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# Acoustic analysis of Korean stop sounds in patients with dysarthrias

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**Purpose:** Korean 'stops' are considered an especially good acoustic variable since they are sensitive to speech intelligibility and reflect physiological coordination between laryngeal and supra-laryngeal mechanisms. The purpose of the study was to evaluate the acoustic characteristics of both the dysarthria and control groups in the production of nine Korean stops, /p, p', $p^h$, t, t', $t^h$, k, k', $k^h$/, in VCV contexts.

**Methods:** The participants comprised eight patients with dysarthria and eight age- and gender-matched normal adults. After the acoustic analysis of the closure duration, aspiration duration, and the ratio of closure duration to closure-aspiration combined duration, the results were compared among three types of phonation and places of articulation for Korean stops.

**Results:** The dysarthria group (DG) had longer closure durations, suggesting slower articulatory movements of the DG than the normal control group (NC). Although statistically not significant except for /ap'a/ and /at'a/, the absolute aspiration durations of the DG were still longer than those of the NC. This resulted in the normal levels of ratios in the DG between closure duration and closure-aspiration combined durations. Furthermore, the DG could change the durational aspects of stop production distinctively according to types of phonation more than they could according to the places of articulation. This trend was more prominent during the closure duration than during the aspiration duration.

**Conclusions:** This finding suggested that while the DG has centralized tongue positions, they control the tenseness and the timing coordination between laryngeal and supra-laryngeal articulators to distinctively produce different types of phonation of stops.

**Keywords:** Dysarthria, Acoustic analysis, Korean stops, Closure duration, Aspiration duration

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## INTRODUCTION

Dysarthria is a motor speech disorder that occurs due to abnormalities in the central and/or peripheral nervous system. The speed, strength, range, steadiness, and tone of motor speech behaviors are affected by the abnormal performances of nerve fibers and muscles [1,2]. This disorder is known to influence five speech components, including respiration, phonation, articulation, prosody, and resonance [1,2]. Because all phonemes in the language are influenced by the disorder, the overall intelligibility, rather than the percentage of correctly produced consonants, has been of interest to both clinicians and researchers.

"Speech intelligibility" is a measurement that scores how much listeners can understand through auditory perception of what they have heard [3]. Generally, speech intelligibility is graded by counting the number of words or syllables that are possible to transcribe, or by scoring how much a listener can understand using equal or ratio scales [4]. These scoring systems have often been criticized due to their subjectivity and problems with reliability. The acoustic approach is an alternative, more objective way to describe the variability and intelligibility of speech [1,2].

According to studies of the acoustic characteristics of clear speech, increased vowel spacing is associated with greater intelligibility [3,5-7]. Reduced stop burst omission, increased root mean square (RMS) intensity by 10dB, increased voice onset time (VOT) of voiceless consonants, and increased consonant-vowel ratio are also well-known characteristics of clear speech [8, 9]. Kim and Choi [7] reported that the vowel space was the single most significant factor in the intelligibility of speech in English, accounting for 61.9% of the intelligibility; whereas 89.7% of intelligibility-related variance of speech in Korean was explained by factors such as vowel space (65.4%), VOT (13.4%), and the articulation rate (10.9%). Kim and Choi speculated that one possible reason for this language difference is the denser acoustic and articulatory space for Korean stops, which makes VOT critical for speech intelligibility. Only one study [10], which investigated speech production of adults with cerebral palsy, did not find significant influence of VOT on intelligibility as much as tongue strength did. Therefore, in the Korean language, nine stops appear in high frequency among all Korean consonants, and the VOT contrast contributes to the overall intelligibility [7]. Additionally, stops are not only the indicators of speech intelligibility, but they also reflect the coordination of laryngeal and supra-laryngeal level mechanisms [11,12].

Stops are sounds produced by blocking the air flow from the lung completely in the middle of the vocal track and letting it out all at once making a burst [13]. Korean stops have triplets of phonologically distinct plosives at three different places of articulation: bilabials (p, $p^h$, p'), alveolars (t, $t^h$, t') and velars (k, $k^h$, k') [14]. Each plosive has different features in the vocal fold opening/closing timing aspect at the laryngeal level and in the degree of tenseness, width, and duration of constriction in the supra-laryngeal articulatory level [14]. Korean alveolar stops showed a stop order of tense > aspirated > lax stop in the average width of tongue-palate constriction after Shin [14] investigated Korean alveolar stop productions through electro-palatography. Hong and Kim [15] reported that the glottis opened while producing the lenis, and opened wider while producing the aspirated stop with increased subglottal pressure, and almost closed and fixed while producing the tense stop.

English stops can be subdivided into two categories by VOT: voiceless and voiced stops. Although Korean stops can be divided into three groups according to the types of phonation, they cannot be distinctively categorized by VOT feature alone. This is because the tense and lax stop overlap in their VOT lengths [16,17]. In Korean stops, one type of phonation is distinguished from the other two at each place level by two features: tenseness and aspiration [17]. Among the three types of phonation of stops, tense and aspirated stops have tense features, and they are distinguished from the lax stop because of this tenseness, while the tense stop is distinguished from the aspirated stop by the aspiration feature [18]. Acoustically, the tense feature is shown in the closure duration while the aspiration feature is found in the aspiration duration while producing stops [19,20]. Aspiration duration is similar to VOT since aspiration represents an air leakage through the glottis after releasing the closing gesture of articulators in the vocal track, and it may be captured in the spectrogram without the obvious burst noise.

When a Korean stop is surrounded by vowels in a 'vowel-consonant-vowel' sequence, the closure duration of the lax stop becomes much shorter than that of the tense and aspirated stops. The closure duration follows this order: tense > aspirated > lax [21-23]. The VOT of an aspirated stop is reported to be longer than that of a tense stop in VCV contexts [24]. On the other hand, the closure duration becomes the shortest in the velar stop, while the VOT becomes the longest in the velar stops among all three articulation placements [25-30].

Many studies have investigated the acoustic characteristics of stop consonants produced by dysarthria patients. According to Kim et al. [31], the most prominent VOT error characteristic was substitution: spastic dysarthria patients substituted more than 83% of tense stops for aspirated stops, and flaccid, ataxic, and hypokinetic dysarthria patient groups substituted aspirated ones for lax stops [31]. Lee et al. [32] also observed omission, substitution, and nonspeech sounds as the three major types of errors found in adults with dysarthria that influenced intelligibility. The other aspect of dysarthria speech characteristics was breathiness of phonation, which was found among children with dysarthria and patients with hypokinetic dysarthria, especially among patients with Parkinson's disease [33]. Breathiness appeared with decreased intensity at high frequency or sometimes as blurred formant contours with noises around formants on the spectrogram. One study has reported that patients with dysarthria showed longer closure duration and VOT than patients in the normal group when they produced stop consonants [34,35]. Compared to normal speakers, English speakers with hypokinetic dysarthria produced a reduced contrast in VOT between voiced and voiceless stops [36,37]. A reduced VOT contrast was also observed among Korean stops at bilabial placement [38] and at alveolar placement [39] when they were produced by speakers with Parkinson's disease (i.e., hypokinetic dysarthria speakers). In contrast, Fischer and Goberman [40] noted no group differences in the VOT length between hypokinetic dysarthria English speakers and normal English speakers. Similarly, while Korean children with cerebral palsy showed longer closure duration and longer syllable segment duration than those in the normal group, there was no significant difference in the VOT [41]. Lee [10], who investigated the VOT of adults with cerebral palsy, observed longer VOT in those in the more severe group than those in a milder group.

Many of these investigations on durational acoustic features of stop consonants were done on speakers with cerebral palsy, at a certain place of articulation (e.g., bilabial or alveolar) instead of all articulatory placements, or in English dysarthria speakers [42]. However, because of different stop characteristics between English and Korean, it is worth examining whether reduced distinction in the acoustic durational features among Korean stops is true to all Korean stops across all articulation placements when they are produced by speakers with dysarthria.

As the VOT of stop consonant reflects the mechanism of oral motor movements, many studies have tried to explain the oral motor mechanism of dysarthria patients by observing and analyzing the VOT of stop consonants. For example, after comparing children with five types of dysarthria except those with the hyperkinetic dysarthria type, Kim et al. [43] observed that the participants acquired the longer VOT of tense stops and concluded that all dysarthria groups except the ataxic group had reduced laryngeal tenseness. In Kim et al.'s [33] study, spastic and ataxic dysarthria patients showed the longest VOT in alveolar stops, and flaccid and hypokinetic patients showed the longest VOT in the velar stops. Based on this result, Kim et al. [33] concluded that the former had slower movement in the tongue tips, while the latter had slower movement in the tongue body. Overall, the hypokinetic dysarthria group tended to show the slowest responses in tongue and lip movement, while the ataxic dysarthria group showed relatively fast responses. Likewise, Park [41] concluded that Parkinson's disease patients tended to show slowed lip and tongue movement resulting in significantly shortened closure duration, significantly prolonged aspiration duration, and significantly reduced ratio of closure duration to closure and aspiration combined duration.

On the other hand, in terms of the places of articulation, patients tended to report difficulties in producing closure and aspiration duration distinctively based on the articulation placement. In one study, the low functioning patient group with cerebral palsy and the normal control group showed no significant difference in closure duration or aspiration duration according to the articulation placements [44]. On the contrary, Ann [45] found that children with cerebral palsy could produce the longest VOT in the velar stop placement, as was also the case with the normal group. The high functioning group in Jeong et al.'s [44] study could also produce aspiration durations distinctively to some degree according to the articulation placements.

Earlier studies mainly dealt with the acoustic characteristics of Korean stops produced by cerebral palsy; few studies have investigated the acoustic characteristics of Korean stops produced by dysarthria patients. In Lee et al.'s [32] study, the speech characteristics were compared between patients with dysarthria and patients who are normal speakers, but the etiology of patient groups (whether they had cerebral palsy, acquired dysarthria, or mixture of these) was not clearly stated. Moreover, while many studies investigated VOT (e.g., Kim, Kim, and Kim [42]), Korean stops can be explained better using aspiration and closure duration together rather than using VOT alone. In addition, simple comparison of closure duration and aspiration duration between the dysarthria group and normal control group is needed since there has not been a study investigated this.

In this study, the dysarthria group was not divided into subgroups according to their diagnosis. This is due to the fact that identifying types of dysarthria is difficult in the clinical setting, particularly since they may have multiple brain lesions. This means there are often many patients with a mixed type of dysarthria. Duffy [1,46] said that mixed dysarthrias are the primary speech disorder encountered in a large medical practice, far more than any single dysarthria type [1]. He went on to say that, based on data within the Mayo Clinic Speech Pathology practice, mixed types account for 29.9% of all dysarthria patients [1]. Furthermore, a wide range of variability exists in speech characteristics within dysarthria subtypes. For instance, both slow and fast speech rates are the characteristics of hypokinetic dysarthria speech. Also, the speech characteristics, such as imprecise consonants, may appear across different dysarthria subtypes. Admittedly, the Mayo Clinic categorization of dysarthria speakers has been criticized because when acoustic measures were used to predict group membership, the classification by dysarthria type was less accurate than classification by disease type or severity [6]. The problem with this classification system was the absence of perceptual variables necessary for reliable categorization. Also, how listeners perceive speech influences the categorization results, making the categorization process subjective [47].

Furthermore, cerebral palsy is a "persistent disorder of movement and posture caused by non-progressive pathological processes of the immature brain" [48]. As a result, a person's ability to control speech-related muscles is impaired. Developmental components may complicate the speech symptoms of cerebral palsy. The adult speakers with dysarthria, who acquired brain injury after the speech production mechanism was fully developed, are expected to demonstrate different speech characteristics than the ones whose etiology is cerebral palsy. Thus, only the adults with dysarthria need to be investigated solely and were included in the current study. Without dividing the patient group into subgroups, this study investigated the closure duration and aspiration duration in order to explain acoustic characteristic differences among nine Korean stops between the normal control (NC) and dysarthria groups (DG). While the absolute closure duration or aspiration duration produced by dysarthria speakers may be different from the ones produced by normal speakers, the relative ratio may be maintained. Thus, the ratio of closure duration to closure-aspiration combined duration was also included to investigate whether the relative information is more important than the absolute values.

The research questions were as follows: First, we investigated if there is a significant difference in closure duration, aspiration duration, and the ratio of closure to closure-aspiration combined duration between the dysarthria group and the normal control. Second, we explored if there is a significant difference in closure duration, aspiration duration, and the ratio of closure to closure-aspiration combined durations among the places of articulation within each group. Third, we examined if there is a significant difference in closure duration,aspiration duration, and the ratio of closure to closure-aspiration combined duration among the places of articulation within each group.

## METHODS

### Participants

The DG, comprising eight male patients with a mean age of 41;8, had traumatic brain injury (TBI), hemorrhage, or infarction as their etiological factors (Table 1). Patients were participating in speech treatments at the time of study. All patients had at least 3 months after disease onset. None showed symptoms of apraxia. Some of them reported accompanying aphasia, but not to a degree severe enough to affect understanding and performance of the given speech tasks. Patients were over 60 in aphasia quotient (AQ) of the K-WAB (Korean version-the Western Aphasia Battery) or over 70 in severity according to the MTDDA (Minnesota Test for Differential Diagnosis of Aphasia).

The NC, comprising eight male normal adults with a mean age of 41;1, was an age (±3 years) and gender-matched group with the DG. All controls had at least a high school degree education. They all spoke standard Korean language and had no problem in routine communication with no reported neurological disease at the time of study. All participants provided verbal consents to participate in the study prior to their participation.

### Speech Collection and Analyses

The /a/ vowel was inserted before and after the nine Korean stops, /p, p', $p^h$, t, t', $t^h$, k, k', $k^h$/, thereby making disyllabic target words. The words did not intend to have any meaning, but /ap'a/, /$ap^h$a/ and /aka/ meant 'father,' 'sick,' and 'baby' in Korean, respectively. The target stops were located in the middle initial position of a word because the closure duration can be measured in a spectrogram in this position. To explain the three types of phonation of Korean stops at each place level, both closure duration and aspiration duration were needed. While some studies have reported that lenis (i.e., lax stop) in Korean language becomes voiced when it is located between two vowels, other studies have also reported that the lax stop does not always become voiced in the middle of two vowels and that the voiced or unvoiced nature of the lax stop is dependent on the speaker, the rate of speech, and the phonetic context [13]. The participants were made to produce each target word three times, composing a total 432 (=16×9×3) speech samples. Most of the data were collected in a quiet environment: either in an isolated office at a church or in rehabilitation clinics in local hospitals. However, one normal participant's data were collected with potential environmental noise

**Table 1.** Participants' demographic information

| | Place of data collection | Sex | Age (year; months) | POT (months) | Etiology or diagnosis | Speech characteristics |
|---|---|---|---|---|---|---|
| P1 | Hospital | M | 20;0 | 21 | TBI | Short phrases, strained-strangled voice, harshness, vocal fry, mono-pitch, mono-loudness, imprecise consonants |
| P2 | Hospital | M | 24;1 | 12 | TBI (traumatic SAH) | Strained-strangled voice, harshness, vocal fry, variable pitch & loudness, transient hypernsality, slow AMR & SMR, imprecise consonants, distorted vowel |
| P3 | Hospital | M | 42;2 | 10 | Rt. hemiplegia d/t TBI | Short phrases, slow rate, imprecise consonants, harsh voice, mild hypernasality |
| P4 | Hospital | M | 61;9 | 5 | Rt. hemiplegia d/t Lt. pontine ICH7 impression | Mono-pitch, mono-loudness, pitch break, hoarseness, slow AMR & SMR, imprecise consonants, reduced stress |
| P5 | Hospital | M | 55;4 | 44 | Quadriparesis d/t pontine hemorrhage | Short phrases, slow rate, strained-strangled voice, harsh voice, mono-pitch, mono-loudness, diplophonia, voice tremor, imprecise consonants |
| P6 | Hospital | M | 21;11 | 3 | Rt. hemiparalysis d/t Rt. frontal & Lt. basal ganglia hemorrhage | Mono-pitch, short phrases, audible inspiration, hypernsality, imprecise consonants |
| P7 | Hospital | M | 47;11 | 14 | Quadriparesis d/t EDH, SDH epilepsy | Short phrase, imprecise consonants, harsh voice, slow AMR & SMR |
| P8 | Hospital | M | 60;5 | 17 | Lt. hemiplegia d/t Rt. lateral medullary infarct impression | Imprecise consonant (sound substitution), irregular AMR, excessive pitch & loudness variation, mild hypernasality |
| C1 | Church | M | 21;2 | | | |
| C2 | Home | M | 23;1 | | | |
| C3 | Church | M | 39;10 | | | |
| C4 | Office | M | 64;8 | | | |
| C5 | Church | M | 53;7 | | | |
| C6 | Church | M | 21;9 | | | |
| C7 | Church | M | 46;7 | | | |
| C8 | Home | M | 57;10 | | | |

POT, Post Onset Time; P, Patient; M, Male; C, Control; TBI, Traumatic Brain Injury; SAH, Subarachnoid Hemorrhage; ICH, Intracranial Hemorrhage; EDH, Epidural Hemorrhage; SDH, Subdural Hemorrhage; AMR, Alternating Motion Rate; SMR, Sequential Motion Rate.

because he was a security guard in an apartment complex and his office was not located in a completely enclosed environment. The author ensured that any noise in the speech signals was not influential to the durational measures.

The speech sample was collected through a microphone (SONY ECM-MS907) and recorded with a digital recorder (SONY MZ-R91 Minidisc Recorder) in a quiet room most of the time. The recorded speech sample was converted to a phonetic file through a sound blaster, 2-input terminal using the Multi-Speech model 3,700 program with a sampling rate of 44,100 Hz. The speech sample was cut into small segments using the Multi-Speech program and was analyzed acoustically through Praat software.

This study examined three aspects of acoustic measures: the closure duration, aspiration duration, and ratio of closure duration to closure-aspiration combined duration. Closure duration starts at the end of the preceding vowel and ends at the point of initial appearance of burst or aspiration by sudden opening of the vocal track. Aspiration duration starts at the appearance of burst or aspiration produced by sudden releasing of the oral constriction and ends at the onset of vocal fold vibration for the following vowel, which is indicated by the periodicity in the wave form and in the wideband spectrogram [49]. To determine the beginning and the ending of the vowel, the spectrogram, waveform, and recorded speech sounds were examined. The closure duration ratio was obtained by dividing the closure duration by the sum of the closure and aspiration duration.

The normality assumption was not met in a few test conditions, such as the DG's closure duration for /apa, ap$^{h}$a, ata, ak$^{h}$a/, the DG's aspiration duration for /apa, ata/, the DG's ratio of closure duration to closure-aspiration combined duration for /at'a, ak'a/, and the NC's closure and aspiration durations for /ak'a/. Thus, the researchers chose to compare the group effect on each measured duration using the Mann-Whitney non-parametric test. For the comparisons among phonation types and places of articulation within each group, the Friedman non-parametric test was used.

## RESULTS

### Comparison between groups: the closure duration, aspiration duration, and ratio of closure duration to closure-aspiration combined duration

#### *Closure duration and aspiration duration*

The DG showed a tendency for significantly longer closure duration than the NC for all stops except /at'a/ (/apa/ $p=.000$**, /ap'a/ $p=0.003$*, /ap$^h$a/ $p=0.003$*, /ata/ $p=0.007$*, /at'a/ $p=0.065$, /at$^h$a/ $p=0.002$*, /aka/ $p=0.003$*, /ak'a/ $p=0.021$*, /ak$^h$a/ $p=0.050$*). The two groups were not significantly different in aspiration durations for all stops except /ap'a/ and /at'a/ (/apa/ $p=0.161$, /ap'a/ $p=0.038$*, /ap$^h$a/ $p=0.505$, /ata/ $p=0.130$, /at'a/ $p=0.021$*, /at$^h$a/ $p=0.959$, /aka/=0.878, /ak'a/ $p=.130$, /ak$^h$a/ $p=0.798$) (Table 2).

#### *Ratio of closure duration to closure-aspiration combined duration*

As in Table 2, the ratios of closure duration to closure-aspiration combined duration for all stops were not significantly different between the DG and the NC. As shown in the Figure 1, the NC showed a reduced ratio of closure duration to the closure-aspiration combined duration as the place of articulation moved backwards (bilabial, alveolar and velar) at all types of phonation (lax, tense and aspirated types of phonation). This pattern was shown only at the tense stop in the DG.

### Comparison among types of phonation within each group

This study compared the closure and aspiration duration of three types of phonation of each group at each place level (Table 3). Both the NC and the DG showed a closure duration order of tense > aspirated > lax for all places (NC: at bilabial: $p=0.000$**, alveolar: $p=0.001$*, velar $p=0.000$**; DG: at bilabial: $p=0.021$*, alveolar: $p=0.030$*, velar $p=0.021$*). On the other hand, the aspiration duration was produced distinctively according to the types of phonation in the NC (At bilabial: $p=0.002$*, alveolar: $p=0.002$*, velar $p=0.002$*). The NC group yielded the longest aspiration duration for the aspirated stop compared to those for the other types of phonation. The DG showed longer aspiration duration of the aspirated stops compared to those of other types of phonation only at the velar place (At bilabial: $p=0.325$, alveolar: $p=0.197$, velar $p=0.030$*). In other words, the aspiration duration in the DG prominently decreased its distinctiveness among the types of phonation compared to the NC.

Ratio of closure duration to closure-aspiration combined duration differed significantly among types of phonation in the NC (Ratio bilabial: $p=0.011$*, alveolar: $p=0.005$*, velar $p=0.005$*), and the difference among types of phonation was significant only at bilabial placement in the DG (Ratio bilabial: $p=0.021$*, alveolar: $p=0.223$, velar $p=0.197$). When the ratio was significantly different among types of phonation, the ratio was significantly higher in the aspirated stop than in the tense stop (Table 3).

### Comparison among places of articulation within each group

The NC produced significantly reduced closure duration, increased aspiration duration, the reduced ratio of closure duration to the closure-aspiration combined duration, as the place of articulation moved backwards: bilabial > alveolar > velar for closure duration and ratio of closure duration to the closure-aspiration combined duration, and velar > alveolar > bilabial for aspiration duration. If there was an exception to these trends, the aspiration duration for lax stops did not differ significantly according to the place of articulation (Closure duration for lax stops: $p=0.021$*, tense stops: $p=0.002$*, aspirated stops: $p=0.002$*; Aspiration duration for lax stops: $p=0.093$, tense stops: $p=0.002$*, aspirated stops: $p=0.010$*; Ratio for lax stops: $p=0.030$*, tense stops: $p=0.000$**, aspirated stops: $p=0.002$*). The DG showed no significant differences in any of the durational measures according to the place of articulation, except the ratio of closure duration to the closure-aspiration combined duration for aspirated stops (Closure duration for lax stops: $p=0.135$, tense stops: $p=0.128$, aspirated stops: $p=0.687$; Aspiration duration for lax stops: $p=0.197$, tense stops: $p=0.417$, aspirated stops: $p=0.687$; Ratio for lax stops: $p=0.197$, tense stops: $p=0.325$, aspirated stops: $p=0.030$*). In this condition, the ratio was higher in the velar place of articulation than the bilabial place of articulation, and this pattern was opposite to the pattern shown by the NC (Table 4).

## DISCUSSION

The major findings of this study in which dysarthria participants produced nine different Korean stops in VCV context

**Table 2.** Closure duration and aspiration duration: comparison between groups

| | | Closure duration | | | | | | *p*-value |
|---|---|---|---|---|---|---|---|---|
| | | NC | | | DG | | | |
| | | Mean±SD | Median | IQR | Mean±SD | Median | IQR | |
| Bilabial | apa | 63.7±12.21[1] | 63.6 | 16.6 | 189.1±131.4 | 170.2 | 78.4 | 0.000** |
| | ap'a | 195.9±28.6 | 190.9 | 52.4 | 324.4±10.0 | 308.7 | 114.8 | 0.003* |
| | ap$^{h}$a | 155.1±31.9 | 151.7 | 52.6 | 268.2±135.7 | 218.2 | 130.0 | 0.003* |
| Alveolar | ata | 58.6±12.8 | 58.8 | 17.1 | 161.6±110.2 | 138.7 | 93.9 | 0.007* |
| | at'a | 178.4±28.6 | 183.6 | 36.0 | 257.2±114.5 | 247.2 | 112.4 | 0.065 |
| | at$^{h}$a | 144.0±35.3 | 141.1 | 30.9 | 214.7±46.1 | 209.2 | 81.3 | 0.002* |
| Velar | aka | 52.9±21.2 | 59.7 | 29.5 | 131.7±46.1 | 141.4 | 73.1 | 0.003* |
| | ak'a | 152.3±24.1 | 137.7 | 41.2 | 245.9±103.9 | 240.4 | 121.6 | 0.021* |
| | ak$^{h}$a | 120.4±24.4 | 115.1 | 39.1 | 249.8±218.6 | 186.0 | 157.2 | 0.050* |
| | | Aspiration duration | | | | | | *p*-value |
| | | NC | | | DG | | | |
| | | Mean±SD | Median | IQR | Mean±SD | Median | IQR | |
| Bilabial | apa | 19.6±20.1 | 10.3 | 39.9 | 41.8±37.8 | 33.5 | 25.9 | 0.161 |
| | ap'a | 13.3±2.8 | 12.3 | 5.6 | 41.2±30.2 | 35.1 | 31.8 | 0.038* |
| | ap$^{h}$a | 75.6±13 | 75.7 | 9.8 | 113.2±79.4 | 88.9 | 162.4 | 0.505 |
| Alveolar | ata | 26.4±16.8 | 24.9 | 29.8 | 56.3±46.5 | 42.7 | 61.6 | 0.130 |
| | at'a | 19.3±7.5 | 17.4 | 10.5 | 43.9±23.7 | 37.1 | 37.5 | 0.021* |
| | at$^{h}$a | 81.8±23.3 | 84.2 | 39.3 | 103.1±83.7 | 80.6 | 126.1 | 0.959 |
| Velar | aka | 37.9±28.1 | 42.5 | 51.4 | 45.8±45.4 | 26.6 | 62.2 | 0.878 |
| | ak'a | 34.7±21.6 | 27.1 | 16.0 | 55.5±30.2 | 50.2 | 57.7 | 0.130 |
| | ak$^{h}$a | 98.3±25.4 | 103.7 | 29.5 | 147.8±131.9 | 112.2 | 224.6 | 0.798 |
| | | Ratio | | | | | | *p*-value |
| | | NC | | | | | | |
| | | Mean±SD | Median | IQR | Mean±SD | Median | IQR | |
| Bilabial | apa | 0.81±0.16 | 0.85 | 0.33 | 0.82±0.07 | 0.81 | 0.12 | 0.959 |
| | ap'a | 0.94±0.01 | 0.93 | 0.02 | 0.89±0.06 | 0.90 | 0.09 | 0.130 |
| | ap$^{h}$a | 0.67±0.04 | 0.68 | 0.07 | 0.62±0.12 | 0.68 | 0.20 | 0.645 |
| Alveolar | ata | 0.72±0.12 | 0.70 | 0.18 | 0.73±0.17 | 0.78 | 0.35 | 0.878 |
| | at'a | 0.90±0.03 | 0.90 | 0.05 | 0.84±0.12 | 0.87 | 0.10 | 0.161 |
| | at$^{h}$a | 0.64±0.06 | 0.64 | 0.11 | 0.70±0.14 | 0.69 | 0.25 | 0.442 |
| Velar | aka | 0.66±0.18 | 0.58 | 0.24 | 0.77±0.19 | 0.79 | 0.39 | 0.382 |
| | ak'a | 0.83±0.07 | 0.84 | 0.09 | 0.80±0.15 | 0.85 | 0.08 | 0.878 |
| | ak$^{h}$a | 0.55±0.06 | 0.53 | 0.11 | 0.63±0.23 | 0.65 | 0.37 | 0.234 |

[1]millisecond. *$p<0.05$, **$p<0.001$
NC, Normal Control; DG, Dysarthria Group; IQR, Interquartile Range.

were four-fold. First, the dysarthria group had longer closure durations than the normal control group. Second, the aspiration durations of the dysarthria group were also longer than those of the normal control group, but differences did not reach statistically significant levels except for /ap'a/ and /at'a/. Third, these combined outcomes resulted in the ratios of closure duration to the closure-aspiration combined duration that did not significantly differ between the dysarthria and normal groups. Last, the dysarthria group could change the durational aspects of stop production distinctively according to the types of phonation more than they could according to the places of articulation. This trend was more prominent

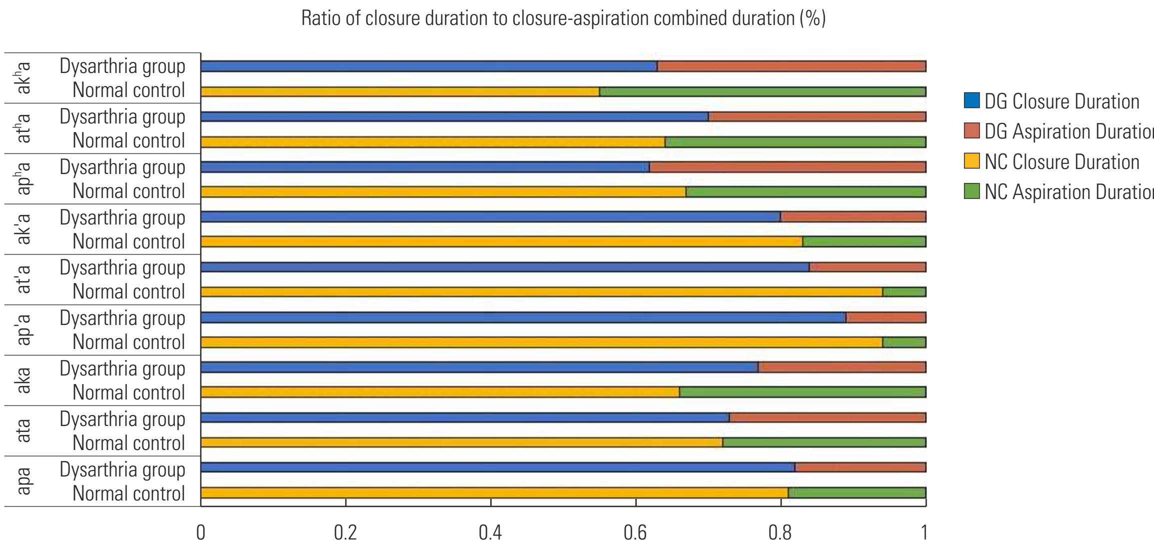


**Figure 1.** Comparison between groups: the ratio of closure duration and aspiration duration to the closure-aspiration combined duration for each stop. DG, Dysarthria Group; NC, Normal Control.

**Table 3.** The distinctiveness of closure and aspiration duration according to the types of phonation within groups

| Groups | Place of articulation | Type of phonation | Closure duration | | Aspiration duration | | Post-hoc (Bonferroni corrected) | |
|---|---|---|---|---|---|---|---|---|
| | | | Test stat | *p*-value | Test stat | *p*-value | CloD | AspD |
| NC | Bilabial | p-pʰ-p' | 16.000 | 0.000** | 12.250 | 0.002* | Tense>Lax | Asp>Lax or Tense |
| | Alveolar | t-tʰ-t' | 14.250 | 0.001* | 13.000 | 0.002* | Tense>Lax | Asp>Lax or Tense |
| | Velar | k-kʰ-k' | 16.000 | 0.000** | 12.000 | 0.002* | Tense>Lax | Asp>Lax or Tense |
| DG | Bilabial | p-pʰ-p' | 7.750 | 0.021* | 2.250 | 0.325 | Tense>Lax | |
| | Alveolar | t-tʰ-t' | 7.000 | 0.030* | 3.250 | 0.197 | Tense>Lax | |
| | Velar | k-kʰ-k' | 7.750 | 0.021* | 7.000 | 0.030* | Tense>Lax | Asp>Lax |

| Groups | Place of articulation | Type of phonation | Ratio | | Post-hoc (Bonferroni corrected) |
|---|---|---|---|---|---|
| | | | Test stat | *p*-value | |
| NC | Bilabial | p-pʰ-p' | 9.000 | 0.011* | Asp>Tense |
| | Alveolar | t-tʰ-t' | 10.750 | 0.005* | Asp>Tense |
| | Velar | k-kʰ-k' | 10.750 | 0.005* | Asp>Tense |
| DG | Bilabial | p-pʰ-p' | 7.750 | 0.021* | Asp>Tense |
| | Alveolar | t-tʰ-t' | 3.000 | 0.223 | |
| | Velar | k-kʰ-k' | 3.250 | 0.197 | |

*$p<0.05$, **$p<0.001$
CloD, Closure Duration; AspD, Aspiration Duration; Asp, Aspirated Stop.

during the closure duration than during the aspiration duration.

This study examined the acoustic characteristics appearing in the stops that distinguish the dysarthria group from the normal control group. The dysarthria group showed significantly longer closure duration than the normal control group at all phonation types and places of articulation except at the alveolar tense stop (/at'a/). This longer duration implicates slower articulatory movements.

On the other hand, no group differences were observed in the length of aspiration duration except /ap'a/ and /at'a/ conditions in the current study. A previous study also showed that the aspiration duration of most stops produced by a cerebral palsy group did not show significant difference with a normal

**Table 4.** The distinctiveness of closure and aspiration duration according to the places of articulation within groups

| Groups | Type of phonation | Place of articulation | Closure duration | | Aspiration duration | | Post-hoc (Bonferroni corrected) | |
|---|---|---|---|---|---|---|---|---|
| | | | Test stat | *p*-value | Test stat | *p*-value | CloD | AspD |
| NC | Lax | p-t-k | 7.750 | 0.021* | 4.750 | 0.093 | Bilab>Velar | |
| | Tense | P'-t'-k' | 12.250 | 0.002* | 12.250 | 0.002* | Bilab>Velar | Velar>Bilab |
| | Aspirated | $p^h$-$t^h$-$k^h$ | 13.000 | 0.002* | 9.250 | 0.010* | Bilab or Alveo>Velar | Velar>Bilab or Alveo |
| DG | Lax | p-t-k | 4.000 | 0.135 | 3.250 | 0.197 | | |
| | Tense | p'-t'-k' | 2.830 | 0.128 | 1.750 | 0.417 | | |
| | Aspirated | $p^h$-$t^h$-$k^h$ | 0.750 | 0.687 | 0.750 | 0.687 | | |

| Groups | Type of phonation | Place of articulation | Ratio | | Post-hoc (Bonferroni corrected) |
|---|---|---|---|---|---|
| | | | Test stat | *p*-value | |
| NC | Lax | p-t-k | 7.000 | 0.030* | Bilab>Velar |
| | Tense | p'-t'-k' | 16.000 | 0.000** | Bilab>Velar |
| | Aspirated | $p^h$-$t^h$-$k^h$ | 13.000 | 0.002* | Bilab or Alveo>Velar |
| DG | Lax | p-t-k | 3.250 | 0.197 | |
| | Tense | p'-t'-k' | 2.250 | 0.325 | |
| | Aspirated | $p^h$-$t^h$-$k^h$ | 7.000 | 0.030* | Velar>Bilab |

*$p<0.05$, **$p<0.001$
CloD, Closure Duration; AspD, Aspiration Duration; Bilab, Bilabial; Alveo, Alveolar.

group except for /ap'a/ and /ak'a/ [45]. Furthermore, according to Caruso and Burton [50] and Kent [51], the VOT of the dysarthria group, which corresponds to the aspiration duration of stops in the current study, was not different from that of the normal control group. Fischer and Goberman [40] noted no group differences in VOT length between the hypokinetic dysarthria English speakers and the normal English speakers. Similarly, Park [41] reported Korean children with cerebral palsy showed a longer closure duration and a longer syllable segment duration than the normal group, but there was no statistically significant difference in VOT. Thus, based on these previous and current study findings, it was speculated that despite the motor speech disorder, the speakers with dysarthria still tried to maintain a VOT length close to normal levels.

Additionally, the results regarding the ratio of closure duration to closure-aspiration combined duration, which did not differ significantly between the normal control group and the dysarthria group at all consonant conditions, suggest that speakers with dysarthria may try to maintain the ratio as closely as possible to that of normal speakers. This information is interesting because it suggests the importance of relativeness in the acoustic information that both normal and dysarthria speakers try to maintain for their intelligibility. Based on the schema theory notion, the importance of relative information in the acoustic signals for speech has been proposed by Kim et al. [52].

The dysarthria group in this study showed abnormally longer closure duration as well as relatively normal aspiration duration than the normal control group did. Usually, an acoustic feature like closure duration reflects tenseness, while aspiration duration is associated with an aspiration feature and related timing control in their speech mechanisms. Thus, this study result suggests that dysarthria patients have relatively more difficulty in controlling tension in their speech mechanisms, such as making constrictions (or closure) and maintaining the tone, compared to controlling the timing of the supra-laryngeal and laryngeal movements and forming aspiration features for stops [53]. However, because closure duration was not significantly different from normal speakers for /at'a/ sound, dysarthria patients appeared to be relatively better at controlling tenseness at the alveolar placement and not at other placements in the current study. In other words, this result suggests that controlling the tenseness using tongue tip was easier for the dysarthria speakers than those of other articulatory structures.

Additionally, there seemed to be a trade-off between the ability to produce closure duration and the ability to produce aspiration duration. While the dysarthria group produced abnormally longer closure duration and relatively normal range of aspiration duration in almost all stop consonants, the dysarthria group produced a normal range of closure duration and abnormally longer aspiration duration only in the /at'a/ condition. Thus, the dysarthria group appeared to achieve accuracy in the closure duration for /at'a/ condition at the expense of accuracy of aspiration duration. Furthermore, significantly longer aspiration durations in /ap'a/ and /at'a/ conditions in the dysarthria group than in the normal control group suggest the dysarthria group has greater difficulty controlling the precise timing of aspiration durations of bilabial and alveolar tense stops. Tense stops have the shortest aspiration durations among all phonation types. Thus, this result may be a natural consequence when considering generally slowed articulatory movements of the dysarthria group.

While measuring closure and aspiration durations, the first author noticed that the closure duration was frequently observed to be voiced in the dysarthria speech samples on the spectrograms. It appeared as a continuing voicing bar (or fundamental frequency) during the closure gap. If voicing occurs in the closure duration, it becomes harder to find bursts or aspirations after the closure period on the spectrogram. Therefore, based on the present research data, a relatively higher frequency of omissions of the aspiration duration was observed after voiced closure durations. Under this influence, it was expected that the average aspiration duration would be shortened in a few stop conditions in the dysarthria group regardless of phonation types. This higher frequency of voiced closure duration may reveal a limited ability to control the laryngeal mechanism in the dysarthria group. Despite this fact, although it did not reach a statistically significant level, the average absolute values of aspiration duration were still longer in the dysarthria group than the normal control group in all stop consonants. This longer average absolute values of aspiration duration indicated the overall slow speech production habit in the dysarthria group.

The closure duration differed distinctively based on the types of phonation in both the normal control and the dysarthria group. This result is surprising because the researchers concluded above that overall closure duration was longer in the dysarthria group than in the normal control group. Thus, it appeared that the dysarthria group, despite their slower articulatory movement, was able to make the distinctive differences in the closure timing required to produce different phonation types. However, a more controlled ability to make distinctive closure duration according to the types of phonation and a less controlled ability to make distinctive aspiration duration according to the types of phonation in the dysarthria speakers reveal that, despite their slower articulatory movements, the dysarthria speakers can generate distinctive articulatory tenseness in order to produce different phonation types of phonation.

In the normal control group of the current study, the aspiration duration also differed distinctly based on the types of phonation, demonstrating a longer aspiration duration of aspirates than that of a lax or a tense stop. However, in the dysarthria group, the aspiration duration was longer in the aspirated stop than in a lenis only at the velar placement (Table 3). That is, the dysarthria group could form longer aspiration duration for aspirated stops than for lax stops only at the velar placement. Thus, while the absolute aspiration durations did not differ significantly between the normal and dysarthria speaker groups (Table 2), making discrimination in aspiration duration based on the types of phonation was remarkably reduced in the dysarthria group than in the normal control group. It is not clear why the dysarthria group was poorer in controlling aspiration durations in other places of articulation. Hardcastle [25] reported that articulation using the tip of the tongue is an easy kinetic function for anyone, and the bulk of the tongue is smaller than that of the lips. Thus, the tongue motion is faster, and duration of articulation using the tongue is shorter [20]. However, the reason why the dysarthria group's production of aspiration duration at the alveolar place of articulation was not as easy and distinctive as it was at the velar place of articulation is unknown. One possible explanation is the large individual variation in the dysarthria group, as indicated by the large standard deviations in both bilabial and alveolar places of articulation, may have affected the statistical results of aspiration duration. In addition, the ratio distinction among the types of phonation was maintained only at the bilabial placement in the dysarthria group. This result implies that the failure to make enough ratio distinction among types of phonation may be the cause of reduced intelligibility in this speaker group.

The results of group comparison of the closure duration based on the places of articulation corresponded to those of the existing studies for normal participants. The existing studies indicated that closure duration increased as the articulatory place approached the front of the vocal tract [25-29]. The length of the closure duration of the superoinferior lips was the first, and it was followed by those of the alveolar and velar places of articulation. Hardcastle [25] suggested that the closure duration of the velar stops is shorter than those produced in other articulation placements because the motion of the tongue body, which functions as the articulator for the velar stop, is slower than that of the tongue tip or lips that function as the articulators for alveolar and bilabial stops respectively.

The normal control group could produce the closure and aspiration durations distinctively across different places of articulation in all phonation types except the aspiration duration for the lax stop condition. This research result of normal control corresponded to Hardcastle's [25] findings. He reported that normal participants demonstrated smaller obturated back cavity for velar stop than those for bilabial or alveolar stops. As the back cavity was formed by the constriction in the velar place, the subglottic pressure and the delay before the vibration initiation for the succeeding vowel increased. This increased pressure and delay resulted in the longest aspiration duration for the velar stop, followed by the alveolar and bilabial stops. This result corresponded with the findings of the present study.

This finding was not in line with Jeong et al.'s [44] findings because Jeong, et al. reported inconsistent and nonsignificant changes in the closure and aspiration duration according to articulatory placements in both low functioning cerebral palsy patients and normal speakers. They observed a few significant changes according to the articulatory placements only in the high functioning cerebral palsy group. Because of the inconsistent pattern shown on their data according to articulatory placements, it is hard to address to what condition the current data matched with theirs. It was concluded that the group differences in the dysarthria speaker selection between their study (on patients with cerebral palsy) and the current study (on non-cerebral palsy patients) may have resulted in different outcomes.

On the contrary, it was difficult to distinguish the places of articulation by measuring and observing the closure and aspiration durations in the dysarthria group. This result suggests that the range of movement of the articulatory organs is limited in the dysarthria group. The closure and the aspiration durations were different among different places of articulation, and patterns of change were similar to those of normal participants. However, differences among places of articulation did not reach the statistically significant level in the dysarthria group. Also, in a few cases, the dysarthria speakers did not change the durational aspects in the way the normal control group did (according to the places of articulation): neither the closure duration in aspirated stop nor the aspiration duration in lax and aspirated stops followed the normal patterns of change among places of articulation. Thus, it was inferred that the dysarthria group may have difficulty in reaching articulatory targets and these articulatory targets can be centralized. All of the dysarthria participants in this study demonstrated imprecise consonants when their speech samples were played back to the authors during the acoustic analysis. These current acoustic study results corroborated the auditory perceptual impression that the first author had.

The acoustic energy appearing in aspiration and transition durations to the following vowel has been a major cue for places of articulation among stop consonants [54]. However, the current study provided the evidence of systematic changes in the closure duration, aspiration duration, and the ratio of the two as the place of articulation changed from front to back in normal individuals, although it did not reach a statistically significant level at the aspiration duration for the lax stop condition. Thus, although the number of participants in the current study was small, because this pattern was observed in normal Korean speakers, it may be legitimate to generalize the results to general speakers. Future researchers and clinicians can utilize these relative durational measures to infer about the places of articulation for Korean stop consonants. Furthermore, these durational measures for Korean stops can be considered for use as an index for intelligibility.

Lastly, dysarthria patients have limited ability to coordinate the timing between the laryngeal and supra-laryngeal level mechanisms while producing stops. Such timing coordination between supra-laryngeal articulatory and laryngeal mechanisms is necessary to produce VOT or aspiration duration. When the coordination is not operated systematically, voiceless stops may be converted to voiced stops due to continuation of vocal cord vibration during the closure duration. In addition, the aspiration duration is frequently omitted when this voicing happens. Kent et al. [55] stated that some patients diagnosed with dysarthria, especially those with Parkinson disease, expelled energy even during closure duration, and that energy was returned to noises or voiced sounds. Kent et al. [55] further stated that noise was made by incomplete closure when an articulatory organ was constricted and that voiced energy was caused by the disharmonious coordination between the laryngeal and supra-laryngeal level mechanisms. Such phenomena were observed in this study. Dysarthria speakers of this current study demonstrated frequent frication noises or voicing features on the spectrogram during the closure duration. To summarize, the current study results indicated the restricted timing coordination between the laryngeal and supra-laryngeal level mechanisms in dysarthria patients.

The findings of the current study are difficult to generalize due to the small number of participants and because these participants produced Korean stops in a restricted speech context. Further investigation is needed to include more speakers with dysarthria in more diverse speech contexts (e.g., phrases, sentences). Future studies could also explore more extensively how durational measures differ among dysarthria subtypes.

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