# Induced Velopharyngeal Fatigue Effects in Speakers with Repaired Palatal Clefts

Jerald B. Moon, Ph.D.[1], David P. Kuehn, Ph.D.[2], Grace Chan, Ph.D.[3], Lili Zhao, M.S.[4]

[1] Associate Professor, Dept. of Speech Pathology & Audiology, University of Iowa, Iowa City, IA

[2] Professor, Dept. of Speech & Hearing Science, University of Illinois, Champaign, IL

[3] Director, Statistical Consulting Center, Dept. of Statistics and Actuarial Science, University of Iowa, Iowa City, IA

[4] Research Assistant, Statistical Consulting Center, Dept. of Statistics and Actuarial Science, University of Iowa, Iowa City, IA

Send correspondence to:
Jerry Moon, Ph.D.
University of Iowa
Dept of Speech Pathology & Audiology
122E WJSHC
Iowa City, IA 52242
(319) 335-8722
jerald-moon@uiowa.edu

Presented at annual meeting of the American Cleft Palate-Craniofacial Association, April, 1998

Running Title: Velopharyngeal fatigue

# ABSTRACT

*Objective*: To address whether speakers with cleft palate a) exhibit velopharyngeal mechanism fatigue specifically involving the levator veli palatini (LVP) muscle, and b) are more susceptible to muscle fatigue than are speakers without cleft palate?

*Methods*: Six adults with repaired palatal clefts and mild-moderate hypernasality served as subjects. Velopharyngeal closure force and levator veli palatini muscle activity were recorded. Subjects were asked to repeat /si/ 100 times while an external load consisting of air pressure (0, 5, 15, 25, 35 cm $H_2O$) was applied via a mask to the nasal side of the velopharynegal mechanism. Fatigue was defined as a reduction in velopharyngeal closure force across the series of /si/ productions, as evidenced by a negatively sloped regression line fit to the closure force data.

*Results*: Absolute levels of velopharyngeal closure force were much lower than those observed previously in speakers without palatal clefts. All subjects showed evidence of fatigue. Further, all subjects demonstrated exhaustion, where they were unable to close the velopharyngeal port against the nasal pressure load. This occurred at pressure load levels lower than those successfully completed by speakers without cleft palate.

*Conclusions*: In speakers with a repaired palatal cleft, the LVP may not possess the same strength and/or endurance that normal speakers possess. Alternatively, the muscle may possess adequate strength, but not be positioned optimally within the velum following cleft palate repair, or be forced to move a velum that is stiffer as a result of surgical scarring.

*Key Words*: fatigue, closure force, velopharyngeal function

The physiologic work required of muscles in the normal speech mechanism during the production of speech is generally accepted to fall towards the lower end of the effort range. For example, lip muscle forces used for speech reach only 10-20 % of maximal lip attainable forces (Barlow and Abbs, 1983; Amerman, 1993). Lingua-alveolar contact forces recorded during consonant production typically fall below 5-10 % of maximal tongue-hard palate contact forces recorded in nonspeech tasks (Robin et al., 1992). Maximum interlabial pressures during /p/ production fall below 20% of maximum (Hinton and Arokiasamy, 1997). Levator veli palatini (LVP) muscle activation levels recorded during speech also fall near the lower end of their total range as determined in nonspeech tasks (Kuehn and Moon, 1994). In other words, the production of speech by normal speakers is a relatively non-taxing activity. Stated differently, "the demands of ordinary speech production fall well within the limits defined by the measures of maximum performance" (Kent et al., 1987; p. 382). As a result, speakers have some reserve capacity that may be drawn upon.

However, some speakers with disordered speech production mechanisms may exhibit reduced strength, or a reduced reserve capacity as greater than normal levels of muscle effort are required for some articulatory gestures. Prolonged contraction of a muscle at levels nearing maximum involves a great deal of physiologic effort (McHenry et al., 1994) and puts the muscle at risk for fatigue. Fatigue is defined as "any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation" (Bigland-Ritchie and Woods, 1984).

Fatigue has been studied in a number of structures involved in speech production, including the tongue, lips, jaw, larynx, and the respiratory system (see Kuehn and Moon, 2000 for references). In general, the consequence of a reduced capacity of the muscles involved in speech articulation to generate sufficient contractile forces is a reduction of articulatory contact force and/or a reduction in the ability to sustain such force over time. In the case of the velopharyngeal mechanism, fatigue of the LVP might be expected to reduce or remove the ability to maintain velopharyngeal closure force and hence, separation of the oral and nasal cavities during oral sound production. Exceeding the threshold of fatigue would lead to excessive hypernasality.

As stated earlier, Kuehn and Moon (1994) reported that the LVP muscle of non-cleft palate subjects functioned towards the lower end of the total operating range, thereby easily avoiding a fatigue state. However, speakers with repaired palatal clefts have been shown to use levels of LVP muscle activity that neared the high end of their total operating range when completing the same speech tasks (Kuehn and Moon, 1995), therefore possibly approaching or perhaps even exceeding a threshold for fatigue should one exist. This phenomenon might explain the hypernasality associated with borderline velopharyngeal inadequacy. That is, speakers who may be able to achieve a tight velopharyngeal seal by maximally contracting the LVP might choose to use lower levels of muscle activation, even though some degree of hypernasality would result, in order to avoid fatiguing the muscle and enduring the excessive hypernasality associated with that physiologic condition.

Velopharyngeal fatigue in normal subjects after prolonged effortful playing of wind instruments has been reported (Bless et al., 1983, Malick et al., 2005). However, the concept of fatigability of the LVP in relation to speech has only recently been addressed. Kuehn and Moon (2000) assessed the susceptibility of normal adult speakers to the effects of induced physiologic fatigue. Velopharyngeal closure force was monitored as speakers repeated the syllable /si/ in one of five different velar loading conditions. Loads were applied by introducing varying magnitudes of air pressure to the nasal cavity. All subjects were capable of resisting fatigue at the lower load levels. Fatigue was observed at the highest load levels, although not for all subjects and not to the same degree. Two subjects studied by Kuehn and Moon (2000) reached a state of exhaustion at higher load levels. As defined by Kuehn and Moon. Exhaustion is "manifested as the lack of a functional separation between the oral and nasal cavities" (p. 496). The results of the Kuehn and Moon (2000) study reinforced the notion that velopharyngeal closure for normal speakers is relatively effortless under typical speaking conditions, but that fatigue and/or exhaustion may be induced once the LVP is required to perform closer to maximal voluntary contraction levels. Tachimura et al. (2004) and Nohara et al. (2006) demonstrated in their studies of three and five speakers, respectively, that the LVP muscle of speakers with repaired palatal clefts showed evidence of fatigue during speech and non-speech tasks that did not result in fatigue in normal speakers.

The adult speakers with repaired palatal clefts studied by Kuehn and Moon (1995) used a relatively high LVP activation level during speech in relation to their total operating range. One might expect that this population is more susceptible to fatigue for that reason. In view of this possibility, the purpose of this study was to address the following research questions:

1) Do speakers with cleft palate exhibit fatigue of the velopharyngeal musculature, specifically the levator veli palatini muscle?

2) Are speakers with cleft palate more susceptible to fatigue of the levator veli palatini muscle than speakers without cleft palate who have been studied previously?

## METHODS

### Subjects

Six adult speakers with repaired palatal clefts served as subjects. Subject ages, gender and cleft type are reported in Table 1. All speakers were judged to exhibit mild-moderate hypernasality as judged by the authors. They had received varying amounts of speech therapy in the past, although none were enrolled in therapy at the time of this study. None of the subjects had undergone secondary surgical management for velopharyngeal dysfunction. Approval for the study was obtained from the Institutional Review Board at the University of Iowa. Informed consent was obtained from each participant subject.

### Independent Variable

Velar loads in the form of constant nasal air pressures to test fatigability in the subjects were supplied by a reverse-flow commercial vacuum cleaner. A variable transformer was used to control the voltage delivered to the vacuum cleaner and hence the level of air pressure output to the subject. Five target velar loading conditions were investigated. As was in the case with our previous study (Kuehn and Moon, 2000), air pressures delivered to the subjects through the nasal mask were: 0 (control condition with vacuum cleaner turned off but with nasal mask on), 5, 15, 25, and 35 cm $H_2O$. As explained by Kuehn and Moon (2000), pilot work determined that the 35 cm$H_2O$ level was safe for subjects.

### Dependent Variables

#### Velopharyngeal Closure Force

Velopharyngeal closure force was transduced using a silastic bulb described by Moon et al. (1994). The teardrop-shaped bulb, flattened anteriorly and posteriorly, is 5 mm thick and 10 mm wide at its widest point. The advantages of the size and shape of the bulb have been discussed previously (Moon et al., 1994, 1995; Kuehn and Moon, 1998). Because the bulb is soft and pliable, and collapsible upon insertion, it is relatively easy to use with most individuals. The bulb is attached to a silastic tube (3 mm outside diameter) that is, in turn, attached externally to a Honeywell Microswitch (model 162PC01D; Honeywell, Freeport, IL) pressure transducer. Transducer output was amplified using a BioCommunications Electronics (model 205; BioCommunications Electronics, Madison, WI) amplifier. The bulb was bench calibrated following procedures outlined by Moon et al. (1994). All closure force values are reported in grams.

To facilitate bulb insertion, a light spray of 2% Lidocaine topical anesthetic was applied to the more patent nasal passage. A negative pressure was exerted on the bulb and tube assembly to flatten the bulb. The force bulb was lightly coated with a surgical lubricant and slid through the nasal cavity. Once positioned in the velopharynx, the tube was attached to the pressure transducer and its output observed on an oscilloscope. The bulb was moved up and down in the velopharynx as the subject produced a series of /s/ sounds until peak force levels were observed on the oscilloscope. Once optimally placed, the bulb tube was taped to the nose to secure the bulb in its vertical position.

### Muscle Activity

LVP muscle activity was recorded using fine-wire 110 µm stainless steel intramuscular electrodes. The electromyographic (EMG) signals were amplified using BioCommunications Electronics preamplifiers (model 301) and amplifiers (model 205).

A light spray of 2% Lidocaine was applied to the oral cavity to facilitate EMG electrode insertion. The electrode wire were threaded through disposable 30 gauge hypodermic needles, and inserted perorally into the dimple of the velum at an angle following the course of the LVP muscle, to a depth of approximately 10 mm. Placement validation involved the observation of EMG activity in association with sustained /s/ production.

### Voice Signal

The audio signal from a dynamic microphone was amplified using a Nakamichi preamplifier (MakUSA, Santa Monica, CA) and Tascam tape recorder (model 22-4; TASCAM, Montebello, CA) amplifier.

## Experimental Procedure

Once the electrode wires were placed in the LVP and checked for signal acceptability, the force bulb was inserted and positioned in the velopharynx. The force bulb tube was then passed through a small hole in a nasal mask and attached to the pressure transducer. The nasal mask was positioned over the face to cover the nose so that air pressure supplied by an external source could be applied to the nasal cavities.

For each subject, completion of the 0 cm $H_2O$ condition was followed by the remaining conditions in increasing magnitude of pressure. This sequence was utilized to avoid the possibility of latent fatigue effects from a higher pressure condition influencing the results of a subsequent lower pressure condition. A 1.5-minute silent rest interval was used between each pressure condition in an attempt to restore the neuromuscular system to a non-fatigued state and to prevent any fatigue “overflow” into the subsequent pressure condition. If a given subject was unable to initiate the task at a given pressure level, the task was repeated at a lower intermediate level (i.e., 10 $cmH_2O$, 20 $cmH_2O$). An attempt was made to have each subject complete at least four conditions. However, two subjects (Subject 2, Subject 6) were able to complete only the three lowest pressure conditions.

Following each rest interval, subjects were instructed to prolong /s/ as nasal mask pressure was monitored and the pressure source adjusted to the next nasal pressure level. This adjustment required about 30 seconds.

For each velar loading condition, subjects were asked to repeat the syllable /si/ 100 times at a conversational rate and loudness, and to inhale quickly between breath groups. Table 2 shows syllable production rates for each subject in each condition, measured over the first 20 syllables within each condition. Although a slightly higher rate was observed for Subject 3 at 0 cm $H_2O$ and for Subject 5 at 5 cm $H_2O$, it appears that the subjects were successful in maintaining relatively stable speech rates across conditions.

## Data Recording and Analysis

Force bulb, EMG activity, and the audio signal were monitored on an oscilloscope (Tektronix model 5111A; Tektronix, Richardson, TX) and recorded on a Sony digital instrumentation recorder (model PC108M; Sony Corp, New York, NY). EMG signals were full-wave rectified, low-pass filtered at 25 Hz, and digitized at a sampling rate of 5000 Hz. Voice and force bulb signals were digitized at a 1000 Hz sample rate. A laboratory computer and commercially available digitization software were used for signal processing. Once digitized, closure force signals were digitally low-pass filtered at 30 Hz.

LVP EMG activation levels were normalized within each subject by identifying the maximum peak value across the entire data set for a given subject and setting that value to 100%.

All other EMG values recorded for that subject were referenced to the maximum value.

Force and EMG measures were recorded during the vowel /i/ to ensure that force measures were related to LVP muscle activity and not influenced indirectly by heightened air pressure in the oral cavity. That is, a loss of tight contact between the velum and posterior pharyngeal wall as fatigue begins to occur could expose a portion of the force bulb to the oral cavity, where elevated oral air pressures during /s/ could apply a force to the bulb unrelated to LVP muscle activation. During vowel production however, intraoral air pressures are at or near atmospheric, leaving only velum-pharyngeal wall contact forces generated by soft palate musculature as the sole determinant of force bulb output.

Although each subject attempted to produce at least 100 syllable repetitions, fewer than 100 velopharyngeal closure force and EMG measurements were obtained in many cases. This was most often due to subjects stopping before reaching 100, but in a few instances signal noise or artifact precluded accurate measurement. In all but one trial, greater than 80 syllable repetitions were measured.

Intra- and intermeasurer reliability were determined for similar force and EMG data in a previous study (Kuehn and Moon, 1998). All Pearson r values exceeded 0.98.

## RESULTS

Tables 3 and 4 show mean velopharyngeal closure force and LVP EMG values for the initial 15-syllable repetitions compared to the final 15-syllable repetitions measured for each subject and nasal cavity pressure condition. Absolute velar closure force levels generated by the subjects were generally low, especially in the 0 cm $H_2O$ condition (Table 3). Forces tended to increase with increasing magnitudes of velar loading, although the magnitude of force increase with increasing velar load varied across subjects. Although some evidence of the same pattern may be seen in the EMG data (Table 4), increases did not occur as consistently across velar loading conditions.

Fatigue was operationally defined as a declination of velopharyngeal closure force over the duration of a task, even though velopharyngeal closure might be maintained. Exhaustion was defined as the inability to functionally separate the oral and nasal cavities.

One approach in studying the effects of physiologic fatigue is to compare the final tokens of a task to the initial tokens of the same task. No subject was able to complete the task at the highest load level (35 cm $H_2O$), and only one subject was able to reach 25 cm $H_2O$. Each of the subjects demonstrated exhaustion at some level at or below 35 cm $H_2O$. As mentioned previously, exhaustion represents an inability to functionally separate the oral and nasal cavities. Subjects experiencing exhaustion could not generate enough closure force to counteract the pressure in the nasal cavity. This occurred at 35 cm $H_2O$ for one subject, 25 cm $H_2O$ for another subject, 20 cm $H_2O$ for two subjects, and at 15 cm $H_2O$ for two subjects.

In most cases (17/22; 77%), mean velopharyngeal closure force was lower for the final syllables than the initial syllables. With respect to EMG, the pattern was variable. In some instances, average muscle activity was higher for the initial fifteen syllables, whereas in other instances it was lower (see Figure 1 for examples). A similar pattern of EMG activity was observed by Kuehn and Moon (2000), who pointed out that muscle activation levels are not consistently associated with changes in closure force, and therefore with fatigue. For this reason, as was done by Kuehn and Moon (2000) in their description of velar fatigue in normal speakers, the results pertaining to closure force only will be presented.

Table 5 shows the statistical results of comparing the difference measures (initial 15 syllables versus the final 15 syllable values) using a Wilcoxon signed rank test. This analysis revealed no significant differences between the initial and final 15 syllables at any condition.

In order to further explore for evidence of physiologic fatigue, changes in closure force observed over all syllables produced within each condition were assessed. Because there is no standard method of portraying fatigue as expressed in the literature, other than demonstrating a declination in force over time, we decided to focus on the slope of the regression line relating force to syllable number as an indication of fatigue. The linear regression line in Figure 1 indicates the slope of the closure force function with respect to syllable number.

Table 6 indicates negative slope values in the 5, 10, 15, 20, and 25 cm $H_2O$ conditions completed by the subjects, with one exception. Subject 5 had a positive slope at 5, 10, and 15 cm $H_2O$. These slope values were statistically tested against the value zero. Only Subjects 2 and 3 showed fatigue at the 0 cm $H_2O$ condition. Subjects 5 and 6 demonstrated fatigue only at the highest level attempted. However, Subject 6 was not able to complete the task at air pressures above 10 cm $H_2O$. Subjects 2, 3, and 4 showed evidence of fatigue at every pressure level attempted, with the exception of 0 cm $H_2O$ for subject 4.

Using the slope of the regression line, as shown in Figure 1 and Table 6, as an indication of fatigue, greater negative slope values are considered to reflect a greater rate of fatigue. Table 7 illustrates the relationship between rate of fatigue and nasal cavity pressure for each subject. A negative correlation indicates that the subject’s slopes tended to decrease as the nasal cavity pressure increased. Although all the correlations are negative, only Subjects 3 and 6 reached statistical significance. That is, the greater the air pressure delivered to the nasal passages, the greater the rate of physiologic fatigue experienced by Subjects 3 and 6.

Averaged across all subjects, nasal cavity pressure had a significant effect on fatigue rate

($p = 0.0453$). However, the effect may not be linear ($p=0.5733$) over the range of pressures tested in this experiment. To further investigate the nature of this relationship, slope values at each experimental condition were compared to that of the control condition (0 cm $H_2O$). As shown in Table 8, fatigue rate at 10cm $H_2O$ and 15cm $H_2O$ was significantly different from the rate at 0 cm $H_2O$ ($p=0.0079$ and $p=0.0415$ respectively). However, there was insufficient evidence to support a significant difference for other comparisons with the control condition, or between any pair of the experiment conditions.

## DISCUSSION

### Absolute Closure force Levels

One of the more striking findings of this study involves absolute closure force levels attained by the six subjects during speech attempts. Using a similar study paradigm, Kuehn and Moon (2000) reported closure force levels for normal adult speakers ranging from 10 – 34 cm $H_2O$ during the 0 cm $H_2O$ load condition, with 8 of the 10 subjects exceeding 20 cm $H_2O$. Comparable values for the speakers with repaired palatal clefts studied here ranged from only 0.31 – 7.10 cm $H_2O$. These magnitudes of closure force are also substantially lower than those reported by Moon et al. (1994) for normal adults during vowel production. Clearly, the speakers with repaired palatal clefts studied could not, or chose not to, generate closure forces typical of normal speakers.

This inability could be attributed to a number of factors. It is possible that, compared to normal speakers, the speakers with cleft palate were trying to close the velopharyngeal port using an LVP muscle that is a) less massive, b) positioned in the velum in such a manner as to have reduced lifting capabilities, or c) that may be different from normal LVP muscle. Relative to the third possibility, previous investigators have observed a greater proportion of Type II fatigable muscle fibers as well as smaller diameter velopharyngeal muscle fibers in individuals with cleft palate (Schendel et al., 1994; Lindman et al., 2001; Collins, 2003). Mitochondrial abnormalities have also been observed in the LVP of speakers with cleft palate (Schendel et al., 1994; Morgan, 2002; Collins et al., 2005).

Interestingly, all of the speakers in the current study increased the magnitude of velar closure force as the load on the velum was increased. So, it appears that these speakers were capable of generating higher closure force levels than observed in the no-load condition, but chose not to. A similar pattern was observed in normal speakers by Kuehn and Moon (2000). As stated by Kuehn and Moon, this pattern of increasing velopharyngeal closure force associated with increased levels of nasal air pressure can be taken as evidence that any latent fatigue effects did not carry over to the subsequent nasal air pressure condition.

## Fatigue versus Exhaustion

As shown in Table 6, significantly negative force regression slopes were observed during at least one condition for all 6 subjects, indicative of fatigue occurring during the trial. For two subjects (2 and 3), fatigue was observed during each completed condition. For Subject 4, fatigue was observed at the three highest nasal air pressure conditions completed. For Subjects 5 and 6, fatigue was observed at only the highest nasal air pressure condition completed.

A test of fatigue rate (slope of regression line) across nasal air pressure conditions (Table 7) revealed a statistically significant effect only for Subjects 3 and 6. For both of these subjects, as can be seen in the “Slope” column of Table 6, the negative slope of the regression line successively increased across each of the conditions completed. Although not statistically significant, some similar trends were observed for other subjects. Rate of fatigue increased from 0 to 5 and again to 15 cm $H_2O$ for Subject 1, and from 0 to the other three conditions completed for Subjects 4 and 5. Only Subject 2 showed no change in fatigue rate across conditions. Interestingly, this subject's fatigue rate at 0 cm $H_2O$ was much higher than observed in the other five subjects for the baseline condition.

The regression slope results, although not consistent across all subjects, do show that the subjects were susceptible to velopharyngeal fatigue. Differences observed between subjects may well be due to the fact that all of these speakers were using a surgically repaired velopharyngeal mechanism. Although specific details regarding factors such as initial cleft condition, type of repair, and surgeon are not available, these six subjects did differ in these regards.

Of perhaps even more interest than the fatigue slopes observed, was the observation that no subject was able to complete all of the nasal cavity air pressure conditions. Of the 10 normal subjects studied by Kuehn and Moon (2000), all but one was able to complete the task at the highest nasal cavity condition (35 cm $H_2O$). Of the six subjects enrolled in the current study, two were not able to advance past the 10 cm $H_2O$ condition, another two were not able to pass the 15 cm $H_2O$ condition, one was able to complete the 20 cm $H_2O$ condition, and one was able to complete the 25 cm $H_2O$ condition. That is, all six subjects experienced exhaustion, some at relatively low nasal cavity air pressure levels. Subjects experiencing fatigue were able to maintain separation between the oral and nasal cavities, although the force of velopharyngeal closure may have decreased over the course of the trial. When experiencing exhaustion however, speakers were unable to separate the oral and nasal cavities. When occurring at the initiation of a trial, speakers were unable to close the velopharyngeal port. That is, the LVP muscle was unable to generate enough strength to elevate the velum in opposition to the nasal cavity pressure head. When occurring during a trial, as was observed at 15 cm $H_2O$ in Subject 3, the LVP “fails” and can no longer generate enough force to maintain a seal. The result is a loss of velopharyngeal closure, leakage of nasal cavity pressure into the oral cavity, and a snorting sound associated with subsequent soft palate vibration.

Kuehn and Moon (2000) theorized a relationship between velopharyngeal fatigue, velopharyngeal exhaustion, and LVP effort level. As shown in Figure 2a, level “d” represents maximal possible force, level “c” depicts starting force level for an utterance, level “b” is the force value associated with the exhaustion threshold, and level “a” represents 0 closure force. The region between “b” and “c” represents the fatigue zone, and the region between “a” and “b” represents the zone of exhaustion. The horizontal line at “c” represents the absence of fatigue. The remaining diagonal lines represent some degree of fatigue, regardless of how slight the negative slope value is. In some instances, the rate of fatigue may be great enough that the threshold of exhaustion is reached, sometimes more quickly (1) than other (2). Once reached, the system “fails”. However, in other instances, the presence of fatigue may not result in a loss of velopharyngeal closure over the course of the particular trial, as depicted by the diagonal lines that never reach the threshold of exhaustion. This may be a consequence of a LVP muscle possessing the strength to produce high initial levels of velopharyngeal closure force, and/or the endurance to resist fatigue over the time span studied.

In the speaker with a repaired palatal cleft however, the LVP may not possess the same strength and/or endurance that a normal speaker would. Alternatively, the muscle may possess adequate strength, but not be positioned optimally within the palate following cleft repair, or be forced to move a palate that is stiffer as a result of surgical scarring. Evidence does exist which shows that speakers with repaired palatal clefts use LVP activation levels during speech that are much closer to their maximum compared to non-cleft speakers (Kuehn and Moon, 1995). As suggested by Kuehn and Moon (2000), individuals using higher muscle activation levels might increase the rate of fatigue, and quickly reach a condition of exhaustion. Reduced muscle strength and/or a stiffer mechanism may also be expected to result in lower velopharyngeal closure forces in the baseline condition. Indeed, speakers in the current study produced much lower closure forces in any given condition compared to the normal speakers studied by Kuehn and Moon (2000). A similar observation was made earlier by Kuehn and Moon (1994, 1995).

Considering these factors, Figure 2a can be redrawn to depict the relationship between fatigue and exhaustion for speakers with repaired palatal clefts (Fig 2b). Even if one assumes that speakers with and without cleft palate do not differ with respect to fatigue rates, the lower starting closure force leaves cleft speakers with a greatly diminished working capacity such that a level of fatigue easily tolerated by speakers without cleft palate could lead to exhaustion in a speaker with cleft palate (e.g. time points 3 and 4). Further, note that the time to exhaustion associated with steeper fatigue rates in normal speakers (Fig 2a; time points 1 and 2), would occur much earlier in the syllable string produced by a speaker with cleft palate (Fig 2b; time points 1 and 2). Assuming that the LVP muscle of speakers with cleft palate possesses less endurance, and therefore an inclination towards higher rates of fatigue, than that of speakers without cleft palate would only exacerbate the problem. This theory would appear to explain why all six speakers with cleft palate experienced exhaustion at nasal cavity air pressures easily tolerated by speakers without cleft palate, some much sooner than others.

If, in fact, LVP muscle strength or endurance is at least in part responsible for the reduced levels of velopharyngeal closure force and more prevalent exhaustion observed in these speakers, it may be that increasing LVP muscle strength could improve velopharyngeal function.

Improvements could be manifest in increased strength that would increase closure forces further away from the threshold of exhaustion. Referring to Figure 2, this would be represented by moving levels “c” and “d” in Figure 2b closer to the level depicted in Figure 2a. Improvements reflected in increased endurance might reduce the rate of fatigue, depicted in Figure 2b by selecting a line with flatter slope.

Kuehn (1991) first proposed a therapeutic technique designed to improve velopharyngeal muscle strength. Using a continuous positive airway pressure (CPAP) machine designed to treat sleep apnea, Kuehn proposed using increasing levels of nasal cavity air pressure as a resistance to be overcome by the LVP muscle during speech. By starting at a relatively low level of resistance and successively increasing the resistance over an eight-week “weight training” program, Kuehn et al. (2002) documented decreased nasality. To determine what effect CPAP therapy might have on velopharyngeal muscle fatigability, one of the subjects participating in the current study (Subject 6) was enrolled in the eight-week CPAP program. Described in more detail by Kuehn et al. (2002), the program involves completing a set of speech tasks six days a week over eight weeks. In each daily session, the subject produced alternating sets of 50 vowel-nasal-consonant-vowel (VNCV) utterances and six sentences until session time expired. The duration of each daily session was successively increased over the eight weeks, as was the nasal cavity pressure. The fatigue protocol followed in the current study was completed prior to and immediately following the eight-week program. Figures 3 and 4 show velopharyngeal closure forces recorded during the 0 cm $H_2O$ nasal cavity pressure condition before and after CPAP therapy. It is readily apparent that closure forces have increased dramatically. Further, while this subject was unable to move past the 10 cm $H_2O$ condition prior to CPAP therapy, he was able to complete the 25 cm $H_2O$ condition following the CPAP program. Although only attempted in one subject, these results do seem to reinforce the notions advanced above regarding relationships between LVP muscle strength/endurance and susceptibility to muscle fatigue. We continue to study these relationships and possible therapeutic approaches such as velar “weight training” for the treatment of velopharyngeal dysfunction.

## REFERENCES

Amerman JD. A maximum-force-dependent protocol for assessing labial force control. *J Speech Hear Res.* 1993;36:460-465.

Barlow SM, Abbs JH. Force transducers for the evaluation of labial, lingual, and mandibular motor impairments. *J Speech Hear Res*. 1983;26:616-621.

Bigland-Ritchie B, Woods JJ. Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve* 1984;7:691-699.

Bless DM, Ewanowski SL, Dibble B. Velopharyngeal valving problems related to extensive playing of wind instruments. Paper presented at XIX Congress of Internat. Assoc. of Logopedics and Phoniatrics. University of Edinburgh, Scotland, UK, 1983.

Collins D. A histological and molecular analysis of levator veli palatini in a population of subjects with cleft palate. Iowa City, IA: University of Iowa; 2003. Doctoral thesis.

Collins D, Moon J, Canady J, Murray J. Identification of mitochondrial DNA mutations in levator veli palatini tissue from children with cleft palate. Paper presented at annual meeting of American Cleft Palate-Craniofacial Association, Myrtle Beach, SC, 2005.

Hinton VA, Arokiasamy WM. Maximum interlabial pressures in normal speakers. *J Speech Lang Hear Res.* 1997;40:400-404.

Kent RD, Kent JF, Rosenbek JC. Maximum performance tests of speech production. *J Speech Hear Disord.* 1987;52:367-387.

Kuehn DP. New therapy for treating hypernasal speech using continuous positive airway pressure (CPAP). *Plastic Reconstr Surg.* 1991;88:959–966.

Kuehn DP, Imrey PB, Tomes T, Jones DL, O'Gara M, Seaver EJ, Smith BE, Van Demark DR, Wachtel J. Efficacy of continuous positive airway pressure for treatment of hypernasality**.**

*Cleft Palate-Craniofac J.* 2002;39: 267–276.

Kuehn DP, Moon JB. Levator veli palatini muscle activity in relation to intraoral air pressure variation. *J Speech Hear Res.* 1994;37:1260-1270.

Kuehn DP, Moon JB. Levator veli palatini muscle activity in relation to intraoral air pressure variation in cleft palate subjects. *Cleft Palate-Craniofac J.*1995;32:376-381.

Kuehn DP, Moon JB. Velopharyngeal closure force and levator veli palatini activation levels in varying phonetic contexts. *J Speech Lang Hear Res.* 1998;41:51-62.

Kuehn DP, Moon JB. Induced fatigue effects on velopharyngeal closure force. *J Speech Lang Hear Res*. 2000;43:486-500.

Lindman R, Paulin G., Stal P. Morphological characterization of the levator veli palatini muscle in children born with cleft palates. *Cleft Palate-Craniofac J.* 2001;38: 438-448.

Malick, D., Moon, J., Canady, J, Gier, D, and Dawson, D. Stress velopharyngeal insufficiency: Prevalence, treatment, and management practices. Paper presented at annual meeting of American Cleft Palate-Craniofacial Association, Myrtle Beach, SC, 2005.

McHenry MA, Minton JT, Wilson RL, Post YV. Intelligibility and nonspeech orofacial strength and force control following traumatic brain injury. *J Speech Hear Res.* 1994;37:1271-1283.

Moon JB, Kuehn DP, Huisman JJ. Measurement of velopharyngeal closure force during vowel production. *Cleft Palate-Craniofac J.* 1994;31:356-363.

Morgan M. Mitochondrial abnormalities in cleft palate tissue. Presented at the University of Iowa Hospitals and Clinics, Otolaryngology Head and Neck Surgery Institute- Resident Research Meeting: 2002, Iowa City, IA.

Nohara K, Tachimura T, Wada T. Levator veli palatini muscle fatigue during phonation in speakers with cleft palate with borderline velopharyngeal incompetence. *Cleft Palate-*

*Craniofac J.* 2006;43:103-107.

Robin DA, Goel A, Somodi LB, Luschei ES. Tongue strength and endurance: relation to highly skilled movements. *J Speech Hear Res.* 1992;35:1239-1245.

Schendel S, Cholon A, Delaire J. Histochemical analysis of cleft palate muscle. *Plastic and Reconstructive Surgery* 1994;94:919-923.

Tachimura T, Nohara K, Satoh K, Wada T. Evaluation of fatigability of the levator veli palatini muscle during continuous blowing using power spectra analysis. *Cleft Palate-Craniofac J.* 2004;41:320-326.

## FIGURE LEGENDS

Figure 1. Velopharyngeal closure force (VPCF) and levator veli palatini (LVP) EMG data for Subject 3 (10 cm $H_2O$; upper) and Subject 1 (15 cm $H_2O$; lower). Bothe graph pairs show decreasing force, whereas the upper pair demonstrates decreasing overall muscle activation and the lower pair demonstrates overall increasing activation level.

Figure 2. Theorized relationship between velopharyngeal closure force and time for speakers without cleft palate (A) and speakers with cleft palate (B). Each line on the graph from starting point c represents force generation for an individual subject; a – 0 force level, b – force level at exhaustion threshold, c – beginning force level for a given utterance string, d – maximum possible force; dark gray region - zone of exhaustion; light gray region – zone of fatigue. (A adapted from Kuehn and Moon (2000) with permission).

Figure 3. Velopharyngeal closure force values produced by Subject 6 in the 0 cm $H_2O$ condition prior to CPAP therapy program.

Figure 4. Velopharyngeal closure force values produced by Subject 6 in the 0 cm $H_2O$ condition following CPAP therapy program.

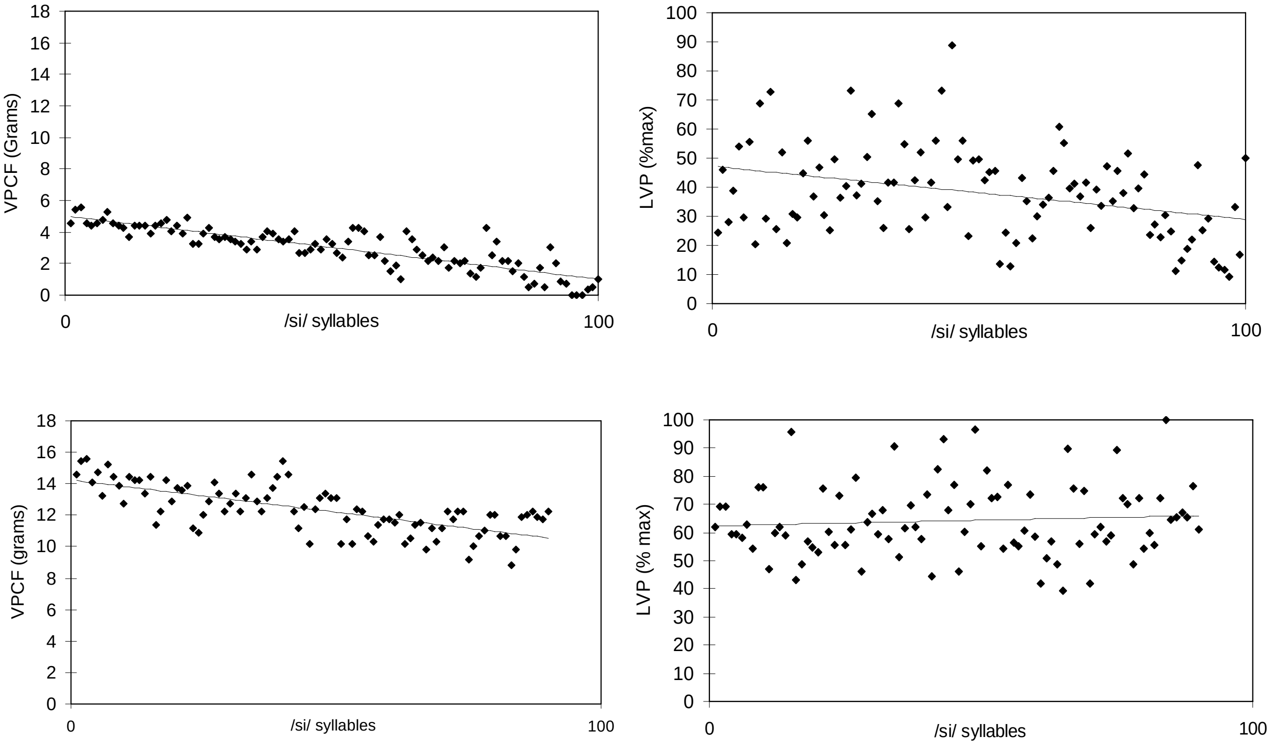

Figure 1. Velopharyngeal closure force (VPCF) and levator veli palatini (LVP) EMG data for Subject 3 (10 cm $H_2O$; upper) and Subject 1 (15 cm $H_2O$; lower). Both graph pairs show decreasing force, whereas the upper pair demonstrates decreasing overall muscle activation and the lower pair demonstrates overall increasing activation level.

Figure 2. Theorized relationship between velopharyngeal closure force and time for speakers without cleft palate (A) and speakers with cleft palate (B). Each line on the graph from starting point c represents force generation for an individual subject; a – 0 force level, b – force level at exhaustion threshold, c – beginning force level for a given utterance string, d – maximum possible force; dark gray region - zone of exhaustion; light gray region – zone of fatigue. (A adapted from Kuehn and Moon (2000) with permission).

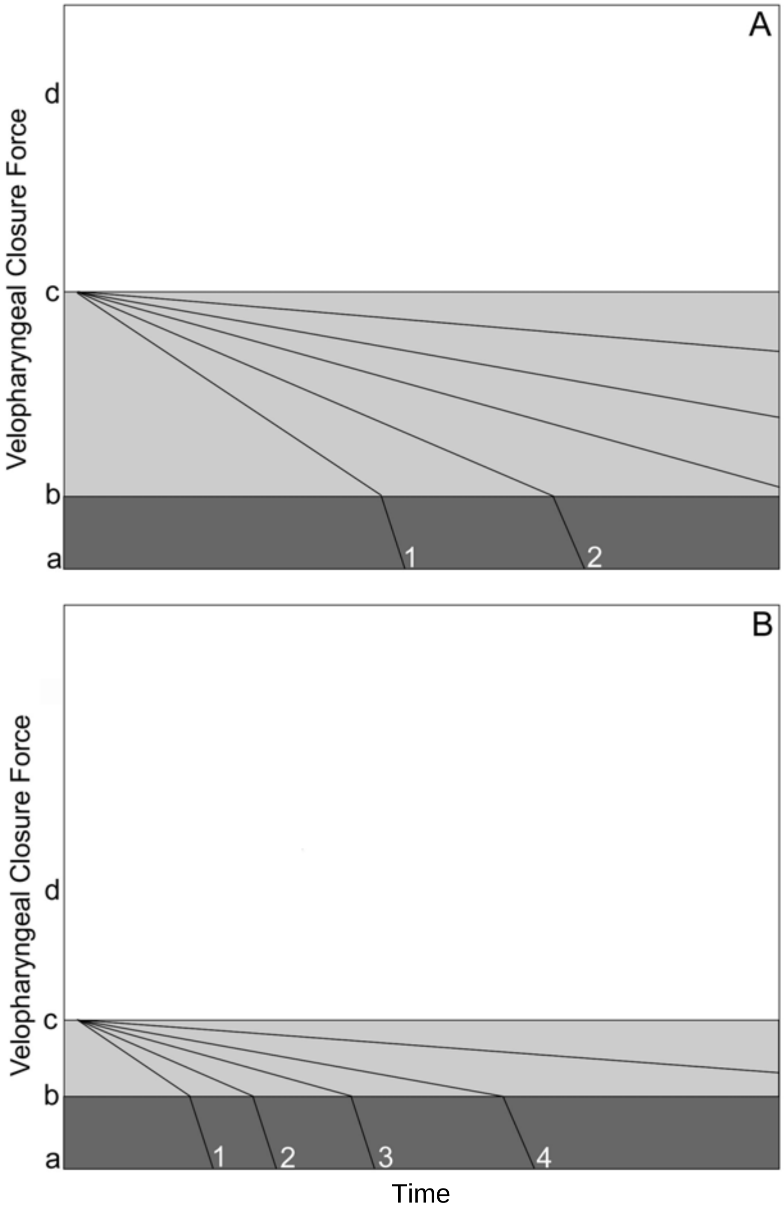

Figure 3. Velopharyngeal closure force values produced by Subject 6 in the 0 cm $H_2O$ condition prior to CPAP therapy program.

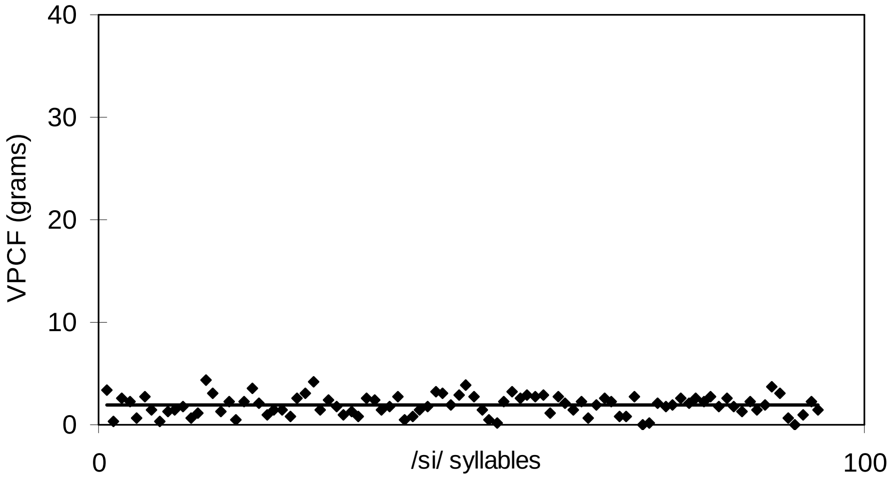

Figure 4. Velopharyngeal closure force values produced by Subject 6 in the 0 cm $H_2O$ condition following CPAP therapy program.

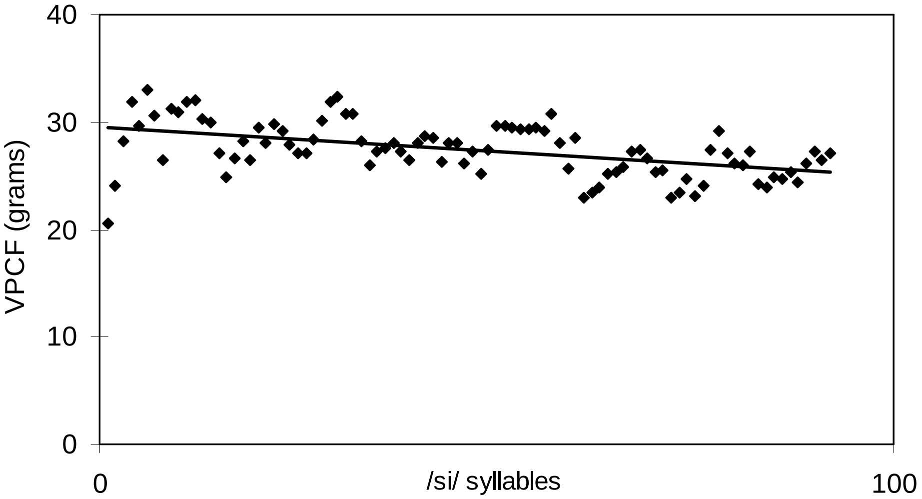

**Table 1**. Subject information

| Subject | Gender | Age | Cleft Type |
|---|---|---|---|
| 1 | Female | 34 | CPO |
| 2 | Female | 29 | UCLP |
| 3 | Female | 27 | BCLP |
| 4 | Female | 40 | BCLP |
| 5 | Male | 40 | BCLP |
| 6 | Male | 19 | UCLP |

UCLP – unilateral cleft lip and palate
BCLP – bilateral cleft lip and palate
CPO – cleft palate only

**Table 2**. Average rates for /si/ syllable production in syllables per second for the initial 20 syllable repetitions (EX – exhaustion; NA – not attempted).

| **Subjects** | **Condition** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **0 cm $H_2O$** | **5 cm $H_2O$** | **10 cm $H_2O$** | **15 cm $H_2O$** | **20 cm $H_2O$** | **25 cm $H_2O$** | **35 cm $H_2O$** |
| **S1** | 1.67 | 1.38 | NA | 1.56 | 1.29 | EX | NA |
| **S2** | 1.63 | 1.59 | 1.57 | EX | NA | NA | NA |
| **S3** | 1.92 | 1.40 | 1.41 | 1.35 | EX | EX | NA |
| **S4** | 1.59 | 1.55 | 1.61 | 1.40 | EX | EX | NA |
| **S5** | 1.59 | 2.04 | NA | 1.70 | NA | 1.74 | EX |
| **S6** | 1.63 | 1.56 | 1.55 | EX | NA | NA | NA |

**Table 3**. Mean velopharyngeal closure force values in grams for the initial and final 15 syllable repetitions (EX – exhaustion; NA – not attempted)

| | | **Condition** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Subject** | | **0 cm $H_2O$** | **5 cm $H_2O$** | **10 cm $H_2O$** | **15 cm $H_2O$** | **20 cm $H_2O$** | **25 cm $H_2O$** | **35 cm $H_2O$** |
| **S1** | **Initial** | 7.10 | 11.44 | NA | 14.31 | 10.77 | EX | NA |
| | **Final** | 7.54 | 10.80 | | 11.19 | 11.15 | | |
| **S2** | **Initial** | 2.67 | 6.05 | 9.65 | EX | NA | NA | NA |
| | **Final** | 1.82 | 4.62 | 8.12 | | | | |
| **S3** | **Initial** | 0.38 | 1.97 | 4.62 | 3.46 | EX | EX | NA |
| | **Final** | 0.30 | 0.22 | 0.88 | 0.03 | | | |
| **S4** | **Initial** | 3.20 | 6.60 | 12.44 | 6.45 | EX | EX | NA |
| | **Final** | 3.08 | 4.13 | 10.65 | 4.74 | | | |
| **S5** | **Initial** | 0.61 | 8.88 | NA | 15.46 | NA | 19.80 | EX |
| | **Final** | 0.53 | 11.40 | | 16.84 | | 19.31 | |
| **S6** | **Initial** | 1.84 | 7.43 | 17.00 | EX | NA | NA | NA |
| | **Final** | 1.85 | 6.95 | 12.63 | | | | |

**Table 4**. Mean levator veli palatini EMG values in percent relative to maximum within subjects for the initial and final 15 syllable repetitions (EX – exhaustion; NA – not attempted).

| | | **Condition** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Subject** | | **0 cm $H_2O$** | **5 cm $H_2O$** | **10 cm $H_2O$** | **15 cm $H_2O$** | **20 cm $H_2O$** | **25 cm $H_2O$** | **35 cm $H_2O$** |
| **S1** | **Initial** | 58 | 41 | NA | 65 | 69 | EX | NA |
| | **Final** | 50 | 43 | | 67 | 61 | | |
| **S2** | **Initial** | 50 | 49 | 54 | EX | NA | NA | NA |
| | **Final** | 42 | 49 | 53 | | | | |
| **S3** | **Initial** | 25 | 31 | 42 | 43 | EX | EX | NA |
| | **Final** | 23 | 31 | 24 | 39 | | | |
| **S4** | **Initial** | 38 | 37 | 44 | 32 | EX | EX | NA |
| | **Final** | 39 | 47 | 49 | 50 | | | |
| **S5** | **Initial** | 20 | 36 | NA | 56 | NA | 69 | NA |
| | **Final** | 11 | 29 | | 54 | | 69 | |

**Table 5.** Paired t-test statistics, two-sided p values comparing closure force means (grams) for the initial 15 syllables to the final 15 syllables and p values for the Wilcoxon signed rank test. The test is not applicable for conditions 20 and 25 due to insufficient data.

| Condition | N | Mean Diff | SD | T | Prob>\|T\| | signed rank(P) |
|---|---|---|---|---|---|---|
| 0 | 6 | 0.11 | 0.42 | 0.67 | 0.5344 | 0.4375 |
| 5 | 6 | 0.71 | 1.74 | 1.0 | 0.3652 | 0.4375 |
| 10 | 4 | 2.86 | 1.41 | 4.05 | 0.0271 | 0.1250 |
| 15 | 4 | 1.73 | 2.21 | 1.57 | 0.2153 | 0.2500 |
| 20 | 1 | -0.38 | NA | NA | NA | NA |
| 25 | 1 | 0.49 | NA | NA | NA | NA |

**Table 6.** Regression slopes between syllables and force value for each subject under different conditions, and p values for testing zero slopes.

| Subject | Condition | Syllable # | Slope | p-value |
|---|---|---|---|---|
| 1 | 0 | 95 | 0.0047 | 0.2984 |
| | 5 | 90 | -0.0121 | 0.0217 |
| | 15 | 90 | -0.0410 | <0.0001 |
| | 20 | 95 | -0.0048 | 0.2154 |
| 2 | 0 | 77 | -0.0155 | 0.0254 |
| | 5 | 89 | -0.0147 | <0.0001 |
| | 10 | 90 | -0.0187 | <0.0001 |
| 3 | 0 | 100 | -0.0032 | 0.0024 |
| | 5 | 100 | -0.0179 | <0.0001 |
| | 10 | 100 | -0.0400 | <0.0001 |
| | 15 | 51 | -0.0831 | <0.0001 |
| 4 | 0 | 82 | 0.0086 | 0.1244 |
| | 5 | 100 | -0.0299 | <0.0001 |
| | 10 | 100 | -0.0202 | <0.0001 |
| | 15 | 100 | -0.0255 | 0.0028 |
| 5 | 0 | 95 | 0.0012 | 0.6452 |
| | 5 | 88 | 0.0161 | 0.1746 |
| | 15 | 95 | 0.0096 | 0.1517 |
| | 25 | 100 | -0.0101 | 0.0215 |
| 6 | 0 | 94 | -0.0004 | 0.9140 |
| | 5 | 86 | -0.0059 | 0.2487 |
| | 10 | 81 | -0.0650 | <.0001 |

**Table 7.** Pearson and Spearman correlation statistics and p values to test the strength of the relationship between fatigue rate slope and air pressure condition.

| **Subject** | **n** | **Pearson Correlation** | **P-value** | **Spearman Correlation** | **P-value** |
|---|---|---|---|---|---|
| 1 | 4 | -0.4438 | 0.5562 | -0.40 | 0.6000 |
| 2 | 3 | -0.7559 | 0.4544 | -0.50 | 0.6667 |
| 3 | 4 | -0.9719 | 0.0281 | -1.00 | <0.0001 |
| 4 | 4 | -0.6887 | 0.3113 | -0.40 | 0.6000 |
| 5 | 4 | -0.5765 | 0.4235 | -0.40 | 0.6000 |
| 6 | 3 | -0.9019 | 0.2844 | -1.00 | <0.0001 |

n = number of nasal cavity air pressure conditions completed

**Table 8.** Comparison of fatigue rate slopes across conditions.

| Compared Conditions | | Difference | p-Value |
|---|---|---|---|
| 0 | 5 | 1.0000 | 0.5392 |
| 0 | 10 | 0.0413 | 0.0079 |
| 0 | 15 | 0.0343 | 0.0415 |
| 0 | 20 | 0.0068 | 0.7688 |
| 0 | 25 | 0.0187 | 0.4529 |
| 5 | 10 | 0.0313 | 0.0861 |
| 5 | 15 | 0.0243 | 0.0881 |
| 5 | 20 | -0.0032 | 0.8917 |
| 5 | 25 | 0.0088 | 0.7201 |
| 10 | 15 | -0.0070 | 0.6925 |
| 10 | 20 | -0.0345 | 0.1548 |
| 10 | 25 | -0.0226 | 0.3839 |
| 15 | 20 | -0.0275 | 0.3058 |
| 15 | 25 | -0.0156 | 0.5249 |
| 20 | 25 | 0.0120 | 0.7039 |