around the abdomen at the level of the umbilicus.

MAXIMUM MANEUVERS. Subjects first performed a series of maximum maneuvers for purposes of normalizing EMG activities, allowing us to compare drive to the muscle across subjects. These maneuvers comprised maximum protrusions of the tongue out of the mouth and maximum forces exerted against the hard palate, against the lower incisors and against a tongue depressor that an investigator held at the subject’s lips. Interestingly, in all subjects, maximum GG EMG activities were recorded during unimpeded protrusions.

UNIMPEDED PROTRUSIONS. Tongue position was detected by a battery-powered isotonic transducer (Harvard Apparatus, Kent, UK) (Bailey et al. 2007b). The transducer was connected to the tongue by a thermoplastic housing affixed to the dorsum of the tongue (Fig. 1A). This coupling posed minimal impediment to movement and subjects were able to swallow and speak during the experiment. The position signal was amplified

FIG. 1. Schematic of the experimental setup. A: tongue position was detected by a battery-powered isotonic transducer coupled to the tongue via a lever arm that engaged a thermoplastic housing affixed to the dorsum of the tongue surface. B: impeded protrusion trials were conducted with the aid of a rigid force transducer that was brought into place to engage the lever arm, thereby preventing protrusion.
IMPEDED PROTRUSIONS. In this task, an isometric force transducer (World Precision Instruments, Sarasota, FL) was attached to the lever arm described earlier (Fig. 1B). Because forward movement of the tongue was impeded in this configuration (see Fig. 1B) the task approximated an isometric contraction. Subjects were required to attain force targets of 10 and 30 g using visual feedback of the target force and their task was to match the target force.

Subjects completed three trials comprising each of the tasks in sequence as follows: unimpeded protrusions; impeded protrusions; unimpeded protrusions (see Fig. 3).

SINGLE MOTOR-UNIT ACTIVITIES. In addition to recording whole muscle EMG activities we also characterized the activities of 33 GG single motor units in a subset of individuals (n = 7). Each trial comprised three unimpeded protrusions and three impeded protrusions. Subjects were provided with auditory and visual feedback (i.e., via an ongoing display of the spike record on a slowed timescale) of motor-unit discharge. For the unimpeded protrusion task, subjects were instructed to maintain the tongue in the least-protruded position that was also associated with stable motor-unit discharge (i.e., firing without interruption) for 10 s. Subjects were then instructed to retract the tongue and then slowly advance the tongue to recruit the target motor unit. The force transducer was subsequently coupled to the lever arm and subjects were instructed to increase force exerted on the transducer to recruit the target motor unit, to match the force produced to the target force (i.e., 10 or 30 g), and then to slowly reduce force output back to the baseline level.

Data analysis

All data were acquired and analyzed using Spike2 and custom-designed software (CED). Quantitative comparisons of EMG activities were made as follows. Average whole muscle GG and intrinsic muscle activities were expressed as a percentage of the maximal response (% max), as defined earlier. Single motor-unit action potentials were discriminated using a template-matching algorithm based on waveform shape and amplitude as discussed previously (Bailey et al. 2007b). For analysis of average discharge rate and variability, only those motor units whose activities could be followed throughout each series of unimpeded protrusion and impeded protrusion tasks were included. The initial firing rate at recruitment was calculated from the first 10 interspike intervals (ISIs) in both the unimpeded and impeded protrusions. Peak firing rate was determined as the highest magnitude of whole muscle GG EMG activities (% max) in impeded protrusion tasks was two- or threefold lower relative to activities in the unimpeded protrusion task (Fig. 4; P < 0.05). In contrast, intrinsic muscle EMG activities tended to be higher in impeded protrusion than in the unimpeded protrusion.
Relative to GG EMG, the intrinsic muscle EMG activities were significantly smaller in magnitude in the unimpeded protrusion task and significantly larger in the impeded protrusion tasks (i.e., 30 g, Fig. 4).

Representative raw recordings showing the instantaneous firing rate of a discriminated single GG motor unit, tongue position, and tongue protrusion force are presented in Fig. 5. Consistent with previously published findings (Bailey et al. 2007b), we observed systematic changes in GG muscle motor-unit firing rate as a function of unimpeded tongue protrusion tasks (see Fig. 5, left). In this example, the motor unit was recruited about 5 mm from the rest position and discharged at an initial rate of 10.8 ± 2 (SD) Hz, increasing to a peak rate of 22.5 ± 2 Hz. For all unimpeded protrusion trials, the firing rate at recruitment was 11.5 ± 4 Hz and increased to 25.3 ± 4 Hz at peak displacement. By contrast, firing rate did not exhibit any systematic change either as a function of increased or decreased protractive force but rather remained stable throughout (Fig. 5, right). Thus for all impeded protrusion trials the average firing rate was 16.4 ± 8.2 Hz, slightly higher than that measured at the onset of the unimpeded protrusions (10.8 ± 2).

The absence of any correspondence between firing rate and force during impeded protrusion tasks supports the hypothesis that GG motor-unit activities are modulated in accordance with tongue position, but not isometric force production. These findings have important implications for our understanding of how the nervous system controls tongue muscles during simple protrusion tasks, as explained in the following text.

DISCUSSION

Summary

Hydrostats have been extensively studied at a kinematic level yet we know remarkably little about patterns of muscle

FIG. 3. Genioglossus (GG) and intrinsic muscle electromyographic (EMG) activities during successive unimpeded (left) and impeded protrusion (right) trials. Top: force recording (g). As depicted in Fig. 1A, force was not measured in unimpeded protrusion trials and is set to zero (left). Middle: position of tongue relative to the subject’s neutral or rest position (mm). Lower: raw intrinsic muscle EMG activities. Bottom: raw GG EMG activities.

FIG. 4. Average whole muscle GG and intrinsic EMG activities for the group (n = 10) in unimpeded protrusions and 2 levels of the isometric force (10 and 30 g) tasks. Values are expressed as a percentage of the appropriate maximum mean EMG activity (% max). * Indicates a significant difference between GG and intrinsic muscle EMG for a given task (P > 0.05). + Indicates a significant task-related difference in GG EMG activities.
and motoneuron activities and their relationship to hydrostatic movements. In this study, we characterized the activities of extrinsic and intrinsic protrudor muscles in human subjects performing unimpeded and impeded protrusion tasks. We show that whereas there is activation of GG and intrinsic tongue muscles in both tasks, the magnitude and shape of the drive to the intrinsic muscles and to the GG are very different, at least within the framework of the simple tasks attempted here.

Critique of method

We selected a site in the anterior tongue body for purposes of recording intrinsic protrudor muscle activities (Napadow et al. 1999). However, because intrinsic muscle fibers interdigitate within the tongue body and are not spatially distinct, it was not possible for us to definitively identify the specific intrinsic muscle(s) that we recorded from at that location. Although it is most likely that we recorded the activity of verticalis and transversus, which are both tongue protrudor muscles, we do not know the relative contributions of each muscle to the recording. In addition, we cannot exclude the possibility that at least some of the electrical activity that we recorded originated in tongue muscles other than verticalis and transversus (Slaughter et al. 2005; Stal et al. 2003).

The complex interdigitation of muscles confers on the mammalian tongue a remarkable flexibility of movement that underpins highly coordinated behaviors such as speaking and swallowing. Based on kinematic (Gilbert et al. 2007; Hiiemae et al. 2002; Stone et al. 2004) and electromyographic studies (Kayalioglu et al. 2007; Liu et al. 2007) the tongue is considered to comprise several regions or “segments” capable of semi-independent movement. Evidence for distinct muscle compartments (Mu and Sanders 1998, 2000) and regional differences in muscle fiber type (Sokoloff 2000; Stal et al. 2003) add some support to independent regional control, although this has not been demonstrated in human subjects. Under the current protocol, subjects were required to perform simple protrusion tasks, using both impeded and unimpeded planar movements, in an effort to characterize muscle activities under each condition separately. Whereas these findings provide new insight into the nervous system modulation of tongue movement, caution should be exercised in extrapolating the results to more complex natural behaviors.

The target forces adopted under the current protocol were an order of magnitude smaller than those reported previously in “submaximal” protrusions exerted against the upper incisors or palate (i.e., 5–24 N) (Blumen et al. 2002; BuSha et al. 2002; Mortimore et al. 2000; Scardella et al. 1993; Solomon and Munson 2004; Weijnen et al. 2000). The present targets were established based on the force exerted by each subject on the teeth and palate (alveolar ridge) in verbal counting and swallowing tasks (10–50 g). Based on this assessment, it is our view that the force targets were within the physiological range and that the EMG activities reported here in impeded protrusion tasks approximate those developed by the tongue in speech and some gustatory functions.

Drive to tongue protrudor muscles in impeded and unimpeded protrusion tasks

Three main findings arise from the current data set. First, within the framework of these very simple tasks, both impeded and unimpeded protrusions beyond the teeth involve activation of the mutually orthogonal intrinsic fibers in the anterior tongue and the extrinsic GG. Although respiratory-related activation of tongue muscles has been documented previously in rat (Bailey and Fregosi 2004; Bailey et al. 2005) and human (Mateika et al. 1999; Oliven et al. 2007), to our knowledge this is the first time activation of both extrinsic and intrinsic tongue protrudor muscles has been demonstrated in human subjects performing volitional unimpeded and impeded protrusion tasks. Thus the present findings provide valuable new support for a fundamental tenet of the muscular hydrostat theory originally proposed by Smith and Kier—that there is a constant...
interaction of intrinsic and extrinsic tongue muscles in all tongue movements (Smith and Kier 1989).

Second, we have shown previously that GG MU activities are tightly modulated in accordance with tongue position (Bailey et al. 2007b) but not force. Importantly, because the sustained firing rates evident in the force task approximate those previously recorded in static holding maneuvers (Bailey et al. 2007b) we suggest that the GG muscle fulfills a supportive but not a primary role in the generation of protrusive force (see following text). In contrast, the GG plays a prominent role in unimpeded displacement tasks. Intrinsic protrudor muscles, on the other hand, appear to play a major role in both tasks. The data suggest that the multivectorial intrinsic muscles that comprise the core of the anterior tongue (i.e., verticalis and transversus) generate most of the tongue protrusion forces, but only when stabilized by contraction of the GG muscle, as discussed in the following text.

**Working model for human tongue protrusion and force**

On the basis of current observations we have devised a working model to clarify the roles fulfilled by the GG and the intrinsic muscles in each task (see Fig. 6). Consistent with the traditional view of tongue protrusion, GG contraction advances the tongue base, whereas activation of the intrinsic protrudor muscles in the tongue tip reduces the diameter of the anterior body of the tongue. Because the tongue is a constant volume structure, the reduction in tongue diameter secondary to intrin-

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**Fig. 6.** A working model of tongue muscle activation in unimpeded and impeded protrusions. **Left panels:** schematic lateral view of the tongue showing the extrinsic tongue muscles (genioglossus [GG], hyoglossus [HG], and styloglossus [SG]) that have external bony origins on the mandible (m), hyoid bone, and styloid process, respectively. The intrinsic muscles transversus (t) and verticalis (v) interdigitate extensively and have both origins and insertions in the central tongue body. **Right panels:** force and position traces, with corresponding integrated GG and intrinsic muscle activities. **A, left:** tongue configuration at rest (dashed outline) and in unimpeded protrusions. In this task there is activation of both the GG and intrinsic muscles (see EMG activities at right), with corresponding changes in position but not force. GG activation causes anterior movement of the tongue base (denoted by arrow) and activation of the intrinsic muscles verticalis and transversus compresses the tongue body, contributing to protrusion beyond the mandible, as described in the text. **B, left:** schematic of the tongue configuration at rest (dashed outline) and during an impeded protrusion against an external structure (black bar, representing the force transducer). As in A, impeded protrusions also involve activation of the GG and intrinsic muscles. Contraction of the intrinsic muscle fibers compresses the tongue body, resulting in expansion in the long axis, which registers as protrusive force. However, force will not be registered unless GG activation fulfills a platform function that stabilizes the tongue base (denoted by double-headed arrow), thereby resisting rearward movement that would otherwise occur in this soft-bodied structure. In this task the magnitude of the intrinsic muscle activities exceeds that of the GG (see right panel). The magnitude and direction of the forces contributed by the 2 extrinsic retractor muscles, hyoglossus (HG) and styloglossus (SG) (arrows), are also incorporated into this working model. Although the activities of these muscles and resultant forces were not recorded in our experiments, based on respiratory-related tongue muscle activities in human subjects (Mateika et al. 1999; Oliven et al. 2007), we postulate that the retractor muscles also are coactive with the GG and intrinsic muscles in these tasks. Activation of the HG may be of particular importance in protrusive force tasks as a secondary stabilizer of the tongue base (Oliven et al. 2007).
sic muscle-mediated contraction results in elongation of the tongue. What is crucial, however, is that although the GG contraction certainly moves the tip of the tongue forward, full tongue protrusion requires activation of the intrinsic protruder muscles (McClung and Goldberg 2000). This is consistent with our observation that during unimpeded protrusions, GG and intrinsic muscle activities are of comparable magnitude (Fig. 6, right).

Our data also show that impeded protrusions involve activation of GG and intrinsic muscle activities. As stated earlier, contraction of the intrinsic muscles compresses the anterior tongue, effecting expansion in the long axis that, when impeded, results in the development of protrusive force. In this scenario, GG activation fulfills a vital platform function that counteracts (or resists) rearward movement as intrinsic muscle contraction attempts to elongate the tongue. Note that in this case neural drive to the intrinsic muscles is greater than that for the GG (Fig. 6, right), consistent with a supportive role for the GG and a primary role for intrinsic protruder muscles.

In conclusion, we suggest that GG activation plays a central role in impeded protrusions, providing a stable platform against which the intrinsic muscles in the anterior tongue can develop protrusive force against immobile structures such as the teeth or palate. This “functional” platform or skeleton is of critical importance for tongue function, as it is in other structures that lack a true bony skeleton (e.g., tentacles and trunks). Nonetheless, successful protrusions of the tongue are not possible in the absence of activation of the intrinsic protruder muscles, verticalis and transversus. The potential for the CNS to independently modulate stiffness/force and position by carefully recruiting multiple tongue muscles is important for a host of lingual functions, not the least of which is the development of forces within the vocal tract in speech for purposes of phonetic stress and in chewing for bolus formation.

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REFERENCES


