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Effects of tongue position and lung volume on voluntary maximal tongue protrusion force in humans

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ABSTRACT

Maximal voluntary protrusion force of the human tongue has not been examined in positions beyond the incisors or at different lung volumes. Tongue force was recorded with the tongue tip at eight positions relative to the incisors (12 and 4 mm protrusion, neutral and 4, 12, 16, 24 and 32 mm retraction) at functional residual capacity (FRC), total lung capacity (TLC) and residual volume (RV) in 15 healthy subjects. Maximal force occurred between 12 mm and 32 mm retraction (median 16 mm). Maximum force at FRC was reproducible at the optimal tongue position across sessions ($P = 0.68$). Across all positions at FRC the average force was highest at 24 mm retraction (28.3 ± 5.3 N, mean ± 95% CI) and lowest at 12 mm protrusion (49.1 ± 4.6% maximum; $P < 0.05$). Across all tongue positions, maximal force was on average 9.3% lower at FRC than TLC and RV (range: 4.5–12.7% maximum, $P < 0.05$). Retracted positions produce higher-force protrusions with a small effect of lung volume.

1. Introduction

There have been few investigations of the 'length-tension' curves for tongue protrusion in humans (Bu Sha et al., 2000; BuSha et al., 2002). Resting length is usually used with the tongue tip near the incisors to measure maximal force of voluntary tongue protrusion (Blumen et al., 2002, 2004; Eastwood et al., 2003; Eckert et al., 2011; McSharry et al., 2012; Mortimore et al., 1999, 2000; Pittman and Bailey, 2008; Scardella et al., 1993) or retraction (Ulrich Sommer et al., 2014). As the human tongue is a unique structure with four pairs of intrinsic and extrinsic muscles acting as a hydrostat (incompressible with a constant volume), its capacity to generate protrusion force is likely to reflect the action of several muscles (Abd-El- Malek, 1938; Anderson, 1881; Takemoto, 2001). Previous investigators have argued that altering tongue length and measuring maximal muscle force gives insight to the length-tension properties of the normal human genioglossus while downplaying the contribution of intrinsic muscles (Bu Sha et al., 2000; BuSha et al., 2002). Bailey and colleges have shown that tongue protrusion in humans requires activation of both genioglossus and intrinsic muscles (Pittman and Bailey, 2008) and that they suggest intrinsic muscles have a major role for airway dilation in rats (Bailey et al., 2006).

For human skeletal muscle, length-tension curves are typically measured across different joint angles and the force is measured under isometric conditions. Force can be altered by many factors such as sarcomere length, the series elastic elements, muscle architecture, and the relationship between moment arm and joint angle (Gordon et al., 1966; Kjaer, 2004; Lieber and Ward, 2011). Therefore, without a skeletal support system, study of the length-tension relationship of the human tongue in vivo remains challenging. Only two studies have examined 'position-force' relationships of the human tongue, but, they did not examine the tongue beyond the resting (neutral) position (Bu Sha et al., 2000; BuSha et al., 2002).

The volitional control of the tongue may be affected by changes in lung volume by at least two mechanisms. First changes in tracheal traction at different lung volumes may alter the mechanics of the tongue muscles and their ability to produce protrusion force (Amatoury et al., 2014; Van de Graaff, 1991). Changes in lung volume alter tension transferred through the trachea to the hyoid arch (Van de Graaff, 1988). Second, volitional control of the human tongue may be altered by inputs from pulmonary and chest wall receptors (Saito et al., 2002). Respiratory rhythm (Saboisky et al., 2006, 2010; Sauerland and Mitchell, 1975; Tsuiki et al., 2000) is modulated by feedback from pulmonary stretch receptors (e.g. Cohen, 1969; Colridge and Colridge, 1986; Hwang and St John, 1987; Saito et al., 2002) and this has a greater inhibitory effect on the discharge of hypoglossal motoneurons compared to phrenic motoneurons (Hwang and St John, 1987; Kuna, 1986; Sica et al., 1984; van Lunteren et al., 1984). How these afferents influence voluntary activation of the human tongue is not known. However, at

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high lung volumes the excitability of cortical pathways to the inspiratory scalene muscles is increased (Hudson et al., 2012). Therefore, we hypothesized that voluntary strength of the tongue might vary with lung volume.

The aims of this study were first, to measure the maximal tongue protrusion force at eight tongue positions, including positions with the tongue beyond the incisors, second, to measure maximal tongue protrusion force at three lung volumes. Third, to assess the reproducibility of protrusion force at the optimal tongue position in each subject. Preliminary results have been presented (Saboisky et al., 2013).

2. Methods

Experiments were performed on 15 healthy subjects: age 29.0 ± 2.4 years; height 169.9 ± 5.0 cm; 9 female and 6 male; weight 65.9 ± 7.9 kg; body mass index 22.6 ± 1.5 kg/m^2; (mean ± 95% confidence interval). Two further subjects were excluded from analysis due to an inability to perform the task. Each subject gave informed written consent to the procedures which had been approved by the Human Research Ethics Committee of the University of New South Wales and conformed to the Declaration of Helsinki (2008).

Subjects were lying comfortably supine, wore a nose clip and breathed through a customized mouth piece (Fig. 1). Airflow was measured through a pneumotachometer and a disposable air filter (Respirgard IITM 303E Vital Signs, GE, Englewood, CO, USA; Hans Rudolph, 3700, Kansas City, USA). A volume signal was generated on-line by integration of airflow (Hewlett Packard 8815A, Waltham, MA, USA). End-tidal CO_2 was monitored continuously at the distal end of the pneumotachometer ($PETCO_2$, Datex Instrumentarium, CD-102-21-02, Helsinki, Finland). Subjects were instructed to maintain a normal respiratory rhythm for the three breaths leading into the maximal manoeuvres. Minute ventilation prior to the manoeuvres at each lung volume did not differ across tongue position (FRC P = 0.246, TLC P = 0.140, RV P = 0.545, *repeated measures ANOVA on ranks*).

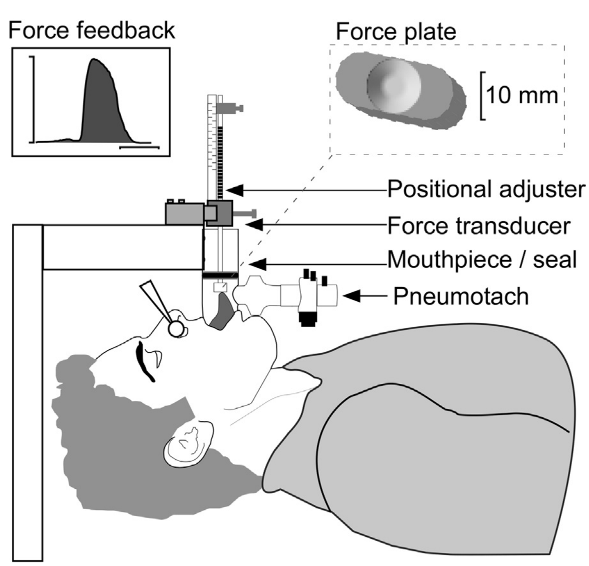

Fig. 1. Experimental methods and set up and protocol. Experimental set-up showing subject lying supine. Subjects breathed through a customized mouth piece that included a calibrated linear tongue force transducer, together with an air-filter and pneumotachometer with a nose clip on. Feedback of protrusion force was given directly via an oscilloscope (~2 s per div) and verbal encouragement was provided during maximal efforts. Inset on right shows an expanded view of the tongue force plate. A concave spherical depression (11 mm diameter) for the tongue tip was machined 2 mm deep into the Teflon force plate.

Tongue force was measured with a customized apparatus. We used a modified perspex tube (40 mm diameter, 3 mm wall thickness) as the mouthpiece with two 3 mm circumferential grooves (2 mm and 5.5 mm from the end of the tube) to locate and fix incisor teeth. The proximal end of the tube had been heated to form an elliptical shape to fit the mouth (~50 mm × ~26 mm).

Maximal tongue protrusions were performed against a smooth Teflon force plate (24 mm × 12 mm) in the centre of the mouth piece (Fig. 1, inset). The plate was attached to a strain gauge via a stainless-steel shaft that traversed the length of the tube (250 N; Xtran, Melbourne, Australia). The proximal edge of the plate relative to the incisors was used to determine tongue position. The shaft had groves at 4 mm increments to enable reproducible positioning of the tongue. The tube was airtight with an O-ring around the shaft that was not coupled to the mouth piece (see Fig. 1).

Maximal voluntary tongue protrusion force was measured across retraction to protrusion positions in three sessions in the laboratory. Subjects performed three brief maximal voluntary contractions (MVCs, ~2 s duration) at each of the eight positions; protrusion to 12 mm and 4 mm beyond the incisors, neutral (0 mm, aligned with incisors), and retraction to −4, −12, −16, −24 and −32 mm behind the incisors (measured from the tip of the tongue to the incisors). Each contraction was separated by at least 1 min of quiet breathing (Fig. 2). Tongue protrusions at the eight positions were repeated at different lung volumes: functional residual capacity (FRC, day 1), total lung capacity (TLC, day 2), and residual volume (RV, day 3). During tongue protrusion efforts, subjects were asked not to breathe. At TLC and RV they were instructed to relax their inspiratory muscles against a closed glottis. In each session the order of the eight positions was randomized. During the maximal voluntary tongue protrusions subjects received continuous feedback of tongue force on an oscilloscope (2 s/division) and were verbally encouraged to produce maximal efforts.

The tongue position at which each subject produced the largest protrusion force at FRC was tested again at the second and third visit. This served two purposes. First, repetition of the contractions at FRC enabled normalization of results between days to a common task. Secondly, the reproducibility of the measurement of tongue protrusion force at FRC could be assessed across the individual subjects.

Subjects were not asked specifically to close their glottis at FRC. Therefore, we performed a further study in 8 of the subjects to investigate whether the glottis being open or closed affected the tongue protrusion force. Each subject performed five maximal tongue protrusion efforts with the glottis open and five with glottis closed at FRC in a randomized order at a tongue position of −16 mm. The mean of the five contractions from each subject was assessed with a one-way repeated measures ANOVA. The group mean for the glottis closed was 32.1 ± 8.6 N and for the glottis open was 32.7 ± 9.8 N (P = 0.5). Therefore the overall relative increase in maximal voluntary protrusion force at RV and TLC compared to FRC is probably not affected by whether or not the glottis was open or closed.

An additional control study was conducted in four subjects to assess whether maximal tongue protrusion force was affected by gravity in the supine posture. We measured maximal tongue protrusion force as described above in protruded and retracted tongue positions (−24, −12, 0 [neutral] and 12 mm) in both the supine and prone postures. No significant difference in maximal tongue protrusion force was detected between postures (P = 0.2).

Data were recorded with a 16-bit A/D converter (CED 1401; Cambridge Electronic Design Ltd., Cambridge, UK) and Spike2 software (version 6.16; Cambridge Electronic Design). Force was sampled at 5000 Hz, airflow and volume at 1000 Hz, and $PETCO_2$ 100 Hz. Off-line analysis was conducted with Spike2 software (version 6.16; Cambridge Electronic Design). Maximal voluntary tongue