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INTRA-OPERATIVE LARYNGOSCOPIC INSTRUMENT FOR CHARACTERIZING VOCAL FOLD VISCOELASTICITY

Mark P. Ottensmeyer[1], Michael Yip[2], Conor J. Walsh[3], James B. Kobler[4], James T. Heaton[4] and Steven M. Zeitels[4]
[1]The Simulation Group, CIMIT/Massachusetts General Hospital
[2]Department of Mechatronic Engineering, University of Waterloo
[3]Department of Mechanical Engineering, Massachusetts Institute of Technology
[4]Center for Laryngeal Surgery and Voice Rehabilitation, Massachusetts General Hospital

INTRODUCTION

Our society depends on communication, the most natural form of which is speech. Trauma, disease and the normal aging process will cause many to suffer degraded or lost vocal fold function, and it has been observed that this number is growing [1]. The vocal folds are the vibrating structures in the larynx that enable us to generate voice, from speech to opera singing. The vibrating portions of the folds consist of an external 0.1mm thick layer of epithelial cells, a soft, gel-like 0.5mm thick layer called the lamina propria (LP), a 0.3mm thick vocal ligament and an underlying thyroarytenoid muscle [2]. The fundamental frequency of speech in men is in the 100-150Hz range, and between 200 and 300Hz in women [3].

The folds' smooth surfaces meet medially during vibration, briefly stopping airflow before reopening. Polyps, cysts, tumors or loss of tissue distort the surface leading to incomplete or asymmetric closure and reduced or lost ability to phonate [4]. A solution under development to replace lost tissue is the injection or implantation of replacement tissue (engineered or graft), stem cells and/or biocompatible materials under the epithelium to restore normal vocal fold shape and visco-elastic properties [5].

Specifying the mechanical behavior of the implants requires data on the properties of healthy vocal folds. Excised canine epithelium has a Young's modulus (E) in tension of 41.9kPa for <15% strain [6]. Human LP has a modulus somewhere between 100 and 4000Pa [7,8], exhibits shear thinning and has a dynamic viscosity (μ) of 1Pa·s at 1Hz. It is mechanically stable over time and through freezing and thawing [9]. Tests in [7] were made at least 18 hours post-mortem, and like other tissues [10], LP may act differently after excision.

Implants injected as a liquid and then caused to gel *in situ* will need to be tested to determine when the desired final state has been achieved. Intra-operative functional tests, in which the patient phonates to test the repair, may be impossible due to the use of deep anesthesia. Thus, a laryngoscopic measurement instrument that can measure visco-elasticity of healthy, damaged and repaired vocal tissues over the relevant strains and strain rates would help quantify and guide phonosurgical procedures (Figure 1).

Prior *in vivo* instruments have been designed for static or very low frequency deformations of tissues [11,12]. This paper describes a novel instrument for measuring vocal tissue properties in the range of frequencies and deformations of normal phonation by applying tangential shear to the folds.

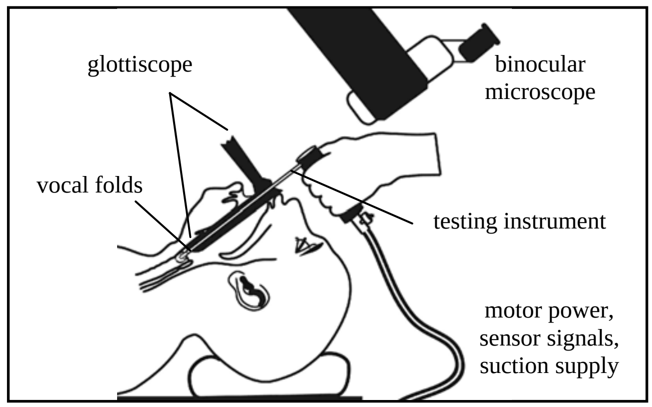

Figure 1: Intra-operative vocal fold testing through glottiscope under binocular microscope viewing.

METHODS

The specifications of a useful instrument are determined by the properties of the vocal tissues. It must generate motions up to ±0.5mm from below 100Hz to over 300Hz. Using a shear stiffness of <10mN/mm [8], and μ=1Pa·s and a tangential deformation over a 1mm^2 x 0.5mm thick columnar body of lamina propria, the net visco-elastic reaction force at 300Hz is about 7mN, putting a lower limit on the force sensor range. Tissue contact *in vitro* may use adhesives, but must be atraumatic for human use. Access to the vocal folds is through a glottiscope, a tube approximately 20cm long and 2cm in diameter, which provides line-of-sight access. The device must be long and narrow to pass through the tube without obstructing the surgeon's view.

This design (Figure 2) uses a 0.12" outer diameter steel tube for structural support, and an inner 0.083" tube driven coaxially by a Scotch yoke mechanism. A piezoelectric force transducer and a tip that enables suction attachment to the tissue is mounted at the distal end of the inner shaft. The moving mass is approximately 5g, requiring at least a 4.2W drive motor to achieve 300Hz. To reduce handle vibration, the yoke also drives a counter-mass 180º out of phase with the moving shaft. This doubles the total driven mass and the power required. The prototype uses a MicroMo2444-048-B 37W brushless DC servomotor and BLD 3502-SE2P PWM servo amplifier, sufficiently powerful to overcome friction and explore higher frequencies. The Scotch yoke creates sinusoidal motion, has a lower reflected inertia than a ballscrew (essential at high rates, in contrast with low rate devices [11]), and eliminates the resonant behavior of a voice-coil driven, flexure-mounted drive (e.g. [13]).

The position sensor is mounted coaxially with the moving shaft and has a 3mm range of motion (M-DVRT-3, MicroStrain, Inc., Williston, VT).

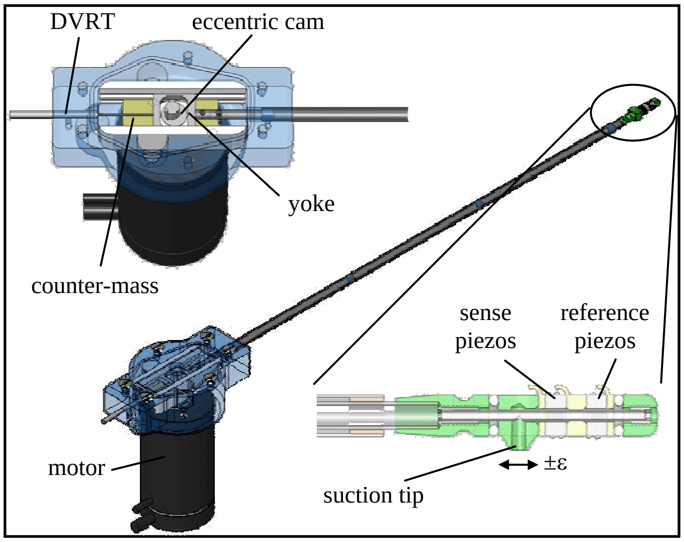

Figure 2: Vocal Cord Compliance Interrogator (VoCCI) & detail of drive & position sensing and force transducer

Mounting a commercial force sensor between the yoke and the moving shaft would increase the moving mass, obstruct viewing and result in the sensing both the small tissue force and the inertial load of the shaft. Figure 2 shows a collocated sensor which minimizes both problems. The suction tip is preloaded against a stack of piezoelectric polymer disks (mechanically in series, electrically in parallel) and slides freely with respect to the inner tubing. A matched static reference piezo-stack is similarly compressed, and its output is subtracted to remove pyroelectric signals and RF noise. Low sensor capacitance and large shunt resistors (~60pF and 50MΩ), which drain amplifier leakage currents, produce a high-pass characteristic with the -3dB characteristic frequency below 20Hz. As the electrical signal is generated by the sensor itself, we increase electrical safety by avoiding the voltage source that would be needed for strain gages.

The DVRT was calibrated by measuring output voltage and shaft position (using a digital multimeter and micrometer). The motor speed constant and linearity were measured by increasing the command voltage (Measurement Computing PC-CARD-DAS16/16AO) and measuring the output frequency with a digital oscilloscope (Techtronix TDS 2014).

Force sensor calibration was performed with the sensor stationary, subjected to sinusoidal loading using another tissue testing device [13]. Tests over the full frequency range and with a range of applied force amplitudes were used to determine the actual filter characteristic and the linearity of the sensor in the pass-band.

RESULTS

The position sensor calibration constant is 1.32V/mm, and the motor speed constant is 91Hz/V.

Error! Reference source not found. shows the magnitude of the ratio of the raw sensor output voltage fast Fourier transform to the input force FFT. The compensation piezo-stack signal was not subtracted in this result. The measured calibration constant is ~3mV/mN. Linearity is being determined.

An early proof-of-concept test (Figure 4) indicated that cyanoacrylate adhesives would remain attached under high frequency testing rather than tearing off the epithelium.

DISCUSSION & CONCLUSIONS

This prototype system demonstrates the basic capabilities necessary to measure the biomechanical properties of vocal folds over the frequency and strain range of interest. At least to the level of enabling the testing of tissue samples, it is suitable as a bench-top instrument. The speed, range of motion, power and force-measurement specifications all meet or exceed those necessary for our experiments. Surgeon feedback regarding the form factor of a full scale model has indicated a need to improve the form-factor of the device, as the structure housing the Scotch yoke is too large for human clinical work.

Force signal processing is currently under refinement, as is the implementation of the suction attachment method.

Future work will include *in vitro* and *in vivo* animal testing,

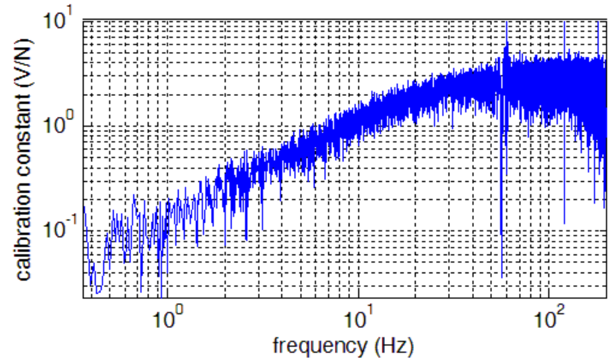

Figure 3: Uncompensated piezoelectric force sensor frequency response.

Figure 4: Proof-of-concept tests using adhesive contact system.

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