Analysis of Swallowing Events: Signals and Systems Perspective

Abstract — This study aims to apply a set of signal processing techniques to analyze a set of events including swallowing saliva, water, solid food, clearing throat and coughing. Data includes five subjects who each recorded 20 repetitions of each event type and can be loaded into the MATLAB workspace for analysis by running 'OpenData.m'. The primary objective of this paper is to investigate the characteristics of each event and obtain practical applications where the characteristics are utilized. The analysis approach comprises of several steps: illustrating time domain analysis, quantification of signal size, illustration of frequency spectra, bandwidth estimation and correlation analysis between event types. Key findings are summarized through graphs and descriptive statistics are provided where applicable.

I. Introduction

This study explores the sounds that are produced when we cough and clear our throats, as well as when we swallow different substances, such as liquids and solids. The study attempts to be understandable and simple for others to repeat by utilizing mathematical analysis of these sounds. The two primary components of the research are gathering the sound data and analyzing it using MATLAB. Five participants provided the sound data, making sure the recordings were clear and noise-free by repeating many swallowing and coughing motions. Even though there were some difficulties with the mic that was utilized, the study closely examines these noises in several ways, such as determining their loudness, seeing how they change over time, and looking for patterns. By using this methodical and mathematical approach, the study hopes to clarify the idea behind signals.

II. Methods

The following section describes the mathematical approach to analysing the sample data to ensure transparency and reproducibility of the study and its results. Section A describes the data collection method and consideration for signal quality insurance as well as the data structure in which data is stored. Section B described the data analysis methods used, which include illustrating time domain analysis, quantification of signal size, illustration of frequency spectra, bandwidth estimation and correlation analysis between event types.

A. *Data collection*

Sample data was collected from five subjects who each recorded 20 repetitions for each event type, which included swallowing saliva, swallowing liquid, swallowing solid, clearing throat, and coughing in random order. The total repetitions for each event type are thus 100. The quality of each signal is confirmed through satisfaction of three criteria: the signal is clear of reasonable amplitude and no other background noise or sound is recorded. A notable limitation of the sample data is the use of different microphones by subjects. The type of microphone used or the use of a windscreen or 'pop filter' had a substantial impact on the quality of the signals.

B. *Data analysis*

Time domain analysis (Time-domain plot and duration analysis)

In the context of analysing swallowing recording data, examining signals in the time domain represents how the amplitude of the sound recording data of swallowing events changes over time. This analysis provides insights into both the magnitude of the sound and the corresponding time at which these amplitude variations occur. 20 iterations from 5 different subjects for each type including saliva, liquid, solid, clearing throat and coughing were plotted on top of one another, in the time domain in Figure 1.

Duration analysis was performed to understand the attributes of each swallowing event. The mean duration of each event was determined by conducting a duration analysis for each iteration and calculating the average value of these duration measurements. The sample was selected with the criteria of noise-to-signal ratio which indicates how small the amplitude of the noise and how big the amplitude of the signal compared to the noise. It was visually determined that Rana's coughing recording, Rana's cleaning throat audio, Chaim's fluid swallowing recording, Rana's saliva recording and Rana's solid recording were ideal for each event due to the high noise-to-signal ratio, as seen in Figure 1.

The duration of each event was identified using a signal detection algorithm. It was calculated by subtracting the on-set index from the off-set index divided by the sampling rate to obtain the duration in seconds (s). The on-set index was set to the first signal samples that exceeded the threshold amplitude. The offset index was set to the last sample amongst the samples whose amplitude was below the threshold. The threshold was adjusted to the amplitude of the noise level which varied by the type of microphone used for the recording.

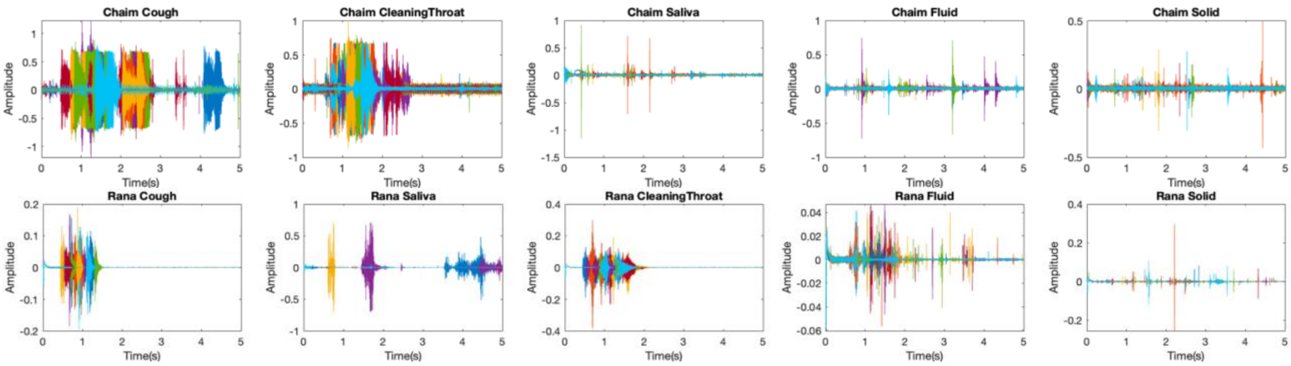

Figure 1 - Time Domain Plots for Chaim and Rana

Quantification of signal size

Quantification of the signal size is crucial for analyzing sample signals as it provides notable differences between event types and could simplify spotting anomalies. The size of the signal was quantified as the average maximum amplitude in the time domain for each event type per subject. The MATLAB script produces the bar plot by finding the maximum value [amplitude] of each signal and taking the sum of these values for each subject. The average is found through the division of this sum by the number of samples.

Looking at Figure 2 below, it is apparent that the quietest sounds are for fluid, solid, and saliva, and coughing is louder than cleaning the throat.

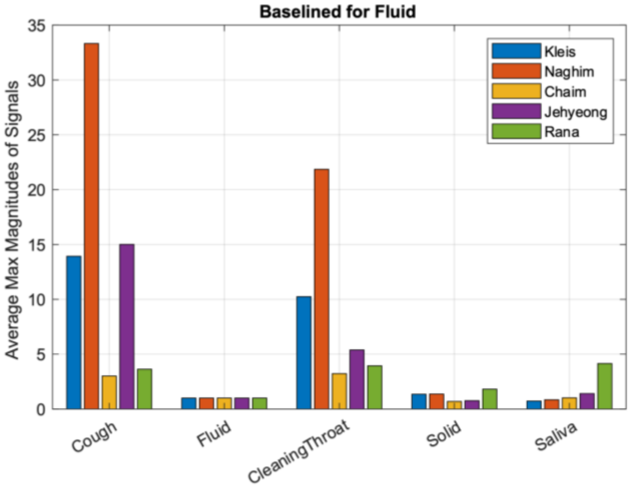

Figure 2 - Average Maximum Amplitude

Frequency spectra

The frequency spectrums here are calculated based on an average of the Fourier transforms over 20 iterations of each event, (an event being a person and a type, for example, Chaim and Cough is considered one event). This data is then graphed for each event (FrequencySpectrums.m), shown below in Figure 3.

Bandwidth estimation

The Bandwidth is estimated using a -3 dB cutoff, which is 50.1% of the original amplitude [1]. This is calculated in Bandwidth.m, and then added to the graphs in FrequencySpectrums.m (red dashed lines).

Looking at Figure 3, we can suggest several conclusions. Please note that the red dashed lines are bandwidth upper and lower bounds. Where there is no lower bound, it is a baseband signal.

Firstly, the data implies that the Frequency spectra of the events are more dependent on the person and/or microphone used than the type of event. Because of this, it is difficult to suggest, based on this data, that one type of event consistently has a different frequency spectrum than other types of events.

However, it is compelling that the different microphone set-ups produce quite different graphs, even for events which would sound similar to us. For example, looking at the frequency spectrum for Rana's events, the frequency is consistently a baseband signal with a bandwidth of just under 500 Hz, for all events. This implies that Rana's microphone setup has a physical or software-based low pass filter and therefore seems to produce a baseband signal, with effectively no frequencies above 1000 Hz.

However, considering Jehyeong's (Jay's) data, we see a bandwidth of between 200 – 1000 Hz, shifted when swallowing fluid or solid to around 200 – 1500 Hz. This suggests that Jay's swallowing produces noise of between 1000 and 1500 Hz, whereas Jay's coughing, clearing throat and swallowing saliva do not produce those 1000 – 1500 Hz noises. Jay's data also shows that his microphone setup produces lots of higher-pitched noises.

Correlation analysis

Correlation is the measure of similarity between two signals. In this paper, cross-correlation was chosen as it measures the similarity of two data sets based on the displacement to one another. This can be applied to compare the similarity of different signals to draw comparisons such as identifying whether the signals are from the same person or of the same swallowing type [3][4]. All data has been normalized as consistent correlation values will make the data easier to compare. Both the time domain and frequency graphs were produced using CorrelationSAS.m and CorrelationFourierSAS.m respectively however, the frequency domain tells us a lot more about the similarities between signals and therefore will be the focus of this analysis.

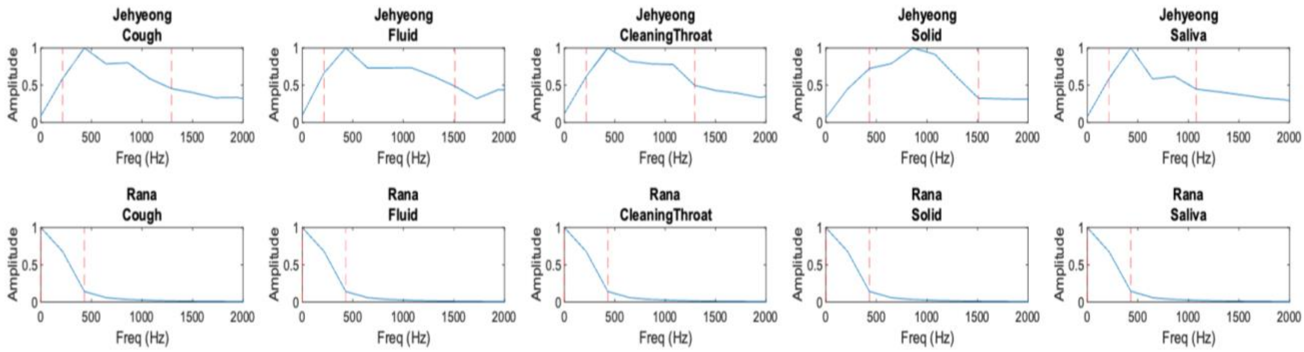

Figure 3 - Frequency Spectrum for Jehyeong and Rana

There were over 100 graphs produced and for the sake of brevity not all graphs have been included in this report, however, graphs relevant to the conclusions made have been included. For each graph on the x-axis, there is the shifted frequency domain (unit Hz) and on the y-axis the displacement correlation normalized between 0 and 1.

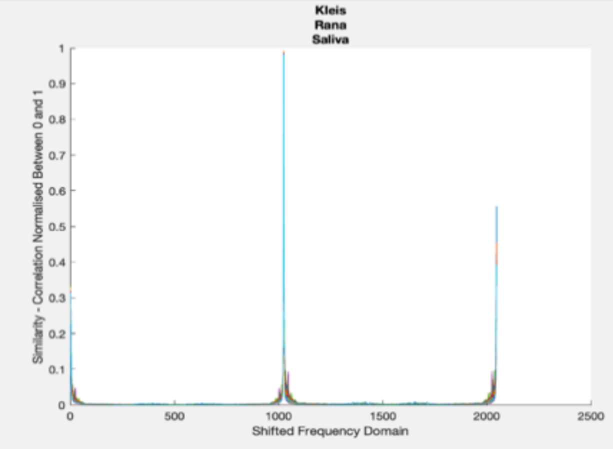

Figure 4. Kleis & Rana Saliva Correlation Graph

Signals with high similarity do not deviate significantly from each other. Additionally, noisy signals influence the similarity and correlation will deviate from signals without noise. Consider figures 4 & 7, both low-noise data sets.

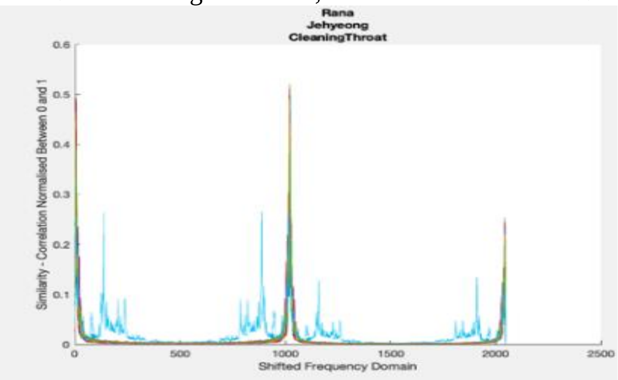

Figure 5. Rana & Jehyeong Cleaning Throat Correlation Graph

We can see that Rana & Kleis have similar saliva and fluid signals. This can be determined by the displacements which are represented by each line. We see a high at just over 1000Hz and at just over 2000Hz (likely an overtone) which are the main deviations. This is due to the differences in swallowing but overall, the shapes of each line are remarkably similar to one another and therefore we can conclude that Rana & Kleis have similar saliva and fluid signals.

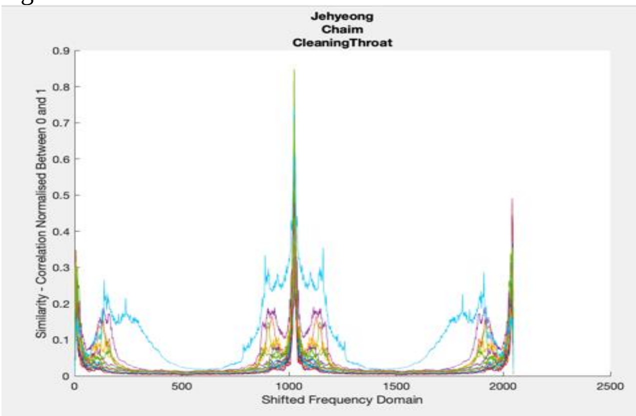

Figure 6. Jehyeong & Chaim Cleaning Throat Correlation Graph

Higher noise data such as what is found in Figures 6 & 8 are somewhat harder to interpret. We can see that overall, the shape of each line is similar, however, due to the higher noise it is harder to determine how similar the signals are.

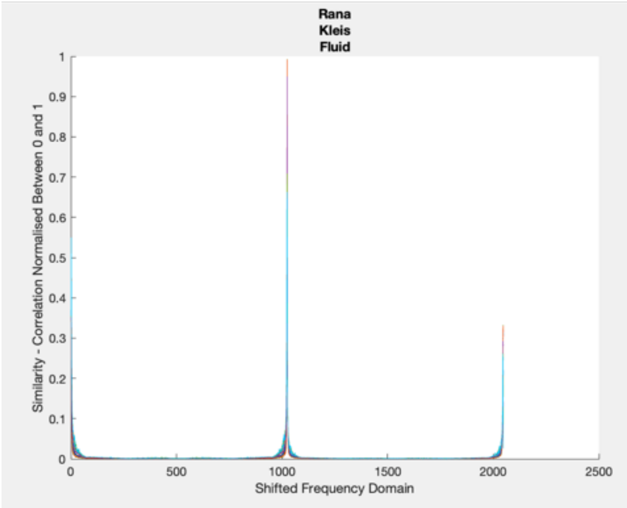

Figure 7. Rana & Kleis Fluid Correlation Graph

As you can see in Figure 6 the light blue line deviates significantly from the rest of the displacements but follows a similar trend. This shows that whilst not entirely similar the general trend is the same. Again, there is a deviation around 1000Hz and just over the 2000Hz point. We can reasonably conclude that Jehyeong's and Chaim's Cleaning Throat and Fluid data are similar although repeating to get samples with lower noise would provide further clarity to this conclusion.

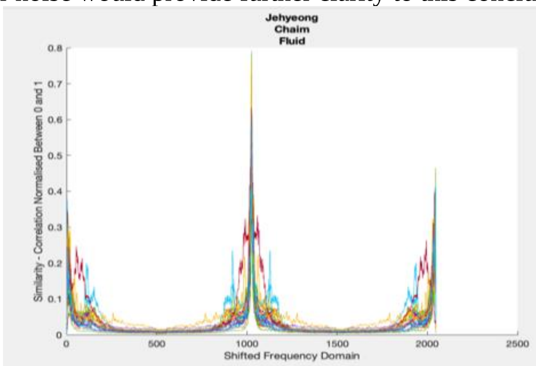

Figure 8. Jehyeong & Chaim Fluid Correlation Graph

If we consider Figure 5, we can see an example of data with low correlation. We can interpret this result from the graph because we see a large deviation at several points along the graph that do not align with each other. We can reasonably conclude that Rana & Jehyeong do not have similar Cleaning Throat signals.

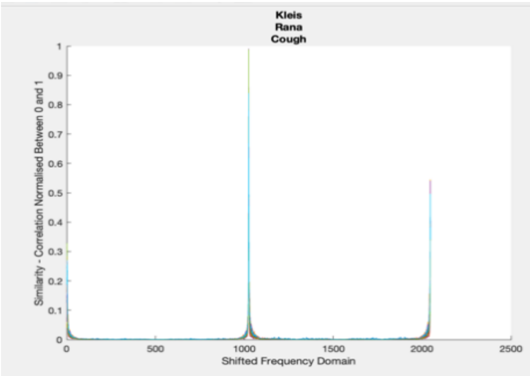

Figure 9. Kleis & Rana Cough Correlation Graph

III. Results

Time domain analysis

The time-domain analysis provided the duration of each event. As shown in Figure 10, the duration of coughing was found to be 0.0920 seconds, while each iteration of swallowing saliva took 0.9840 seconds. Additionally, clearing the throat lasted 0.4668 seconds, swallowing solids took 1.7826 seconds, and swallowing fluids required 1.8609 seconds. The result was illustrated in Figure 10.

Events such as cleaning the throat and coughing, which do not involve swallowing, typically exhibited shorter durations. In contrast, events involving swallowing, such as solid, fluid, and saliva, consistently demonstrate longer durations. This is attributed to the complexity of the swallowing process which involves coordinated multiple muscle movements. On the other hand, coughing and clearing the throat involves simpler muscle actions and can be completed more quickly [2].

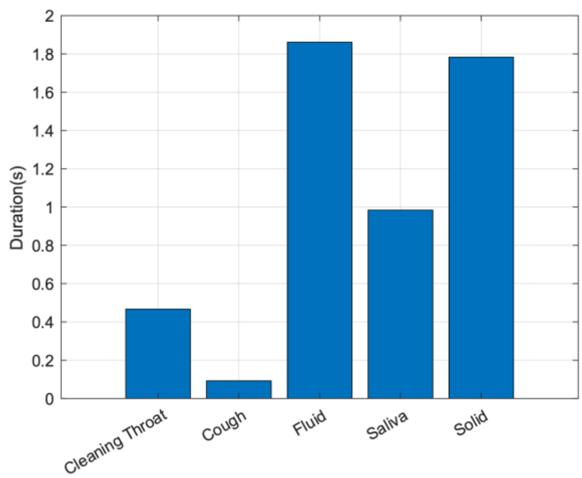

Figure 10. The duration of each event

Correlation analysis

The correlation analysis showed that typically there was a strong correlation between Kleis, Rana & Nagim's data however, this deviated for the solids & cleaning throat except for Nagim and Rana. Furthermore, there was no strong correlation across any of the cleaning throat data. Chaim and Jehyeong's data deviated most significantly from Rana's for the Saliva, Solid and Cleaning Throat but were similar to each other and different to Kleis and Nagim's data in the same fields. Finally, all fluid samples were very similar to each other as they had strong correlations.

IV. Conclusion

This study applied a set of signal-processing techniques to analyse and identify key characteristics of various event types. Analysis revealed intricate differences and similarities in the acoustic signals and highlighted the differences between individual and technological factors such as microphone type on the recorded signals. Correlation analysis provided insights into the distinctiveness of the signals related to the same event but across different subjects: indicating that classification based on solely acoustic properties is challenging. However, an improved sampling method involving high-quality microphones could make it possible to use signal processing as illustrated in this report for developing diagnostic tools for health conditions which may be characterized by deviations from regular swallowing behaviour. Despite challenges posed by signal quality and lack of reference data, the findings indicate potential for future study and options to explore practical applications.

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Jehyeong Kim	K20077066	20
Nagim Ibragimov	K22031784	20

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[2] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6800740/. National Library of Medicine. Accessed 28/03/24

[3] https://uk.mathworks.com/help/matlab/ref/xcorr.html Matlab Cross Correlation Function Documentation. Accessed 28/03/24

[4] http://www.ee.ic.ac.uk/hp/staff/dmb/courses/E1Fourier/00800_Correlation.pdf Correlation Powerpoint Imperial College London Accessed 2