A Sensor-Augmented Saxophone Mouthpiece for Unveiling the Mechanics of Saxophone Tone Formation

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Abstract. This paper presents a sensor-augmented saxophone mouthpiece which promotes data collection from musicians. The collected data aims to unveil the mechanics of saxophone tone formation from the embouchure and air flow control—for which only limited knowledge exists due to its occlusion concealed by the players’ mouth. Ultimately, by grasping and modeling how musicians play, we aim to develop intelligent music tutoring systems. Towards this aim, we provide the first steps of a sensor-augmented mouthpiece from which we compute air pressure, air flow, and mouthpiece-reed tip opening indicators of a performance. Different strategies to capture these indicators have been studied under controlled lab conditions as a basis to develop a prototype mouthpiece which is evaluated by an expert saxophonist.

Keywords: Sensor technology, Saxophone, Tone formation, mouthpiece, embouchure, tutoring systems.

1 Introduction

The mechanics of the embouchure and air flow in relation to tone formation have long been discussed in the literature by renowned saxophonists and pedagogues. Of particular note are: the impact of the contact point and pressure of the lip in the reed which regulate the mouthpiece-reed tip opening; the air flow rate and direction; the tongue position inside the mouth cavity, and the vocal tract ‘tuning’ [8, 11]. Despite its invaluable contribution to the pedagogy of the saxophone, the lack of a systematic approach to these performance elements is evident. Not only do they mostly happen inside the mouth cavity, and thus are difficult to analyze with the naked eye, but also the methods used to frame these conjectures are often personal and insensitive to the anatomic diversity of the saxophonists’ orofacial complex.

¹ The embouchure is a common term used by saxophonists to denote the overall mechanics of the orofacial complex in combination with the saxophone mouthpiece.
More recently, *in vitro* experiments attempted to establish links between the aforementioned elements and the resulting tone quality in a systematic approach. Among these, we can highlight the study of pitch bend and glissando [6], vocal tract ‘tuning’ [10], air flow rate [9] and the mechanical response of saxophone reeds [5]. In contrast to empirical judgments by experienced musicians, these studies commonly used simulations of the saxophone performance setting (e.g., a mechanical vocal tract system [9]) or they forced the saxophonist to perform particular techniques for long periods of time [10, 4]. This may undermine the evaluation insight for real performance or pedagogic contexts.

Motivated by the need for robust indicators of saxophone performance, most notably those related to tone formation and quality resulting from the manipulation of the embouchure and air flow, we strive for an augmented mouthpiece which can reliably measure three performance indicators—mouthpiece-reed tip opening, air pressure, and air flow rate—using transparent and non-intrusive methods which do not undermine the performance. To this end, we provide the first steps towards a device that can be used by saxophonists outside of the lab to learn on a large scale basis how experienced saxophonists play and, ultimately, underpin intelligent music tutoring systems and augmented musical instruments with artistic impact.

The remainder of paper is structured as follows. Sec. 2 details the target attributes in this study as well as the motivation to pursue them. Sec. 3 describes the sensor technology, components, and methods used to augment a prototype saxophone mouthpiece. Sec. 4 details the prototype development and sensor integration. Sec. 5 reports the methods and results resulting from the assessment of our study. Sec. 6 presents conclusions and future work.

## 2 Saxophone Tone Formation: Towards Objective Quality Measures

From an early apprenticeship phase, pedagogic saxophone textbooks stress the importance of tone quality as the result of refined control over the embouchure and air flow [2, 3]. Typically, mastering the embouchure and air flow is defined as a combination of three actions. The first concerns the amount of the mouthpiece inserted in the oral cavity, which is generally one third of the bevel part of the mouthpiece from its tip. The second relates to the tip opening of the mouthpiece-reed system as a result of the pressure exerted in the reed by the lower lip. Finally, the third action is related to an optimal oral cavity muscle support to seal and focus the air flow ² [8]. From these observations, we identified three objective measures—tip opening, air pressure, and air flow rate—to be extracted from our proposed augmented mouthpiece.

(i.e., the saxophone tip, located at the thinner extreme of the conical saxophone structure).

² While these recommendations can be easily found in many pedagogic textbooks, we draw attention to the lack of a universal consensus on both the attributes of
The mouthpiece-reed interaction forms a system which acts as a self-sustained oscillator responsible for sound creation and propagation along the instrument body [9]. The pressure exerted by the player’s lower jaw (including lip and dentition) on the reed manipulates the degree to which the reed can vibrate as well as the opening of the mouthpiece-reed tip system (see Fig. 1), and thus the choice of this indicator is evident due to its strong implications in tone formation and quality.

![Fig. 1. Representation of the mouthpiece-reed and player’s mouth interaction.](image)

To excite the mouthpiece-reed system, a saxophonist must increase the air pressure inside his/her mouth above the atmospheric level, which in turn will generate an airflow towards the instrument. As to generate the inflow, the lips will force the reed to close to increase the pressure. As the air travels through the mouthpiece, the friction between its particles and the walls of the instrument will cause its pressure to drop. By continuously providing an airflow which is higher than atmosphere pressure, the saxophonist perpetuates this process, which will allow a sound wave to be formed. The choice of an air pressure indicator aims to provide a metric which can be used to understand the links between air pressure and saxophone tone attributes such as loudness and timbre (e.g., brightness or warmth).

The air pressure inside the mouthpiece creates an air flow capable of propagating the oscillatory movement (i.e., sound waves) resulting from the reed excitation. For this reason, the volume (air flow rate) exhaled along the mouth and in the mouthpiece together with a refined control over the embouchure is critical in the tone formation, further characterizing the practice of saxophone playing.

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an ‘optimal’ tone quality—mainly due to its subjective nature—or even objective causal links between embouchure, air flow and tone quality attributes.
3 Materials and Methods

3.1 Tip Opening

To measure the tip opening of the mouthpiece-reed system as a result of the pressure exerted by the saxophonist on the reed, three approaches were considered, each adopting a different sensor technology (see Fig. 2): 1) a Force-Sensing Resistor (FSR), 2) a piezo-resistive bend sensor, and 3) a Light Dependent Resistor (LDR) linked to a Light-Emitting Diode (LED). The motivation behind the adoption of each sensor along with its technical description is detailed next.

Force-Sensing Resistor Following [6], an FSR sensor attached to the reed was used to measure the tip opening from the amount of pressure the player exerts on the reed. The chosen model was the Interlink Electronics’ FSR 400, due to its reduced contact area (a square of 5mm side length), thickness (0.35mm), and response time (fewer than 3 microseconds). These characteristics makes it feasible to attach to the saxophone reed, with minimal impact in the performance as well as offering an adequate response times to capture the nuances from a performance.

Piezo-resistive bend sensor Based on the assumption that the reed has to bend in order to close the tip opening, an alternative piezo-resistive bend sensor attached to the reed was used to measure the tip opening from the sensor bending resistance as a result of the player’s pressure on the reed. The appropriate contact area and low thickness (0.43mm) of the linear Flex Sensor from Spectra
Light Dependent Resistor A third alternative to measure the tip opening adopts an LDR sensor linked to an LED inside the mouthpiece. This highly exploitative approach enhances the non-intrusiveness of the augmented mouthpiece design as it would not require any component in contact with the reed. The underlying approach was to light the mouthpiece chamber, in particular from the middle regions to the tip opening, with an LED. The LDR sensor would then measure the intensity of the light reflected in this zone. Our hypothesis was that the tip opening would result in different light intensity values. The lower the light intensity inside the mouthpiece, the larger the tip opening, as the light would dissipate to the oral cavity of the player. We used a GL5528 LDR together with a 1.8mm diameter white LED. The choice of this LDR sensor was due to its small dimension and responsiveness to the visible spectrum of light.

3.2 Air Pressure
To measure the air pressure inside the mouthpiece, we used the MPX2100DP, a differential sensor from the series of silicone piezo-resistive sensors, ranging from 0 to 100kPa, thus comprising the typical pressure values inside the mouthpiece between 2 – 5kPa [10, 9, 5, 7]. Following the design of a Pitot tube in aviation, the sensor was connected to a polyurethane tube placed at 60° from the upper part of the mouthpiece. To minimize the inertia and avoid a significant dissipation of energy across the tube, it was used a short diameter (∼4mm) and low elasticity polyurethane tube.

3.3 Air Flow Rate
The industrial standard to measure air flow rate typically uses high-cost ultrasonic sensors or two pressure sensors placed on either side of a constriction section of a pipe (e.g., a Venturi tube). Due to the lack of such a constriction inside the mouthpiece, the temperature of the player’s exhaled air (above atmosphere) as a metric of air flow rate, given the high correlation between the two indicators [1] was measured. To this end, an NTC thermistor inside the mouthpiece, whose resistance decreases accordingly to the amount of exhaled (warm) air from the player, was used. While a small thermistor of approximately 5.5mm can provide a rough measure of the air flow through the mouthpiece, it also has two important drawbacks for our augmented mouthpiece design. The first is a slow cooling time of about 20 seconds and, the second, is the continued resistance decrease while exposed to a constant flow rate due to the accumulated warmth inside the mouthpiece. In light of these limitations, we decided to pursue this design and adopt a 6.8kΩ NTC thermistor to measure the air flow rate inside the mouthpiece due to its small size and preferred temperature of about 25°C. Informal experiments using this model inside a mouthpiece showed an expressive resistance variance between 5kΩ and 8kΩ.
4 Prototype Development and Interface

4.1 Prototype Development

A 3D printed prototype mouthpiece including all sensor technology presented in Sec. 3 was created to allow a precise control over the replication of the model under consideration – an important factor for an unbiased evaluation. For this initial prototype, we used polylactic acid (PLA) to print a mouthpiece based on a Yamaha mouthpiece model.  

![Fig. 3. Printed sensor-augmented saxophone mouthpiece prototype.](image)

Fig. 3 presents the printed mouthpiece mounted with the sensor technology. The mouthpiece design includes two orifices on to insert the pressure sensors polyurethane tube and the thermistor on the top and lateral side of the mouthpiece, respectively. The location of both orifices was chosen with respect to the ligature placement (i.e., metal device which holds the reed onto the mouthpiece in single-reed instruments). PLA-adherent epoxy-catalyst Araldite Rapid glue was used to attach the tube and thermistor to the printed mouthpiece, guaranteeing a tight sealing of the mouthpiece orifices.

4.2 Signals Post-Processing and Interface

An interface in LabVIEW was created to visualize the temporal evolution of each of the three indicators detailed in Sec. 3, as it is shown in Fig. 4. The performer started by slightly pressing the reed without producing any air flow, to verify the correct position of his lip regarding the tip opening sensor. After a short pause, the note C5 was played. In order to counteract the low cooling time of the temperature sensor, which misrepresents the respective air flow level, the ‘Tare Air Flow’ button was pressed shortly after the note was played.

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3 The printed 3D (CAD) model can be found online at: [http://www.thingiverse.com/thing:14495](http://www.thingiverse.com/thing:14495), last accessed on 17 February, 2017.
Fig. 4. Labview interface displaying the air pressure, air flow and tip opening indicators of the following sequence of events: employing pressure on the reed, followed by an articulated note (C5).

The indicators are reported in the interface via an Arduino microcontroller to which the sensor technology is connected. Additionally, we used this software package to smooth the collected signals using median filters with latencies smaller than 200 milliseconds. Finally, a strategy to tare the temperature signal was created, so that the cooling time of the thermistor could be canceled if the corresponding button was pressed.

5 Preliminary Evaluation

A preliminary evaluation of the prototype was conducted. It aimed to assess the efficacy of the proposed methods in capturing the performance indicators under consideration as well as the readiness and robustness level of the prototype. To this end, two methodological approaches were adopted. The first, compared the performance of the three sensors – FSR, piezo-resistive bend sensor, and LDR – in capturing the tip opening. Drawing on the conclusions of the previous test, we then developed the prototype shown in Sec. 4. The second, used this prototype to conduct informal sessions with a highly experienced saxophonist with an international musical career of more than 40 years, to subjectively assess the quality
of the indicators and readiness level of the prototype. The subjective tests aimed at providing a set of recommendations on how to proceed with the research and allow for enhanced augmented mouthpieces which can promote smart tutoring tools and an active participation in professional music performance settings.

5.1 Tip Opening Sensors Evaluation

Our experimental setting to test the sensors under study to measure the tip opening consisted of a clamp exerting controlled forces on a mouthpiece-reed system. For all force levels exerted by the clamp on the reed, we annotated the sensors’ output and, with the assistance of a pachymeter, measured the tip opening. To account for the variability in the pressure points of different performers, the task was repeated at three different positions on the tip of the reed: left point, middle point, and right point.

To evaluate the results of the test, we investigated whether the sensor response (voltage) varied linearly with the tip opening of the mouthpiece-reed system. Fig. 5 shows the results of the test for the FSR sensor for the three reed-pressure points by comparing the tip opening vs. the voltage output by the sensor. A correlation coefficient of $R^2 = 0.973$ for an average of the three pressure point positions denoted a consistent relation between the variables and thus validated the relevance of this sensor in capturing the tip opening.

The results for the piezo-resistive bend sensor and LDR were highly erratic. First, the piezo-resistive bend sensor showed no variation in the output voltage
for any force employed in the reed. This means that the degree of bending of the reed was not sufficient to generate a visible response from the bending sensor. The lack of sensibility of this sensor could not be compensated for by any amplification, which determined its exclusion for the task. Second, the output voltage of the LDR system was highly inconsistent over time for a given static force, and thus we could not guarantee a causal linkage between the variables. A plausible explanation for the constant changes in the sensor output is the occurrence of LED light reflections inside the mouthpiece. These reflections may occur on the interior walls and change with respect to the oscillatory movements of the reed. As such, the LDR sensor output is more likely related to the geometry of the mouthpiece and the reed oscillatory movements rather than the tip opening and the impact it can have on the light intensity inside the mouthpiece. In light of these results, the FSR was integrated in the mouthpiece prototype shown in Fig. 3.

5.2 Prototype Subjective Evaluation

The subjective evaluation consisted of a series of tests with an expert saxophonist to understand the readiness level of the mouthpiece for a concert setting. To this end, the prototype was tested at different stages of development and noted all observations that were made by the expert. The results of these interactions were relevant to improve our tool towards a functioning prototype which can be then used to collect performance indicators from a large number of expert saxophonists.

While the overall design of the mouthpiece (without sensors) seemed to convey ‘optimal’ results for performance, once the sensors were mounted, the saxophonist reported difficulties, notably when playing in the low register of the instrument. He emphasized the need for more air, which we believe is due to the dissipation of air to the polyurethane tube (responsible for measuring the air pressure). A possible solution to this problem could involve the adoption of the air flow indicator as a measure of the energy only.

When the saxophonist was performing with the interface in LabVIEW, repeated comments demonstrated the stability of the metrics (i.e., when a stable embouchure and air flow was performed the indicators were static). Additionally, the saxophonist tested the indicators separately and made several remarks concerning unexpected behavior of their interaction. For example, when applying different degrees of pressure to the reed (and thus changes to the tip opening) while attempting to maintain the same sound volume, the air pressure and air flow rate indicators were expressively changing. Thinking the air flow was being kept the same throughout the experiment, this results contradicted his expectations. Furthermore, they suggest an integrated, yet not obvious, interaction between all these indicators.
6 Conclusions and Future Work

We have presented the first steps towards a sensor-augmented mouthpiece that unveils parameters related to tone quality formation, which are concealed by the player’s mouth. A reliable strategy to compute the tip opening of the mouthpiece-reed system, air pressure, and air flow rate indicators were provided. A lab experiment validated the FSR sensor as a sensible choice for capturing the tip opening of the mouthpiece-reed system. Informal subjective tests with an expert saxophonist validated most of the design decisions of our sensor-augmented mouthpiece prototype, yet drew our attention to the significant dissipation of air energy in the piezo-resistive air pressure sensor, thus enforcing the need for a non-intrusive design.

Valuable recommendations resulting from this study will guide us in future work towards an enhanced prototype which can then be applied to collect more data from experience performers. The first and foremost result from our subjective experiment was the disconnect felt by the expert saxophonist between expected behavior of the indicators and the objective metrics provided by the sensor technology. This disconnection reinforces the importance of pursuing this research line towards a better understanding of a phenomenon which has been for long out of reach due to the lack of technological solutions. Furthermore, the importance of a transparent design in sensor-augmented mouthpieces was evident in our subjective tests. Towards this aim, we will strive for a solution which could use the performers’ own mouthpiece. However, while this scenario is difficult to reach with existing sensor technology, we recommend the minimal interference to the mouthpiece, most notably to avoid the dissipation of the air from the mouthpiece chamber and the adoption of wireless technology to minimize constraints imposed during experimental performance settings. On a lower and more technical level, although our evaluation discouraged the use of an LDR sensor for capturing the tip opening of the mouthpiece-reed system, we believe that a careful study of the placement of the LED and the LDR sensor within the mouthpiece chamber could lead to a robust indicator for the tip opening and simultaneously promote a more transparent design solution than the currently proposed FSR sensor.

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References