Research Note

Age-Related Variability in Tongue Pressure Patterns for Maximum Isometric and Saliva Swallowing Tasks

Melanie Peladeau-Pigeon^a and Catriona M. Steele^{a,b}

Purpose: The ability to generate tongue pressure plays a major role in bolus transport in swallowing. In studies of motor control, stability or variability of movement is a feature that changes with age, disease, task complexity, and perturbation. In this study, we explored whether age and tongue strength influence the stability of the tongue pressure generation pattern during isometric and swallowing tasks in healthy volunteers.

Method: Tongue pressure data, collected using the Iowa Oral Performance Instrument, were analyzed from 84 participants in sex-balanced and decade age-group strata. Tasks included maximum anterior and posterior isometric pressures and regular-effort saliva swallows. The cyclic spatiotemporal index (cSTI) was used to capture stability (vs. variability) in patterns of pressure generation. Mixed-model repeated measures analyses of covariance were performed separately for each task (anterior and posterior isometric pressures, saliva swallows) with between-participant factors

of age group and sex, a within-participant factor of task repetition, and a continuous covariate of tongue strength.

Results: Neither age group nor sex effects were found. There was no significant relationship between tongue strength and the cSTI on the anterior isometric tongue pressure task ($r = -.11$). For the posterior isometric tongue pressure task, a significant negative correlation ($r = -.395$) was found between tongue strength and the cSTI. The opposite pattern of a significant positive correlation ($r = .29$) between tongue strength and the cSTI was seen for the saliva swallow task.

Conclusions: Tongue pressure generation patterns appear highly stable across repeated maximum isometric and saliva swallow tasks, despite advancing age. Greater pattern variability is seen with weaker posterior isometric pressures. Overall, saliva swallows had the lowest pressure amplitudes and highest pressure pattern variability as measured by the cSTI.

The tongue plays a major role in swallowing function as the primary source of propulsive forces that transport the bolus from the oral cavity into the pharynx. It is well established that tongue strength declines with age, but the impact of these changes on bolus propulsion or swallowing physiology is not well understood. Age-related reductions in tongue strength are clearly seen in measures of maximum isometric pressure, both for the anterior and posterior tongue and particularly for individuals aged 70 years and older (Adams, Mathisen, Baines, Lazarus, & Callister, 2013; Clark & Solomon, 2012; Crow &

Ship, 1996; Fei et al., 2013; Nicosia et al., 2000; Robbins, Levine, Wood, Roecker, & Luschei, 1995; Stierwalt & Youmans, 2009; Utanohara et al., 2008; Vanderwegen, Guns, Van Nuffelen, Elen, & De Bodt, 2013; Vitorino, 2010; Youmans & Stierwalt, 2006; Youmans, Youmans, & Stierwalt, 2009). Recent data from a large population study in Belgium (Vanderwegen et al., 2013) and a meta-analysis by Adams and colleagues (2013) also show a sex difference with stronger tongue pressures in men than in women.

The implications of reduced tongue strength for swallowing function in healthy older adults remain unclear. Several studies report associations among tongue weakness, increased risk of aspiration, and postswallow residue in healthy seniors (Butler et al., 2011, 2012; Cook et al., 1994; Feng et al., 2013). On the other hand, evidence also suggests that healthy seniors do not show reduced tongue pressure amplitudes in the submaximal effort contexts of saliva or bolus swallows (Fei et al., 2013; Nicosia et al., 2000; Robbins et al., 1995; Youmans et al., 2009). This finding is in contrast to data from people with dysphagia

^aToronto Rehabilitation Institute, University Health Network, Ontario, Canada

^bRehabilitation Sciences Institute, University of Toronto, Ontario, Canada

Correspondence to Catriona M. Steele: catriona.steele@uhn.ca

Editor: Krista Wilkinson

Associate Editor: Nancy Solomon

Received September 7, 2016

Revision received January 30, 2017

Accepted June 9, 2017

https://doi.org/10.1044/2017_JSLHR-S-16-0356

Disclosure: The authors have declared that no competing interests existed at the time of publication.

of neurogenic origin, in whom reduced tongue pressure amplitudes have been observed in both isometric and swallowing tasks (Clark, Henson, Barber, Stierwalt, & Sherrill, 2003; Robbins et al., 2007; Rogus-Pulia et al., 2016; Steele et al., 2013, 2016).

In this study, we were interested to explore the extent to which tongue pressures are generated in a stable manner by healthy adults. In particular, we investigated changes in the stability of tongue pressure patterns associated with age, sex, and expected age-related changes in tongue strength. In studies of motor control, the stability or variability of movement is a feature that varies with age, disease, and task complexity and in the context of perturbation. For some tasks, such as running and plantar flexion, kinematic analyses suggest that variability does not increase as a function of age (Challis, 2006; Silvernail, Boyer, Rohr, Bruggemann, & Hamill, 2015). Other studies point to age-related increases in variability for repeated isometric quadriceps contraction (Christou & Carlton, 2001), finger tapping and reaction tasks (Shammi, Bosman, & Stuss, 1998), and lip movements in a speech repetition task (Wohlert & Smith, 1998). Increased variability has also been described as a feature of lip, tongue, and finger force generation in adults with Parkinson's disease (Gentil, Perrin, Tournier, & Pollak, 1999). With respect to strength-variability relationships, studies of arm movement show that a given force can be generated more accurately, that is, with less variability, by stronger muscles compared with weaker muscles (Hamilton, Jones, & Wolpert, 2004; Sosnoff & Newell, 2006). On the other hand, reduced variability and an inability to adapt to perturbation are sometimes seen in the context of injury or disease, such as those seen in running with ankle instability (Terada et al., 2015).

The literature contains very little information regarding stability or variability in swallowing behaviors. Previous articulatory studies have used the cyclic spatiotemporal index (cSTI; Smith & Goffman, 1998; Smith, Goffman, Zelaznik, Ying, & McGillem, 1995; Smith, Johnson, McGillem, & Goffman, 2000) to quantify the variability of tongue movement in speech and swallowing tasks (Steele & Van Lieshout, 2008, 2009). The cSTI is an indexing method that captures the time-evolving variability of motor patterns across task repetitions within an individual. Using this measure, slower and more variable tongue movements have been found during sequential water swallowing tasks compared with a speech repetition task (Bennett, van Lieshout, & Steele, 2007), but differences were not seen in the variability of tongue movement or tongue-jaw coordination during swallowing tasks for adults aged under versus over 50 years (Steele & Van Lieshout, 2008, 2009). By contrast, individuals with Parkinson's disease were shown to have significantly smaller amplitude and more variable tongue movements during swallowing tasks compared with both older and younger healthy controls (Van Lieshout, Steele, & Lang, 2011).

The current study explored the extent to which tongue pressure pattern variability changes as a function of age, sex, and strength in healthy adults. Given that

tongue strength is known to decline with age and that greater variability in force generation is seen in the context of limb muscle weakness, we hypothesized that higher cSTI values, indicating greater variability, would be seen in association with age-related reductions in tongue strength in isometric tasks. Given reports of higher tongue strength in men, we also hypothesized that cSTI measures would be lower (i.e., less variable) in men than women. Conversely, given the fact that swallowing pressures do not decline with age, we hypothesized that changes in the cSTI would not be seen in older adults during swallowing tasks.

Method

This study was part of a larger project exploring both sensory and motor functions in healthy swallowing. Data were collected over a 6-month time frame in two locations: (a) the exhibit area of a public science museum and (b) a research laboratory located inside a rehabilitation hospital. The project received human subject approval from the local institutional research ethics board.

In total, 346 healthy volunteers (164 men and 182 women) aged 12–86 years consented to participate. This article focuses on an analysis of tongue pressure data from a subset of 84 participants, whose data were randomly sampled from the larger data set to provide a sex-balanced, age-distributed data set (i.e., six men and six women per decade age-group stratum; age range = 12–79 years, mean age = 44 years). The number of female participants over the age of 80 years was too small to permit inclusion of an over-80 stratum in this analysis.

Inclusion/Exclusion Criteria

All participants completed a brief intake interview to confirm eligibility. Participants were excluded if they reported a medical history of stroke, brain injury, neurodegenerative disease, frequent or chronic sinus infections, major surgery to the head or neck, radiation to the head or neck, gastrointestinal problems, or insulin-dependent diabetes; dysphagia, dysarthria, facial muscle weakness, xerostomia, or altered taste or smell; gastrointestinal problems; use of sleeping pills or anti-Parkinsonian medication; use of recreational drugs; cigarette smoking; or alcohol consumption in excess of one drink per day in the past 12 months. It should be noted that some of these exclusion criteria were related to the collection of oral sensory data that are not addressed in this article.

Data Collection

Tongue pressure data were collected using the Iowa Oral Performance Instrument (IOPI; IOPI Medical, Redmond, WA). The IOPI devices were calibrated as per manufacturer instructions before the beginning of the study and on a quarterly basis throughout data collection. Recalibration was also performed whenever a device was noticed to have a resting pressure above zero. The IOPI signals

were digitized using a data acquisition box (DI-145; DATAQ Instruments, Inc.) and displayed in real time on a laptop computer screen using a custom user interface designed in Excel Visual Basics for Application, as shown in Figure 1. This display provided biofeedback to the participants throughout initial task training and data collection. Tongue pressures were recorded in kilopascals at a sampling frequency of 30 Hz.

After a brief orientation to the equipment, tasks, and computer display, participants were asked to complete five anterior maximum isometric tongue presses (AMAX), five posterior maximum isometric tongue presses (PMAX), and five regular-effort saliva swallows (RESS). These tasks were performed in the same order by all participants. For the AMAX task, the air-filled bulb was placed behind the front teeth, and the participants were asked to use their tongue to squeeze the bulb against the roof of their mouth as hard as possible. For the PMAX task, the bulb was moved approximately 2.5 cm further back from the anterior position, so that the straight edge of the IOPI bulb was aligned with the first molar tooth (Gingrich, Stierwalt, Hageman, & LaPointe, 2011); with the bulb in this position, the participants were asked to use the back of their tongue to squeeze the bulb against the roof of their mouth as hard as possible. Finally, the bulb was returned to the anterior position for the RESS task, and participants were asked to swallow their saliva in a comfortable manner. Demonstration and training, involving two or three repetitions of each task with verbal feedback by a trained research assistant, were completed before beginning data collection.

Participants were instructed to perform the five repetitions of each task at a comfortable pace. The research assistant monitored bulb position throughout each set of task repetitions; if bulb movement was suspected, the participants were instructed to open their mouth so that bulb placement could be confirmed and corrected, if necessary. A post hoc review of the signals showed that both the

anterior and posterior isometric tasks were completed at average frequencies of one press every 4 s (95% confidence interval [CI] [3.3 s, 4.2 s]). The saliva swallows were performed at an average frequency of one swallow every 7 s (95% CI [6.4 s, 7.5 s]). Rests were provided between tasks and averaged 8.5 s (95% CI [7 s, 10 s]) between the anterior and posterior isometric task blocks and 10 s (95% CI [8.8 s, 11.6 s]) between the PMAX and saliva swallow task blocks.

Data Processing

Postprocessing of the tongue pressure data was completed using Excel Visual Basics for Application. A segmentation algorithm was used to identify the time point and amplitude of three events for each task repetition, based on a moving window standard deviation function: (a) departure from baseline, (b) peak pressure, and (c) return to baseline. The cSTI was calculated across all repetitions of a given task for each individual participant. To do this, the pressure waveform segments for each task repetition were time-normalized to create a zero-to-one time scale and then amplitude-normalized to the peak amplitude of each respective cycle; this process is illustrated in

Figure 2. Illustration of the method used to calculate the cyclic spatiotemporal index across five successive cycles of a tongue pressure generation task. The gray shaded section from 0.14 to 0.24 of the normalized timeline in the upper panel is expanded in the lower panel.

Figure 1. Example of the biofeedback display used during data collection, showing the amplitude of five successive tongue–palate presses. Each pressure cycle has been represented with a different line format to permit easy referencing in Figure 2.

the top panel of Figure 2. The standard deviation of the overlaid time- and amplitude-normalized pressure cycles was then calculated iteratively at 2% intervals (see bottom panel of Figure 2). The cSTI is computed as the sum of these standard deviation values at 2% intervals, across 50 values per task. Higher index values represent greater pattern variability across five repeated cycles or five task repetitions.

Data Analysis

All statistical analyses were performed in IBM SPSS 24.0 using an α criterion of .05. Descriptive statistics for peak tongue pressure amplitude (in kilopascals) and cSTI were calculated separately by task, sex, and age group. Frequency tables and chi-square tests were used to identify significant differences in the location (i.e., task number) of the highest peak pressure amplitude seen across each task block. Mixed-model repeated measures analysis of variance of cSTI was performed within task, with between-participant factors of sex and age group and a continuous covariate of peak amplitude. A diagonal covariance structure was found to have the best model fit. Post hoc Sidak tests were planned to clarify any significant pairwise comparisons for between-participant factors, whereas a post hoc exploration of significant covariate relationships was performed using scatter plots and linear regression.

Results

Table 1 shows means and 95% CIs for peak pressure amplitude (in kilopascals) by task, sex, and age group.

Table 2 provides corresponding descriptive statistics for the cSTI parameter.

Table 3 shows the frequency with which the highest peak amplitude measure occurred on the first, second, third, fourth, or final task repetition within each task series. For the isometric pressure tasks, this highest peak amplitude was most commonly seen on the first task repetition. By contrast, for the RESS task, the strongest pressures were most commonly seen on the final task repetition. Chi-square statistics exploring the task repetition location of these highest pressure values within task failed to find significant patterns by age group: AMAX, $\chi^2(24) = 26.06$, $p = .35$; PMAX, $\chi^2(24) = 22.2$, $p = .57$; and RESS, $\chi^2(24) = 23.22$, $p = .51$.

With respect to the main study questions, the mixed-model repeated measures analyses of variance failed to identify significant main effects or interactions of sex and age group on cSTI for the AMAX task. Similarly, the correlation between tongue strength and the cSTI on the AMAX task was not significant ($r = -.11$). For the PMAX task, a significant main effect of tongue strength was found, $F(1, 53) = 7.497$, $p = .008$. Similarly, for the saliva swallow task, a significant main effect of tongue strength was observed, $F(1, 41) = 6.33$, $p = .02$. These relationships took the form of weak-to-modest correlations, which are illustrated in Figures 3 and 4. In Figure 3, greater variability, in the form of higher cSTI values, is seen during PMAX tasks for participants with lower tongue strength ($R^2 = .16$, $r = -.395$, $p < .001$). In Figure 4, a weaker but opposite trend is seen for RESSs, namely, greater variability (i.e., higher cSTI values) with higher swallow pressures ($R^2 = .09$, $r = .29$, $p = .015$).

Table 1. Descriptive statistics by decade age group and sex for peak tongue pressure amplitude (in kilopascals) by task.

Sex	Age group	N	Peak anterior maximum isometric pressures				Peak posterior maximum isometric pressures				Peak regular-effort saliva swallows			
			Mean	SD	95% CI		Mean	SD	95% CI		Mean	SD	95% CI	
					Lower bound	Upper bound			Lower bound	Upper bound			Lower bound	Upper bound
Female	10–19	6	64.57	15.50	45.33	83.81	67.33	15.49	48.10	86.56	47.01	19.45	22.85	71.16
	20–29	6	48.27	12.32	35.34	61.20	50.26	9.27	40.52	59.99	33.63	19.54	9.36	57.90
	30–39	6	52.01	14.57	36.71	67.30	54.38	14.82	38.83	69.94	47.73	13.64	33.41	62.04
	40–49	6	61.60	21.73	38.79	84.41	64.96	19.42	44.58	85.34	58.13	20.41	36.72	79.55
	50–59	6	56.74	18.83	36.98	76.50	55.57	15.16	39.66	71.48	36.23	5.38	27.67	44.80
	60–69	6	52.71	14.44	37.56	67.86	52.94	11.43	40.94	64.93	44.27	10.88	26.96	61.58
	70–79	6	42.00	11.09	30.36	53.64	45.18	11.97	32.62	57.74	37.05	7.26	28.04	46.06
Total		42	53.73	16.29	48.59	58.87	55.52	14.98	50.79	60.25	44.16	16.32	38.55	49.77
Male	10–19	6	60.29	15.81	43.70	76.89	54.47	19.38	34.14	74.81	49.01	21.96	25.97	72.05
	20–29	6	54.06	11.32	42.18	65.93	52.60	16.62	35.16	70.04	36.45	15.57	20.11	52.79
	30–39	6	70.89	14.40	55.78	86.00	65.66	6.21	57.95	73.37	31.37	23.34	–5.77	68.51
	40–49	6	61.54	20.08	40.46	82.61	60.83	10.02	50.32	71.35	40.39	12.51	20.49	60.28
	50–59	6	49.31	12.96	35.71	62.91	52.74	10.68	41.53	63.95	40.63	15.82	20.99	60.27
	60–69	6	45.84	12.87	29.86	61.82	50.88	18.43	28.00	73.77	40.27	22.05	5.18	75.36
	70–79	6	47.69	15.80	31.10	64.27	47.47	12.48	34.38	60.56	38.79	9.84	26.57	51.01
Total		42	55.90	16.23	50.77	61.02	54.79	14.22	50.24	59.33	39.94	16.92	34.04	45.84

Note. CI = confidence interval.

Table 2. Descriptive statistics by decade age group and sex for the cSTI of tongue pressure generation by task.

Sex	Age group	N	cSTI: anterior maximum isometric pressures				cSTI: posterior maximum isometric pressures				cSTI: regular-effort saliva swallows			
			Mean	SD	95% CI		Mean	SD	95% CI		Mean	SD	95% CI	
					Lower bound	Upper bound			Lower bound	Upper bound			Lower bound	Upper bound
Female	10–19		6.39	1.53	4.48	8.29	4.95	1.73	2.80	7.09	8.85	1.57	6.90	10.80
	20–29		5.43	1.24	4.12	6.73	5.33	0.85	4.44	6.23	9.08	2.22	6.33	11.83
	30–39		5.29	3.34	1.78	8.80	6.36	3.16	3.04	9.68	8.77	2.83	5.80	11.73
	40–49		4.19	1.64	2.47	5.91	3.47	1.14	2.27	4.67	8.87	2.10	6.66	11.07
	50–59		6.45	1.29	5.09	7.81	4.71	1.27	3.38	6.04	7.03	1.58	4.52	9.55
	60–69		5.45	2.09	3.25	7.64	4.93	2.20	2.62	7.24	8.43	1.30	6.36	10.49
	70–79		5.83	1.59	4.15	7.50	6.62	2.00	4.52	8.72	9.97	2.25	7.17	12.77
Total		42	5.55	1.94	4.94	6.16	5.20	2.03	4.56	5.84	8.81	2.01	8.14	9.48
Male	10–19		7.24	2.46	4.66	9.82	4.66	1.71	2.87	6.46	8.47	3.03	5.29	11.65
	20–29		4.89	1.23	3.60	6.17	4.74	1.38	3.29	6.19	8.42	1.85	6.48	10.36
	30–39		5.64	3.14	2.35	8.94	3.92	0.72	3.03	4.82	10.25	2.15	6.83	13.66
	40–49		4.91	2.37	2.42	7.40	4.62	3.04	1.43	7.80	9.83	0.90	8.39	11.26
	50–59		5.60	1.40	4.12	7.07	5.13	1.72	3.33	6.93	8.82	1.77	6.62	11.02
	60–69		6.39	2.57	3.19	9.59	4.64	1.97	2.20	7.08	8.76	0.65	7.73	9.79
	70–79		5.98	1.32	4.60	7.37	5.13	2.49	2.51	7.74	8.88	1.43	7.10	10.65
Total		42	5.79	2.15	5.11	6.47	4.77	1.90	4.17	5.37	9.03	1.80	8.44	9.62

Note. cSTI = cyclic spatiotemporal index.

Discussion

In the largest known study to date of tongue pressure strength in healthy adults, Vanderwegen and colleagues (2013) identified a significant decline in strength after the age of 70 years and a significant sex difference across the life span with higher pressures seen in male participants. Although the main purpose of this study was to study stability or variability in patterns of tongue pressure generation rather than tongue strength, the data are in general agreement with Vanderwegen et al.'s findings. Specifically, peak maximum isometric tongue pressures in younger participants were higher than those seen in the older age groups, with this difference being particularly striking in

female participants over the age of 70 years. It should be noted that Vanderwegen and colleagues were more successful in recruiting participants aged 80 years and older, with 30 men and 30 women representing each decade from the age of 20 to 80+ years. This study is also consistent with previous literature showing that swallowing is a sub-maximal effort task (Fei et al., 2013; Nicosia et al., 2000; Youmans et al., 2009).

To our knowledge, this is the first study applying the cSTI parameter to the analysis of tongue pressure waveforms.

Table 3. The frequency (and percentage of time) with which the highest peak pressure was generated according to the task repetition number within each task series.

Task repetition	Count (%)	AMAX	PMAX	RESS
1	Count	27	27	7
	% of task	32	32	8
2	Count	18	14	15
	% of task	21	17	18
3	Count	7	6	18
	% of task	8	7	22
4	Count	14	25	16
	% of task	17	30	19
5	Count	18	12	28
	% of task	21	14	34
Total	Count	84	84	84

Note. AMAX = anterior maximum isometric pressures; PMAX = posterior maximum isometric pressures; RESS = regular-effort saliva swallows.

Figure 3. Scatter plot of cyclic spatiotemporal index (cSTI) by peak maximum pressure for posterior isometric pressure tasks.

Figure 4. Scatter plot of cyclic spatiotemporal index (cSTI) by peak swallow pressure for regular-effort saliva swallows.

Although no direct comparison can be made with the previous literature, other cSTI-related conclusions may be of interest. The cSTI has historically been used to evaluate lip movement variability in repetitive speech production of /b/ and /p/ consonants in a consonant–vowel–consonant context, with a mean value of 13 ($SD = 2.5$) in young adults (Smith, Goffman, Zelaznik, et al., 1995). Higher mean values of 24 ($SD = 4.0$) in 4-year-olds (Smith, Goffman, & Stark, 1995) were interpreted to reflect less stable speech patterns. When applied to the evaluation of tongue movement waveforms in healthy adults, values of 15 and higher were reported for swallowing tasks, compared with values of 12 or lower for speech tasks (Bennett et al., 2007; Steele & Van Lieshout, 2009). Greater movement variability, with cSTI values in the order of 25, has been reported for tongue movements during discrete liquid swallowing tasks by adults with Parkinson's disease (Van Lieshout et al., 2011). Thus, in comparison with the values reported for speech-related lip and tongue movement and for swallowing-related tongue movement, the cSTI values for the different tongue pressure generation tasks in this study (i.e., 4–6 for maximum isometric tasks and 8–10 for saliva swallows) appear highly stable.

The hypothesis that greater pressure pattern variability would be seen in association with tongue weakness was confirmed within the posterior isometric tongue pressure tasks but was not seen on the anterior isometric tasks. Overall, however, saliva swallowing pressures were lower than the pressures seen during isometric tasks (with peak pressure amplitudes falling between 57% and 84% of the values seen on anterior isometric tasks) and showed greater pressure pattern variability, with corresponding mean cSTI values by sex and decade age group ranging from 109% to 212% of the values seen on the AMAX task. This finding is consistent with the hypothesis that lower tongue

strength values would be associated with greater pressure pattern variability. Conversely, however, a weak positive correlation between tongue strength and cSTI values was seen within the saliva swallowing data. These strength–variability relationships occurred without an interaction with participant age, and no sex differences were observed in the cSTI measure.

Evidence of stability in tongue pressure generation patterns across age in this study stands in contrast to qualitative observations by Nicosia et al. (2000), who noted a pattern of gradual and multi-peaked pressure building in a sex-balanced sample of 10 adults aged 69–91 years compared with controls aged 48–55 years. Differences between these studies may be attributable to our use of saliva swallows rather than bolus swallows of liquid, use of the IOPI compared with a three-bulb array glued to the hard palate (the KayPentax Digital Swallow Workstation), and the availability in this study of a larger sample spanning the age continuum rather than two discrete groups.

There are several slight differences in data collection methodology, which should be noted between this study and prior studies of tongue pressure generation, most notably the study by Vanderwegen et al. (2013). First, five repetitions of each task were performed in this study, whereas several previous studies have collected only three repetitions of each task. For the maximum isometric tasks, the highest pressures were typically seen on the first task repetition of the series, suggesting that this difference in methods was likely of little consequence. However, for the saliva swallowing tasks, it was common to see higher pressures on later task repetitions (see Table 3). This tendency for swallowing pressures to be highest on the final task repetition may suggest that participants found it necessary to use greater effort to produce the fifth swallow in the series. Given that the saliva swallows were also the final task in the data collection protocol, we cannot rule out the possibility of order effects. It is also possible that peripheral compensation for central fatigue (either overall or within the task set) or possible challenges related to oral dryness may have been present and influenced the data. Finally, it is possible that participants found the task of swallowing with an air-filled bulb in the mouth to be unnatural and that this could have influenced both pressure amplitudes and variability. In future studies, a longer rest period between repeated saliva swallows is suggested as a way of limiting possible fatigue and ensuring the availability of sufficient saliva. In addition, water rinses might be used between repeated saliva swallows to ensure adequate lubrication.

In this study, there was no instruction to maintain maximum pressure for any length of time, which contrasts with Vanderwegen et al.'s description that each task lasted 7–10 s. Furthermore, participants were instructed to perform task repetitions at a comfortable rate; the overall time durations required to complete a series of five task repetitions in this study are much shorter than the time taken in the Vanderwegen et al. study, particularly because we did not impose a 30-s rest period between each task repetition. It is interesting to note that, despite this

difference in methodology, we did not observe a pattern of steadily declining strength across task repetitions in the isometric pressure tasks, suggestive of possible fatigue (see Table 3).

A novel aspect of the data collection protocol in this study is the fact that the tongue pressure waveform was visible to participants on a biofeedback screen. We cannot rule out the possibility that the availability of visual biofeedback influenced task performance. Participants were trained in the three tongue pressure tasks before beginning formal data collection and were oriented to the screen by a trained research assistant. Particular attention was drawn to the amplitude of the maximum isometric pressure tasks. Although participants were instructed to perform saliva swallows as naturally as possible, we cannot rule out the possibility that the prior instructions to perform isometric tasks with maximum effort carried over into the use of effort during the saliva swallow task. Although data for saliva swallows cannot be directly compared with those for bolus swallows, it is interesting to note that peak amplitudes of the saliva swallows in this study fell, on average, between 70%–81% of the values obtained on the AMAX task. This range for percentage of maximum strength used during swallowing is higher than the values of 50%–60% reported in a previous study using liquids from thin to pureed consistency by Youmans and colleagues (2009). A question of particular interest for future studies is the possibility that the visual biofeedback contributed to relative stability in the pressure generation patterns seen across task repetitions and, consequently, to low cSTI values. Furthermore, if the visual biofeedback was having any unintended effect on pressure pattern generation, we cannot rule out the possibility that the influence would have been equal across age groups (Ofori, Samson, & Sosnoff, 2010).

Conclusion

This study has explored age-related differences in the variability of tongue pressure generation patterns during maximum isometric and saliva swallowing tasks in nominally healthy adults. Overall, pressure generation patterns were observed to display a high degree of stability, as shown by low cSTI values. However, the data also provide general confirmation for the study hypothesis that greater pressure pattern variability would be seen in the context of the reduced pressure amplitudes associated with saliva swallowing. It is clearly premature to make inferences regarding the clinical implications of this finding. Future research is needed to explore the possibility that individuals with tongue weakness may also experience challenges in generating tongue pressure patterns in a stable manner, either for maximal effort or saliva swallowing tasks. In addition, studies in clinical populations with dysphagia should explore the relationship between pressure pattern stability and liquid bolus control as well as determine whether tongue pressure resistance training with

either strength or skill emphasis has utility for improving pressure pattern stability.

Acknowledgments

Funding was provided by the National Institutes of Health (Grant 5R01DC011020 awarded to Catriona M. Steele) and Toronto Rehabilitation Institute, University Health Network. The authors gratefully acknowledge support from the Payload Science program at the Ontario Science Centre, Toronto, Ontario, Canada. In addition, the authors thank the following individuals for their assistance with data collection and processing: Edite Folfas, Sarah Hori, Elven Koo, Katherine Kovler, Katy Mak, Sonja Molfenter, Anna Nguyen, Tasnim Shariff, Chantale Spencer, Maddy Steele, Helen Wang, and Clemence Yee.

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