Variability in expiratory trajectory angles during consonant production by one human subject and from a physical mouth model: Application to respiratory droplet emission

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Abstract
The COVID-19 pandemic has highlighted the need to improve understanding of droplet transport during expiratory emissions. While historical emphasis has been placed on violent events such as coughing and sneezing, the recognition of asymptomatic and presymptomatic spread has identified the need to consider other modalities, such as speaking. Accurate prediction of infection risk produced by speaking requires knowledge of both the droplet size distributions that are produced, as well as the expiratory flow fields that transport the droplets into the surroundings. This work demonstrates that the expiratory flow field produced by consonant productions is highly unsteady, exhibiting extremely broad inter- and intra-consonant variability, with mean ejection angles varying from $\pm 30^\circ$ to $-30^\circ$. Furthermore, implementation of a physical mouth model to quantify the expiratory flow fields for fricative pronunciation of [f] and [θ] demonstrates that flow velocities at the lips are higher than previously predicted, reaching 20–30 m/s, and that the resultant trajectories are unstable. Because both large and small droplet transport are directly influenced by the magnitude and trajectory of the expired air stream, these findings indicate that prior investigations of the flow dynamics during speech have largely underestimated the fluid penetration distances that can be achieved for particular consonant utterances.

KEYWORDS
consonant expiration, COVID-19, exhaled airflow, speech

1 | INTRODUCTION

The ongoing COVID-19 pandemic has emphasized the role of expiratory droplets in transmitting infectious diseases.\(^1,2\) Produced by coughing, sneezing, singing, speaking, and breathing, the focus has historically been placed on exploring violent expiratory events that are believed to be of greatest concern, such as coughing and sneezing.\(^3\) However, speaking and breathing are also important pathways for airborne transport of pathogens as they occur much more frequently and do not usually involve protective behaviors (eg, covering your mouth). This can lead to increased concentrations within indoor environments over prolonged periods of time.\(^4,5\) While coughing and sneezing generate on the order of 5000–10 000 droplets/event,\(^6,7\) sustained phonation has been shown to produce $\approx 10$–40 droplets/s.\(^8\) Consequently, speaking for as little as 2–3 min can generate as many droplets as a cough/sneeze. For this reason, quantifying the flow dynamics and droplet transport produced during speech is of utmost importance.
Voiced speech is produced when a critical air pressure is achieved in the lungs, which pushes the adducted vocal folds apart. The resultant fluid-structure interaction produces self-sustained oscillations, characterized by a periodic opening and closing of the glottis, that is, the gap between the vocal folds. The VF motion produces an unsteady flow and pressure field, which forms the raw acoustic source of sound production. The resulting resonances of the vocal tract, soft palate, and oral cavity produce intelligible sound. Articulation of the tongue, lips, and soft palate is used to generate different resonances, and hence, sounds. Unvoiced speech sounds, produced without the vocal folds oscillating, can be classified as: (1) fricatives, which are produced by turbulent air being forced through a narrow constriction (e.g., phonemes [s], and [ʃ]), (2) plosives, or stops, which arise from the sudden release of pressure at an occlusion in the vocal tract (e.g., phonemes [p], and [ɡ]), (3) nasals, which are produced as air is redirected through the nasal cavity (e.g., phonemes [m], and [n]), (4) semivowels, or glides, which include slight variations in vowel production (e.g., phonemes /w/, and /y/), (4) affricates, which are stop-fricative pairs (e.g., phonemes /ʃ/, and /ʒ/), and finally (5) the aspirant /h/, which is a phoneme produced by turbulent air passing through the glottis. For all of these scenarios, the expulsion of airflow is the common connector. However, the time-varying change in vocal tract shape during speech produces a highly transitory and irregular flow pattern exiting the mouth. Surprisingly, investigations aimed at quantifying these flow patterns with application to transmitting the glottis. For all of these scenarios, the expulsion of airflow is the common connector. However, the time-varying change in vocal tract shape during speech produces a highly transitory and irregular flow pattern exiting the mouth. Surprisingly, investigations aimed at quantifying these flow patterns with application to transmitting infectious diseases are in short order, but are greatly needed.

To accurately predict infection risk arising from an expiratory emission source, two fundamental characteristics of the source must be quantified: the emission rate (quantity per time) and size distribution of the droplets being emitted, and the expiratory flow field that transports the droplets into the ambient surroundings. There is a significant body of work that has quantified droplet emissions during counting and sustained phonation. Additional work related to the COVID-19 pandemic has been performed more recently. It is well understood that droplet emissions during speech span the range of ~0.1–200 μm, with a mean size of ~1–2 μm. More recently, droplet size distributions and production rates have been correlated with specific phonemes, which has provided important insight into transient behaviors in speech; information that is needed to develop accurate models of disease transmission from speaking. Investigating droplet dynamics as a function of the most fundamental building blocks of speech can also identify the impact of linguistic differences on transmission rates. The importance of speech loudness on droplet production has also been highlighted, demonstrating that increased vocal intensity can drastically increase droplet production rates.

Recently, a review of techniques for quantifying exhaled airflows has highlighted the surprisingly small number of existing articles focused on quantifying the expiratory fluid dynamics of speech. Efforts that connect flow behavior with specific speech patterns/utterances are even more limited. Early work focused on quantifying general flow behaviors based on mouth area and expelled flow rate for running speech as well as specific utterances. Similar work has measured velocities at the exit of the mouth when counting, reporting a maximum value of 4.6 and 3.6 m/s for male and female volunteers, respectively, when speaking loudly. The time-averaged velocity across all participants was reported as 3.9 m/s. Unfortunately, the time history of the flow field was only estimated at the mouth, which does not elucidate the spatial evolution of the flow during speech, and more importantly, the penetration of the expired flow structures into the surrounding environment.

More recently, this penetration distance has been explored for specific utterances using particle image velocimetry. It was found that plosives achieved the highest penetration distance, followed by both fricatives and nasal sounds. Similarly, correlation image velocimetry has been utilized to quantify the flow field at the exit of the mouth arising from a variety of phrases. Both the trajectory of the expelled air and the structure of the flow field were found to vary as a function of phrase. For example, plosive production was characterized by the formation of individual vortices. Interestingly, while both of these recent studies noted significant unsteadiness in the expiratory flow field, it was not specifically investigated. Variations in the trajectory angle of the expiratory flow will directly influence both large and small droplet transport, and the associated infection risk, and the prescription of a safe distance. The identification of varying trajectory angles would also have significant implications on infectious modeling approaches, as most models assume that expiratory flow is emitted parallel to the ground. While early work has provided some insight into expiratory trajectories during speech, such as identifying spreading angles of the speech plume that were as high as 60°, most prior work was performed using time-averaged measures, which obscure the dynamics of the specific utterances, or were based on investigating only a single utterance. Of note is recent work that has highlighted the surprisingly small number of existing articles focused on quantifying the expiratory fluid dynamics of speech. Efforts that connect flow behavior with specific speech patterns/utterances are even more limited. Early work focused on quantifying general flow behaviors based on mouth area and expelled flow rate for running speech as well as specific utterances. Similar work has measured velocities at the exit of the mouth when counting, reporting a maximum value of 4.6 and 3.6 m/s for male and female volunteers, respectively, when speaking loudly. The time-averaged velocity across all participants was reported as 3.9 m/s. Unfortunately, the time history of the flow field was only estimated at the mouth, which does not elucidate the spatial evolution of the flow during speech, and more importantly, the penetration of the expired flow structures into the surrounding environment.

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showed ad hoc prescriptions of varying trajectory angles greater than 0° greatly increased droplet transport distances.31

Consequently, there remains a need to identify how expired velocity patterns of speech can be expected to vary for different intonations. Consonant production is of greatest interest because expired velocities at the mouth are usually the highest. This work aims to determine if the expired flow field, and the resultant trajectories, change across a wide variety of consonant sound productions. The results highlight how different enunciations and small variations in oral posturing can lead to drastic differences in the expiratory flow behavior. Although results are only presented for one subject, due to institutional restrictions during the pandemic, this limited investigation still provides a useful and important first look at the broad variability and unsteadiness in expiratory flows during speech. The experimental facilities and methods are introduced in Section 2, the results are presented in Section 3 and discussed in Section 4, while Section 5 is left for the conclusions.

2 | METHODS

Two measurement modalities were implemented for the consonant production investigations. First, to investigate inter-consonant variability, experiments were performed with one human subject. The human investigations were approved by the Clarkson University Institutional Review Board. Second, a benchtop physical model of fricative consonant production was utilized to explore intra-consonant variability for both [f] and [θ] phones.

2.1 | Human consonant investigations

Due to the health concerns associated with the COVID-19 pandemic, one human subject was recruited to produce repeated [a]-consonant-[a] utterances in order to measure the expiratory flow trajectory as a function of the consonant. A schematic of the facility in which the measurements were acquired is presented in Figure 1. All measurements were performed by having the subject speak into an enclosed 121.9 cm wide, by 243.8 cm long, by 121.9 cm high box. A cut-out resembling the projected frontal area of a face was placed into an end face of the rectangular box, centered in both width and height, through which the subject spoke. One side of the box included a 61.0 cm high by 182.9 cm wide acrylic window for optical access. An IDT MotionPro camera with a 50 mm Nikkon lens was placed outside the box, looking through the window. The 8-bit camera had a spatial resolution of 1280 x 1024 pixels and acquired images at 30 fps. A planar light sheet was created by placing a 400 mW, 532 nm Aixiz laser inside the box. The laser beam first passed through a beam splitter, with one portion of the beam exiting vertically, and the other continuing horizontally. The vertical beam passed through a planoconvex −10° divergent lens. The horizontal beam also passed through a planoconcave −10° divergent lens before being reflected by a planoconvex mirror (see Figure 1). In this manner the beam optics produced two overlapping laser sheets in the midsagittal plane of the subject. The two overlapping sheets were necessary to generate sufficient beam spreading to span the desired field of view. Care was taken to ensure both beams were precisely aligned. The optics were aligned such that the left most edge of the laser sheet was positioned ≈5 cm from the mouth exit. The illuminated field of view captured by the camera was ≈43.8 cm long by ≈35.1 cm high.

To visualize the intonations, a teaspoonful of all purpose flour was placed on the middle to base of the tongue of the subject to minimize disruptions due to the flour coming into contact with the upper palate or teeth during the pronunciations. During voice production, the expiration of flour from the mouth into the laser sheet produced a high-contrast field that was visualized and captured by the camera. A Blue Microphones—Snowball iCE USB microphone simultaneously recorded the audio using a custom LabView program that synchronized the sound and video acquisition. Each utterance was produced using an [a]-consonant-[a] intonation at comfortable loudness. Due to the open vowel tract configuration (and subsequent low-airflow velocity) little to no flour was expelled during the initial vowel production of [a]. Conversely, during the consonant production, the flour could be observed. Five instances were captured for each utterance. Care was taken to ensure that each utterance and trial was produced at the same constant loudness (measured to be 70–75 dB), using the same intonation patterns that were representative of comfortable speaking.

Repeatability of the approach during post-processing was challenging due to the uncontrollable amount of flour that was ejected during the utterances. This resulted in the algorithm that was employed for computing the trajectory angle (see Section 3) being unable to calculate the trajectory angle in some of the acquisitions. This arose from either: (1) excessive flour expulsion, which caused excessive laser light reflection, thereby saturating the image intensity, or (2) insufficient flour expulsion, which resulted in low light contrast, making it difficult for the algorithm to distinguish the flow patterns from background noise. Nevertheless, qualitative consistency of the flow patterns was observed across the separate acquisitions at each
utterance. The number of acquisitions for which the image intensity was sufficient to compute the expiration angle varied with each utterance. If the algorithm was not able to accurately compute a trajectory angle, the angle was computed manually by visual observation of the expired flour. The mean and standard deviation of the trajectory angle for each utterance were then computed.

It should be noted that the presence of flour on the tongue may influence the expired flow. This is most likely to occur during the production of stop consonants where the tongue comes into contact with the upper palate (e.g., [t], [k], and [g]). For fricative pronunciations produced by a small constriction at the mouth (e.g., [f], [θ], etc.) the presence of flour in the mouth is unlikely to have a significant influence because the dynamics of flow passing through a small area-ratio orifice, relative to the upstream area, are governed by the shape of the orifice and are largely independent of the upstream cross-sectional area.\(^{32}\)

### 2.2 Physical model investigations

Benchtop physical models of fricative consonant production were fabricated to investigate the sensitivity of the expired flow field to small variations in the mouth geometry, and loudness of speech; perturbations that are prohibitively difficult to assess with in vivo investigations due to the confounding variables that will inherently exist across subjects and that will influence the outcomes (e.g., different mouth geometries, prosody, linguistic subtleties, hydration, etc.) To ensure physiological relevance, the geometry was carefully prescribed based on magnetic resonance imaging (MRI) of human oral geometry during intonation of the consonants of interest, and the flow conditions were matched to those produced during normal speech production.

The experimental flow facility for the benchtop, physical experiments, was constructed to be twice life-size to improve the spatial resolution of the velocity field measurements. Dynamic similarity\(^{33}\) ensures that if the appropriate nondimensional parameters that govern the flow are matched, the dynamics between the life-size and scaled-up model will be identical. To this end, the flow parameters were scaled according to Reynolds and Euler number. Reynolds number, which is the ratio of inertial to viscous forces, is given as:

$$Re = \frac{\rho V L}{\mu},$$

where \(\rho\) is the fluid density, \(V\) is the flow velocity, \(L\) is the length scale, and \(\mu\) is the fluid viscosity. Expressing the length scale using a hydraulic diameter, the Reynolds number can be expressed in terms of the flow rate as:

$$Re = \frac{4\rho Q}{(\mu s)},$$

where \(Q\) is the volumetric flow rate, and \(s\) is the perimeter of the tooth gap area through which the flow exits. The Euler number expresses the ratio of pressure to inertial forces and is expressed as:

$$Eu = \frac{p}{\rho V^2},$$

where \(p\) is the pressure. Equating the life-size and scaled model values for the Reynolds and Euler numbers reveals that the scaled-up model velocity scales as \(1/(\text{model scale})\) while the pressure scales as \(1/(\text{model scale})^3\), and the flow rate as \(2 \times \text{model scale}\). For simplicity, all dimensional values reported herein are reported as life-size, unless noted otherwise.

Figure 2 is a schematic of the physical model flow facility. Steady flow was supplied from compressed air (\(=550\) kPa) before being regulated. An inline flowmeter (Dwyer RMC-103) recorded the time-averaged flow rate. The flow then entered a custom-fabricated olive oil atomizer that generated \(\approx 20(1\ \mu m)\) particles for seeding the particle image velocimetry (PIV) measurements. A parallel flow with a manual control valve allowed the seeding density to be controlled by adjusting the ratio of flow through the parallel channels. The flow then entered a 283.2 cm\(^3\) plenum chamber where an inclined manometer (Dwyer 250-AF) recorded the subglottal pressure. Finally, it entered the vocal tract geometry.

Two mouth geometries were investigated based on generalized, static representations of the midsagittal geometry during pronunciation of [f] and [θ], visualized with MRI of the vocal tract from the USC-TIMIT database repository.\(^{34}\) The geometries are shown in Figure 3. These particular utterances were investigated because fricative consonants are expected to produce some of the highest expiratory velocities, thereby establishing an upper bound on the anticipated magnitudes during speech. In addition, note the flatter tongue orientation for [θ] and the modified exit passage created by the lip and tongue versus both lips for [f]. For both models, the upper palate geometry is identical. Consequently, comparison between the two models will provide insight into how slight variations in tongue position can influence the expiratory flow behavior. The airway geometry was then extruded in the medial-lateral direction 2.54 cm...
(life-size) to produce the vocal tract. The vocal tract geometries were sandwiched between two flat cover plates that formed the lateral boundaries of the vocal tract. The plates were sized such that they extended only up to the minimal gap of the lip-tongue/lip-lip geometry. In this manner, the lips protruded out, and from this point on, the flow was free to expand laterally. The left side of the field of view shown in Figure 2 coincides with the edge of the cover plate. All geometries and parts were machined on a computer numerically controlled mill. Mounting pins were implemented into the construction to ensure precise and accurate geometrical alignment.

A constriction was produced by inserting a tooth model that could be precisely adjusted in the vertical direction, which controlled the tooth gap area. The tooth gap height was prescribed as the minimum wall-normal distance, $h$, between the tooth and the tongue/lip (see the inset of Figure 3). Three tooth geometries were investigated (see Figure 3A–C, where the flow direction is out-of-the-page): (A) a uniform two-dimensional (2D) tooth gap, (B) a three-dimensional (3D) tooth gap, and (C) a 3D tooth gap with an additional offset distance. The 3D tooth profile was created by transcribing an arc of radius 6.9 cm on the tooth such that the secant connecting the two points was the width of the vocal tract, thereby mimicking, to the first order, the elliptical orifice area at the mouth exit that is produced during human fricative pronunciation.\textsuperscript{35} The different choice of tooth geometries enables comparison between 2D and 3D approaches for solving the flow behavior (as 2D assumptions are often utilized in computational fluid dynamics investigations to reduce computational cost). Additionally, varying the tooth gap height identifies the sensitivity of the expired flow field to small changes in tooth position relative to the lips/tongue during fricative consonant production. Note that for the 3D tooth geometries, the tooth profile is transcribed in the vertical direction, while the lower palate is angled at 46° for the \textit{[f]} geometry, and 50° for the \textit{[θ]} geometry. Consequently, when projecting the 3D tooth gap area in the streamwise direction of the flow, which is assumed to be parallel to the lower palate, a cross-sectional area of 0.15 cm$^2$ is produced for \textit{[f]}, while \textit{[θ]} produces a cross-sectional area of 0.14 cm$^2$. For the 3D tooth geometry with an additional offset, the offset was adjusted so that the projected cross-sectional area in the flow direction was 0.30 cm$^2$ for both consonant geometries. This increased area is indicative of an aspirated consonant sound. These values were chosen based on physiological measurements of the constriction cross-sectional areas for fricative consonant pronunciations.\textsuperscript{35}

The midsaggital flow field was acquired at the exit of the mouth model using a LaVision Flowmaster PIV system with DaVis 10.0 software. A Litron NanoL laser (50 mJ/pulse) was used to produce a \approx 1 mm thick light sheet. Velocity fields were acquired with a sCMOS camera at 25 Hz with a spatial resolution of 2560 \times 2160 pixels. The scaled-up model field of view measured \approx 80 mm \times 68 mm (40 mm \times 34 mm life-size). The velocity fields were interrogated using a recursive 64 \times 64 pixels and 32 \times 32 pixels interrogation window with 50% overlap, resulting in a scaled-up model spatial resolution of 0.5 mm (0.25 mm life-size). For each flow scenario of interest 900 image pairs were acquired. This resulted in the data being acquired over 36 s in the twice scaled model.

3 | RESULTS

3.1 | Inter-consonant variability

Nine different fricative and plosive consonants were investigated in vivo by enunciating [a]-consonant-[a], as shown in Table 1. Examples of the specific consonant sounds that were produced are
indicated by the bolded letters in the accompanying words shown in Table 1. The angle of the expired trajectories was then directly measured from the video acquisitions using the frame image that corresponded to the initiation of the consonant sound, computed using a custom Matlab script that determined the trajectory of the expired cloud. Figure 4A shows an example of this approach with a zoomed-in video image for the utterance \[\text{[a]}\], with (B) presenting the line fit to the cloud, from which the trajectory angle at the mouth exit is calculated.

To compute the trajectory angle, a threshold value was first applied to the video image to create a binary image. Figure 4B shows a binary representation of the video image from Figure 4A over the first 200 columns of data. The threshold value varied with each utterance due to changes in the lighting conditions caused by the amount of flour that was expelled. The threshold value was individually chosen for each utterance to ensure the structure of the expelled cloud was visible, and that no trajectory information was lost. Each column of pixels in the image was then scanned to find the longest consecutive sequence of rows that were greater than, or equal to, the prescribed threshold value, and the average position of these rows was then calculated. In this manner, the center of the emitted cloud was determined as a function of distance from the mouth for the first 200 columns of data, which corresponded to a length of 6.8 cm. This length was constrained to minimize bias in the flow velocity due to gravitational effects that caused the larger flour particles to settle.

For each utterance, the sensitivity of the computed trajectory angle varied by \(\pm 3^\circ\) over a reasonable span of threshold values (ie, threshold values that were too low introduced obvious background noise, while threshold values that were too high clearly removed data from the expired cloud).

As previously discussed, for instances where insufficient image contrast prevented the algorithm from providing a reasonable calculation, the angle was computed by manually measuring the trajectory angle from two points in the image. The first point was selected on the left boundary of the image (where the flour was initially emitted from the participant) in the middle of the cluster of ejected flour particles. Similarly, the second point was selected at a distance of \(\approx 200\) pixels downstream, again, choosing the middle of the cluster of flour particles. The slope of the line was then computed from these two points.

The sedimentation velocity can be quantified by assuming Stokes flow, such that

\[
V_{\text{sed}} = \frac{g(\rho_p - \rho_f)D^2}{18\mu},
\]

where \(g\) is gravity, \(\rho_p\) and \(\rho_f\) are the particle and air density, respectively, \(D\) is the average diameter of a flour particle, and \(\mu\) is the dynamic viscosity of the air. The density of all purpose flour is \(\approx 525\) kg/m\(^3\), with diameters ranging between \(50\) and \(300\) \(\mu\)m.\(^{36,37}\) In air (\(\rho_f = 1.2\) kg/m\(^3\)) and \(\mu = 1.8 \times 10^{-5}\) kg/(m/s) the sedimentation velocity of the flour particles can, therefore, be expected to be \(V_{\text{sed}} = 0.04 - 1.4\) m/s. For expiratory velocities in the range of 15–30 m/s, as computed in Section 3.2.1, the velocity bias will be, at most, 10% of the freestream velocity at the mouth.

All five expiration for each of the consonants, and the computed trajectories, are shown in Figures 5 and 6. The resultant angle of

| Voiceless fricatives | Voiceless stops | Voiced stop | Aspirant |
|----------------------|----------------|-------------|-----------|
| [afa]                | [apa]          | [aga]       | [aha]     |
| [afa]\^a\)           | Puff           | [aga]       | High      |
| [afa]                | With           | [aka]       | Cat       |
| [asa]                | Say            |             |           |
| [a \ a]              | Show           |             |           |

FIGURE 4 (A) The expired flow trajectory at the start of the consonant pronunciation for the utterance \[\text{[a]}\]. (B) The binary image produced by thresholding the image intensity, and the resulting linear fit (dashed line) from which the trajectory angle at the mouth exit is computed.
expiration is denoted in each image by a red line, with solid lines indicating trajectories computed by the custom code, while dashed lines indicate the trajectory angles that were computed manually. The mean trajectory angles for all of the [a] – consonant – [a] utterances are presented graphically in Figure 7, with the standard deviation of the computed angles reported in parentheses. The number of instances for which the trajectory angle was computed manually is also reported for each consonant as $N_{\text{man}}$.

For the consonant utterances the mean trajectory (see Figure 7) was found to vary over an extremely broad angle, spanning from $+27.2^\circ$ to $-31.5^\circ$. This is similar to the previously reported range of angles found for averaged pronunciations of the word “dul”. However, the specific method used to determine the upper and lower limits of the velocity trajectory in this prior work was not clearly stated, thereby preventing a closer comparison.

There do not appear to be any clear trends in the trajectory angle as a function of consonant type. The mean expiratory angle for voiceless fricatives span from $+27.2^\circ$ to $-25.6^\circ$, while stops (both voiced and voiceless) vary from $-2.3^\circ$ to $-31.5^\circ$. The average angle across all utterances has a slightly downward trajectory of $-9.4^\circ$. A significant amount of variability is observed in the trajectories, as evidenced by the standard deviations and the individual trajectories presented in Figures 5 and 6. Again, it is emphasized that the results presented herein are for a single speaker. Wide variability in the trajectory angle as a function of speaker is also expected, as Section 4 will show how small variations in oral posturing influences the expired flow field.

It is interesting to note that the progression of the voiceless stops, [apa], [ata], and [aka], experience progressively more negative trajectories. This likely arises from the location of the occlusion, which progresses from labial to alveolar, and finally, velar. That is, starting at the lips and then progressing toward the back of the mouth. For labial plosives, the flow is occluded at the lips so the airflow in the mouth immediately preceding opening is essentially zero. Releasing the air will propel it in a direction that is normal to the opening area of the mouth. For alveolar stops, there is some curvature to the flow channel downstream of where the stop occurs, which arises from the geometry of the tongue and upper palate. As the stop is released, this likely contributes to the slight downward trajectory as the flow passes through the oral cavity before exiting the mouth. For the velar plosive, flow constriction occurs at the velum, which is located at the back of the oral cavity. When the velum opens the flow can be expected to generally follow the geometry of the curved upper palate before exiting the mouth. The geometry of the upper
palate, teeth, and lips creates a concave arc that is directed downward at the exit of the mouth, which explains the more negative expiration angle.

In light of this observation, the difference in trajectory angle between voiced and unvoiced velar stops ([aga] and [aka], respectively) is somewhat surprising as it was expected that the expiration angles would be determined by the location of the constriction within the vocal tract and the associated vocal tract geometry, and would therefore be insensitive to whether or not phonation (i.e., vocal fold oscillation) accompanied the production of the consonant. Instead, the voiced stop [aga] exhibited a less negative trajectory. Consequently, investigation of the full class of speech phones, including voiced consonants, may provide additional insight into consonant expiration angles.
Vowels were not explicitly investigated in this work due to the emphasis on consonant production that produces higher expiratory velocities. Nevertheless, the utterance [aha] provides insight into the expected behavior of some sustained vowel intonations. It is produced with the same static vocal tract orientation as the vowel [a], with the only difference being that the vocal folds adduct such that the aspirant [h] is produced from airflow passing through the glottis, as opposed to vocal fold vibration. In addition, there is a slight increase in the flow rate during enunciation of [h]. The path of the air exiting the mouth for [a] as well as for other "open" vowels (e.g., [æ]) is, therefore, expected to follow a similar downward trajectory, as generally predicted by the curvature of the flow channel produced by the upper and lower palate. Closed vowels (e.g., [i], [u]) are likely to lead to more complicated flow trajectories due to significant narrowing of the vocal tract channel that may redirect the flow, cause localized acceleration, and potentially lead to flow separation within the vocal tract.

### 3.2 | Intra-consonant variability

Table 2 reports the parameters of the geometry and flow conditions that were investigated using the physical models. In speech, the subglottal pressure drives the flow, and is directly correlated with loudness. Three subglottal (i.e., plenum) pressures ($p_s$) were investigated for each vocal tract geometry and tooth orientation: 300, 600, and 860 Pa, which are representative of soft, normal, and loud speech, respectively. These conditions resulted in a broad range of Reynolds numbers that spanned from laminar to transitional. For comparison, comfortable breathing usually occurs at a flow rate of $\approx 80$–130 cm$^3$/s, but can increase significantly during exercise, with peak expiratory flow rates reaching as high as $\approx 10 000$ cm$^3$/s.

#### 3.2.1 | 2D tooth geometry

To investigate intra-consonant variability in the expired flow trajectory (i.e., unsteadiness in the mouth jet) steady flow investigations were initially investigated for the [f] and [θ] mouth geometries using PIV. Figure 8 presents the velocity fields as a function of the consonant utterance and the subglottal pressure. Velocity vectors are superimposed on the velocity magnitude, with only every third vector shown. Of significant interest is the very high velocities that are generated at the mouth, with the highest subglottal pressure producing velocities up to 30 m/s at the lips. Even for the lowest pressure, indicative of soft voice, they reach more than 15 m/s. This is a significant deviation from prior work related to particle transport that has reported velocities ranging between 4 and 10 m/s at the exit of the mouth. These prior works historically measured velocities at a finite distance downstream of the lips due to experimental limitations. As can be seen in the current data, the velocity is diffused relatively quickly, with velocities further downstream within the range of previously reported values.

As previously mentioned, the lower palate for [f] and [θ] are angled at 46° and 50° at the tooth constriction, respectively. This causes the jet exiting the tooth gap to be angled up toward and attach to the upper lip. The exception is [f] for a pressure of $p_s = 860$ Pa (Figure 8C). After passing through the tooth gap, the mean flow field initially attaches to the lower lip, but still separates from it and ultimately attaches to the upper lip. A larger spread in the downstream jet width is also observed in the [f] model. At the two lower pressures this behavior is primarily constrained to the region downstream of where the flow separates from the upper lip. However, for $p_s = 860$ Pa a broader distribution of the jet is observed within the lips as well, due to the tendency of the jet to first attach to the lower lip. Because the mean PIV velocity fields are the spatial average of 900 separate acquisitions, this spread in the jet is indicative of flow instabilities that cause temporal variations in the flow trajectory. This behavior will be extensively explored in Section 3.2.2.

For all cases, the flow ultimately attaches to the upper lip due to the Coanda effect. It remains attached until the velocity in the jet decreases to the point that the centripetal acceleration of the flow is no longer able to overcome the adverse pressure gradient arising from the curvature in the geometry. At this point, the flow separates from the upper lip. This asymmetric behavior is similar to observations in voiced speech, where flow through 2D models of the divergent glottis, which is a high-aspect ratio opening that is similar

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**Table 2** Investigated parameters for the [f] and [θ] mouth geometries, including: subglottal pressure ($p_s$), tooth gap profile, tooth gap area ($A_{gap}$), mean flow rate ($Q$) ($cm^3/s$), Reynolds number, and the corresponding figures in which the data are presented.

| $p_s$ (Pa) | Tooth profile | $A_{gap}$ (cm$^2$) | $Q$ (cm$^3$/s) | Re | Figure |
|------------|---------------|-------------------|----------------|----|--------|
| 300        | 2D            | 0.20              | 465.7          | 2378 | 6A     |
| 600        | 2D            | 0.20              | 689.7          | 3521 | 6B     |
| 860        | 2D            | 0.20              | 829.4          | 4235 | 6C     |
| 300        | 3D            | 0.14              | 108.0          | 658  | 7A, 9A |
| 600        | 3D            | 0.14              | 152.6          | 929  | 7B, 9B |
| 860        | 3D            | 0.14              | 193.3          | 1178 | 7C, 9C |
| 300        | 3D            | 0.30              | 513.2          | 3018 | 10A, 11A |
| 600        | 3D            | 0.30              | 767.9          | 4515 | 10B, 11B |
| 860        | 3D            | 0.30              | 753.5          | 5907 | 10C, 11C |

| $p_s$ (Pa) | Tooth profile | $A_{gap}$ (cm$^2$) | $Q$ (cm$^3$/s) | Re | Figure |
|------------|---------------|-------------------|----------------|----|--------|
| 300        | 2D            | 0.20              | 480.8          | 2455 | 6D     |
| 600        | 3D            | 0.20              | 646.6          | 3301 | 6E     |
| 860        | 3D            | 0.20              | 836.3          | 4270 | 6F     |
| 300        | 3D            | 0.15              | 108.0          | 641  | 7D, 9D |
| 600        | 3D            | 0.15              | 153.0          | 908  | 7E, 9E |
| 860        | 3D            | 0.15              | 193.3          | 1147 | 7F, 9F |
| 300        | 3D            | 0.30              | 468.3          | 2684 | 10D, 11D |
| 600        | 3D            | 0.30              | 635.2          | 3640 | 10E, 11E |
| 860        | 3D            | 0.30              | 1004.6         | 4318 | 10F, 11F |
in geometry to the tooth gap area, produces a highly asymmetric jet that predominantly attaches to one wall. Analogous work has shown that this behavior can, however, be exaggerated due to the two-dimensionality of the flow.

These observations, in tandem with the in vivo flow visualizations of Section 3.1 that exhibit a straighter trajectory, indicate that the assumption of a 2D tooth gap likely produces non-physical flow behaviors that do not accurately predict the flow trajectories of human fricative consonant production.

### 3.2.2 3D tooth geometry

To investigate the role of the three-dimensional mouth geometry, the tooth gap was changed to the aforementioned 3D geometry, which is more physiologically realistic. Figure 9 presents the velocity fields for a 3D tooth gap of 0.14 and 0.15 cm² for [f] and [θ], respectively, as a function of subglottal pressure. Velocity vectors are superimposed on the velocity magnitude contours, with only every third vector shown. The velocity magnitudes are again much higher than previously reported values. The mean jet, however, exhibits a much shallower trajectory across all cases. This arises because the flow predominantly attaches to the lower lip, as opposed to the upper lip, as occurred for the 2D tooth gap.

The amount of spread in the mean jet is also significantly increased. This variability in the flow trajectory over the 900 PIV acquisitions is quantified by calculating the trajectory angle of each instantaneous velocity field. Increased variability in this measure indicates an inherently unstable flow field. The trajectory of each PIV snapshot is computed by finding the location of the maximum jet velocity at each x-location over the span of 0 ≤ x ≤ 1.2 cm, where the location x = 1.2 cm corresponds with the exit plane of the lips. A linear line is fit to the points and the slope is computed. Although the tooth geometry cannot be visualized, the flow must pass through the tooth gap. Consequently, the intercept of the line at x = 0 cm is constrained to fall within a position bounded by the lower surface at x = 0 and a distance above the lower surface that is equal to the tooth gap height. Figure 10 presents six instantaneous vector field snapshots for [f] with a 3D tooth geometry, with a gap area of 0.14 cm² at ps =860 Pa. The location of the maximum jet velocity as a function of x-location is plotted as circles and the resulting linear fit that was predicted, from which the expiratory angle α was predicted, is overlaid. The six instances were selected to show the performance of the algorithm over the range of angles that were observed.
Figure 11 plots histogram distributions of the expiration trajectories as bar plots for a 3D tooth gap of 0.14 and 0.15 cm² for [f] and [θ], respectively. The rows denote the indicated consonant, while the columns are organized by subglottal pressure. Bin sizes are 1° in width, with the magnitude expressed as a fraction of the total realizations that were acquired (i.e., N/Nt). The mean and standard deviation of the trajectory angles are reported as well. The mean angle is higher for [f] than [θ] for all subglottal pressures, with a broader spread in the trajectory angle evident for [f], particularly at the higher subglottal pressures. For [f] and [θ] the standard deviations are large relative to the mean value, which reveals a high degree of unsteadiness in the jet trajectory. In comparing the spread of the data, it can be seen that some instances for [f] (e.g., Figure 11A) reach a trajectory angle approaching 35°, which indicates the flow does not attach to the upper lip for a limited number of realizations. In contrast, for [θ], aside from the lowest subglottal pressure, the angles are all below 15°, which indicates the flow does not attach to the upper lip, as was also shown in Figure 9B and C.

Compared with the human data, both scenarios show the same general trend (i.e., the trajectory is directed upward in the positive direction). However, while the mean values of [f] compare favorably with the measured expiratory angle for the human utterance [afa] (11.8°–18.1° vs. 18.0°), when comparing the mean values of [θ] with the human utterance [aθa] the difference in the trajectory angles are large (1.3°–10.2° vs. 39.8°). In addition, in the human data the trajectory angle for [aθa] is greater than for [afa], while the converse is true for the experimental investigations.

This behavior is not entirely surprising as the physical experiments show that due to the high flow unsteadiness arising from the diffuser-like lip geometry during consonant production, a variety of flow configurations are possible. Furthermore, the precise position and trajectory of the articulators are known to vary from one utterance to the next, depending on the surrounding sounds that are generated, the frequency, and the speaking rate. Consequently, the data presented herein actually serves to confirm the high degree of variability in consonant expirations that was expected. That is, small deviations in the geometry can lead to large variations in the flow trajectory.

Figures 12 and 13 present the same velocity field and histogram distributions of the jet trajectory angle as Figures 9 and 11, albeit with a projected tooth gap area that is 0.30 cm² for both consonants. The mean trajectory angles in the histogram distributions are significantly higher for both consonants. Interestingly, the mean trajectory angles for the consonant [θ] (26.3°–30.6°) now compare more favorably with the human data.

Figure 9 Velocity magnitude contours of the expired velocity exiting the 3D tooth gap for [f] (top row) and [θ] (bottom row) at subglottal pressures of \( p_s = 300, 600, \) and 860 Pa shown in the left, center, and right columns, respectively. The tooth gap area is 0.14 cm² for [f], and 0.15 cm² for [θ]. Velocity vectors are superimposed on the plots with the vector spacing downsampling by 1/3.
**Figure 10** Instantaneous vector fields for the consonant [f] at $p_s = 860 \, \text{Pa}$. The location of the maximum velocity is indicated by the circles, with the linear fit, from which the expiration angle $\alpha$ was computed, overlaid as a dashed line.

**Figure 11** Bar plots of the probability distribution of the expired jet trajectory angle, presented as a ratio of the number of instances at each angle over the total number of instances ($N/N_t$). The bin size is $1^\circ$. Data are presented for [f] (top row) and [θ] (bottom row) at subglottal pressures of $p_s = 300$, $600$, and $860 \, \text{Pa}$ shown in the left, center, and right columns, respectively. The tooth gap area is $0.14 \, \text{cm}^2$ for [f], and $0.15 \, \text{cm}^2$ for [θ].
The degree of flow unsteadiness varies significantly depending upon the consonant and the subglottal pressure. Comparing [f] with [θ] in the mean velocity magnitude plots of Figure 12 reveals that for [θ] the flow does not attach to the lower lip. For [f], at \( p_s = 300 \) Pa the flow is initially attached to the lower lip at \( x = 0 \) cm. As the subglottal pressure increases, the point of separation from the lower lip shifts closer to the mouth exit. This is accompanied by a significant broadening in the flow field.

Examining the histogram distributions of the trajectory angles shown in Figure 13 in tandem with the corresponding velocity contour plots (Figure 12) reveals an interesting behavior. For [f] at \( p_s = 300 \) Pa the mean trajectory angle is high (29.9°), while the standard deviation is reasonably low (3.2°). As the subglottal pressure increases, the mean trajectory angle decreases by a factor of 2 while the standard deviation essentially doubles. Remember, at \( p_s = 300 \) Pa the mean flow field for [f] separated earlier from the lower lip, and attached to the upper lip. For [θ], where the flow was always attached to the upper lip, the mean trajectory angle is also high (26.3°–30.6°), but in contrast to the behavior of [f], the standard deviation is very low (1.6°–2.0°). This indicates that configurations where the trajectory angle is high due to attachment to the upper lip tend to be more stable than configurations where the flow initially attaches to the lower lip.

**4 | DISCUSSION**

For the first time, the flow trajectories of consonant productions have been quantified through a combination of human and physical model investigations. Significant inter- and intra-consonant variability has been observed, indicating that consonants, and therefore speech in general, produces a highly unsteady flow field that exhibits complex flow dynamics, with widely varying trajectory angles. These findings demonstrate that the expiratory fluid mechanics due to speech is likely more complex than previous models have considered.\(^{13,21,28–30}\)

The measurement of human expiratory trajectories as a function of consonant utterance shows that there is wide variability, spanning \(-60^\circ\), which is consistent with prior observations.\(^{26}\) While a statistical representation of the flow trajectories was not possible with the limited data set, it is anticipated that there will be wide variation in the specific expired trajectories due to both subject-to-subject variability, as well as utterance-to-utterance variations by the same speaker. MRI studies of the mouth geometry during consonant production\(^{35}\) have shown that tongue placement during fricative production can vary from speaker to speaker. In addition, as previously discussed, during running speech, the articulatory mouth
trajectories that produce the oral geometry for a specific utterance are known to vary based on the sound that both precedes and follows the specific utterance, as well as speaking rate.\textsuperscript{46,47} As quantified in the physical model investigations, small changes in mouth morphometry, tooth gap, etc. can have significant impacts on the resultant flow trajectory. Taken as a whole, this suggests that while the overall span of angles observed in human consonant production will likely be large, the specific angles produced for different utterances are expected to vary significantly across speakers and for varying prosody, speech rate, loudness, etc. While this highlights the inconstant nature of expiratory speech flows it also emphasizes that care should be taken to avoid extrapolating the specific trajectory angles observed herein as being repeatable across a larger demographic. That is, while this work demonstrates that flow trajectories will vary widely during speech, they are only presented for one subject. Consequently, a more detailed investigation with appropriate statistical power is needed to quantify precisely how the trajectories vary in the general population.

Significant differences in the fluid mechanics were observed for flow through 2D, and 3D tooth gaps. The 2D tooth gap area exhibited flow behavior similar to slot jets with an adjacent surface (eg, the lips), which is characterized by the formation of the Coanda effect\textsuperscript{38}; a largely stable phenomenon. In contrast, both the smaller and larger 3D tooth gap areas will likely produce three-dimensional flow structures, which were unfortunately not observable with the planar PIV measurements. This is likely the reason for the significant change in the flow trajectory as the tooth gap area increased; that is, the orifices became more symmetrical. Flow through asymmetric annular orifices has been shown to exhibit behaviors such as the formation of both streamwise and azimuthal vortex pairs,\textsuperscript{48} as well as axis-switching.\textsuperscript{49,50} The generation of vortical structures in the flow influences the flow stability as well, and the tendency to attach to, or separate from, adjacent surfaces. For example, introducing streamwise vorticity is an effective strategy to delay flow separation from a curved surface.\textsuperscript{51} It is not surprising then, that the flow was highly sensitive to the aspect ratio of the tooth gap.

The formation of a divergent passage at the opening of the lips introduced additional instabilities in the flow. Flow through this type of configuration (ie, diffusers) are known to exhibit pronounced unsteadiness that is dependent on the divergence angle produced by the channel wall, the Reynolds number, and the ratio of the throat to exit area.\textsuperscript{33,52} This unsteady "transitory stall" behavior is most pronounced when the included divergence angle of the divergent channel geometry assumes angles between $\approx5^\circ$ and $40^\circ$, with the precise flow regime dependent upon the aforementioned variables. In the current configuration, the physics are likely even more complicated as the expected presence of vortex shedding as the flow separates from the teeth (not captured in the PIV measurements) will introduce additional alternating pressure signatures in the flow between the lip(s)/tongue as the vortices advect through the gap. In

![Figure 13 Bar plots of the probability distribution of the expirated jet trajectory angle, presented as a ratio of the number of instances at each angle over the total number of instances ($N/N_t$). The bin size is 1°. Data are presented for [f] (top row) and [θ] (bottom row) at subglottal pressures of $p_s = 300$, 600, and 860 Pa shown in the left, center, and right columns, respectively. The tooth gap area is 0.30 cm$^2$](image-url)
addition, ambient flow conditions where large regions of recirculating flow may be present are also known to influence the trajectory of a jet exiting an orifice.45

Finally, comparing flow behaviors between two similar, but slightly different, oral geometries produced by the fricative consonants [f] and [v] revealed that the attachment of the flow to the lower versus upper lip significantly increased unsteadiness in the jet. The preferential attachment of the jet arises due to the slight variation in the lip/tongue angle at the teeth. While [f] was angled at 46° from the horizontal, for [v] it was 50°. This small 4° difference resulted in the flow predominantly attaching to the lower lip and exhibiting a wide spread in the jet when the tooth gap area was 0.30 cm² for [f], while for [v] the flow attached to the upper lip and was much more stable.

Collectively, these behaviors reveal that the expired flow for consonant productions can be classified as highly unsteady for both inter- and intra-consonant enunciations. Small variations in personal morphometry, prosody, and articulation can lead to drastically different flow behaviors. It should, therefore, be acknowledged that the relevant physics of speech are probably not adequately captured by models that approximate mean, time-averaged behaviors over very long time scales (eg, single to multiple words). Consequently, stochastic representations of potential flow behavior are more likely to yield relevant and useful insights.

Quantification of the large spread in the expiratory trajectory angles as a function of consonant utterance has direct implications on droplet spread. Large droplets follow a ballistic-like trajectory. Consequently, a change in the ejection angle will directly influence the distance the droplets travel. Similarly, variations in the expiratory angle will influence aerosol transmission, as aerosols are small enough that they faithfully follow the flow patterns. Hence, even though they are not as likely to be forcefully expelled over long distances due to their decreased size (ie, momentum), an upward trajectory to the flow increases the probability that they will rise to a height where they are drawn into, and spread by, ventilation and air circulation units. The implications for modeling source emissions, which historically rely upon assumptions of horizontally oriented emissions,13,21,28–30 are therefore, of significant importance.

The ability to measure the velocity between the lips, as opposed to at some point downstream, also revealed that the velocities of consonant production were three to ten times higher than previously reported values.10,26 Velocities at the tooth gap are expected to be even higher, as the tooth gap constriction is much narrower than the constriction at the lips. For example, the minimal gap at the lip(s)/tongue is ~4 mm whereas the tooth gap, h, is ~0.1 mm. This is another important observation as the momentum with which droplets are expelled is driven by the local flow as the droplets accelerate through the mouth. Consequently, predicting droplet transport based on velocity measurements downstream of the mouth will drastically underpredict the maximum expiratory velocity, and the subsequent calculation of the penetration distance of droplets into the environment.

It is important to note that a significant simplification in the current work is the experimental investigation of consonant expiration as a steady jet, as opposed to a temporally varying puff. It remains to be seen how, or if, this will influence the flow momentum, trajectory angles, and flow unsteadiness, and is a thrust of ongoing work. In addition, there is still a significant gap in the quantification of the expired flow dynamics; particularly, the structure and importance of the three-dimensional flow physics, and how this influences behaviors such as turbulent dispersion of the jet, as well as the entrainment and transport of droplets. Finally, the importance of buoyancy effects arising due to the temperature difference between the expelled and ambient air has been highlighted as an important component of transport dynamics in coughs and sneezes,3,53,54 but remains largely unexplored in speech.

5 | CONCLUSIONS

A combination of in vivo and physical investigations of the flow expired during consonant production has been investigated. This work has direct application to modeling droplet spread to identify safe social distancing metrics and the transport of infectious droplets into the ambient surroundings, specifically during the COVID-19 epidemic.

The identification of in vivo trajectory angles that span from +27.2° to −31.5° as a function of consonant utterance is a crucial finding that highlights the need to consider non-zero trajectory angles when predicting/modeling both large and small droplet spread. The observation that flow velocities at the lip can easily reach velocities of 30 m/s is similarly impactful, as the ballistic-like behavior that governs large-droplet spread depends on both the angle and momentum of the ejected droplet, with increased velocities projecting droplets over farther distances. Even higher velocities are expected at the gap produced by the tooth constriction, in comparison to the velocities at the lips that are reported herein. Aerosol spread will also be influenced by non-horizontal expiratory trajectories, with positive angles more likely to direct aerosols to a higher elevation where they can be drawn into, and distributed through, air ventilation.

Finally, the highly unsteady nature of the flow exiting the mouth for fricative consonants has been highlighted. Small variations in mouth geometry, tooth gap shape and height, and flow rate (eg, subglottal pressure) have been shown to drastically influence the mean expiratory angle of the flow as well as the temporal variation of the instantaneous angle. Flow configurations ranging from a fully separated jet to flow attached to either the upper or lower lip were all observed. The implication is that the expiratory trajectory angles are highly unsteady, suggesting that time-averaged representations over long time scales are likely insufficient for capturing the key dynamics of the flow, and that a stochastic approach to modeling the expiratory velocities of speech may be more appropriate. This also highlights the need for additional work, beyond what is reported herein, to determine how linguistic variables influence expirations.
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CONFLICT OF INTEREST
There is no conflict of interest.

AUTHOR CONTRIBUTION
Tanvir Ahmed: Formal Analysis, Investigation, Methodology, Software, Visualization, Writing-review and editing. Hannah E. Wendlin: Investigation, Methodology. Amir A. Mofakham: Conceptualization, Writing - review and editing. Goodarz Ahmadi: Conceptualization, Funding acquisition, Supervision, Writing-review and editing. Brian T. Helenbrook: Conceptualization, Funding acquisition, Supervision, Writing-review and editing. Andrea R. Ferro: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing - original draft, Writing-review and editing. Deborah M. Brown: Conceptualization, Funding acquisition, Supervision, Writing-review and editing. Byron D. Erath: Conceptualization, Funding acquisition, Supervision, Writing-review and editing.

PATIENT CONSENT STATEMENT
All human subject studies were approved by the Clarkson University Institutional Review board.

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