Research Article

Measuring Hyoid Excursion Across the Life Span: Anatomical Scaling to Control for Variation

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Purpose: A method for controlling for sex-based differences in measures of hyoid movement using an internal anatomical scalar has been validated in young healthy individuals. Known anatomical changes with aging necessitate validation of this methodology in a mixed-age sample. The primary aim of this study was to validate a method for controlling for sex-based differences in measures of hyoid movement across the life span. Measurement error as a potential source of variability was addressed to inform best practice recommendations.

Method: Two distinct data sets previously collected using identical protocols were combined for this study to achieve a data set of young (< 40 years) and older (> 65 years) healthy adults. Data included videofluoroscopic swallow studies with three swallow trials each of 5 and 20 ml thin liquid barium. Previously reported methodology was replicated to validate the use of an anatomical scalar for measuring hyoid excursion in this sample. Hyoid movement was measured using 2 methods (rest-to-peak displacement and peak only) in 3 planes of movement (anterior, superior, and hypotenuse), was expressed in millimeters and individually

scaled units relative to C4, and normalized using the C2–C4 vertebral distance. Mixed-model repeated-measures analyses of variance were run with each of the 6 hyoid measures as the dependent variable (in both millimeters and C2–C4 units), within-subject factors of sex and bolus volume, and a between-subjects factor of age group. We predicted that the C2–C4 scalar would adequately control for sex-based differences across age groups.

Results: Significant differences in absolute hyoid movements (millimeters) were observed by sex, bolus volume, and age group. When measured in %C2–C4 units, all differences between males and females were neutralized. Significant differences between 5- and 20-ml boluses were found for all peak position measures. Significant differences between young and older individuals were found for all peak position measures.

Conclusion: Expressing hyoid excursion as a percentage of the C2–C4 distance appears valid for use across the life span. Peak position is preferable over displacement measures for quantifying hyoid excursion for research and clinical purposes.

Hyoid movement is referenced for defining the stages of swallowing and as an anatomical landmark for kinematic measurements. Temporal and kinematic norms are used to define dysphagia in research and clinical practice. There is wide variation in the normative data on this swallowing parameter (Molfenter & Steele,

2011), and differences may be attributable to methodological variation between studies and measurement error (Molfenter & Steele, 2011). Additionally, hyoid movement varies within and across individuals by factors such as body size (Molfenter & Steele, 2014), age (Kang et al., 2010; Logemann et al., 2000; Logemann, Pauloski, Rademaker, & Kahrilas, 2002), and bolus volume (Ishida, Palmer, & Hiimae, 2002; Kim & McCullough, 2008; Nagy, Molfenter, Péladeau-Pigeon, Stokely, & Steele, 2015).

Significant differences between male and female hyoid movement have led to its treatment as a sexually dimorphic variable (Leonard, Kendall, McKenzie, Gonçalves, & Walker, 2000; Logemann et al., 2000, 2002; Molfenter & Steele, 2014). However, Molfenter and Steele (2014) demonstrated that significant sex differences in hyoid kinematics disappear when hyoid excursion is individually scaled and expressed as a percentage of the C2–C4 vertebral distance. This finding established that analyses of quantitative

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measures of hyoid movement can be collapsed across males and females when size is controlled.

The C2–C4 distance was chosen by Molfenter and Steele (2014) by comparing 13 different anatomical dimensions in the head and neck on lateral videofluoroscopy (VF) to overall body height. The distance from the anterior inferior corner of C2 to the anterior inferior corner of the C4 vertebra was the anatomical referent most highly correlated with height ($r = .83$) in this sample of 20 (10 men, 10 women) healthy young individuals ($M_{\text{age}} = 31.5$, $SD = 5.7$ years) and thus best reflected interperson size differences.

Traditionally, hyoid movement has been captured as a measure of displacement (rest-to-peak; see Figure 2; Dantas et al., 1990; Dodds et al., 1988; Ishida et al., 2002; Leonard et al., 2000). The rest frame is difficult to reliably identify due to preswallow hyoid movement during oral preparation and postswallow clearing gestures (Molfenter & Steele, 2011). Molfenter and Steele (2014) established that peak measures (see Figure 1) were more accurate than displacement, likely by reducing measurement error associated with rest frame selection. Peak-only measurement also captures the most salient information in terms of functional swallowing consequences. Maximal hyoid position is closely coordinated with closure of the laryngeal vestibule and opening of the upper esophageal sphincter (Kendall, McKenzie, Leonard, Gonçalves, & Walker, 2000). The position of the hyoid at rest may not be functionally relevant as long as the system can adequately compensate.

Molfenter and Steele (2014) concluded their study by recommending that the analysis be extended to older and/or dysphagic populations. This further investigation is warranted as age has been shown to affect hyoid excursion (Kendall & Leonard, 2001; Logemann et al., 2000, 2002), and it is unclear whether anatomically scaled hyoid excursion is consistent across different age groups. Known changes to spinal morphology with age may affect the measures

used to scale hyoid excursion. Cervical disc degeneration is present in 95% of people 65 years and older and is associated with a loss of intervertebral disc height (Benoist, 2003; Malcolm, 2002). The vertebral body itself has also been shown to lose height with age, most notably at the level of C3–C6 (Ezra et al., 2017). Osteophytes also frequently develop on vertebral edges to stabilize the spine (Swann, 2009). Kang et al. (2010) observed that the presence of osteophytes might increase vertebral dimension measures in older individuals, thereby affecting comparison of swallowing kinematics across age groups when a vertebral scalar is used. Lastly, changes to cervical spine curvature are known to occur in older individuals. Studies have shown evidence of the normally lordotic cervical spine becoming hyperlordotic, straightened, or kyphotic with age and spinal degeneration (Fujimori et al., 2017; Nojiri et al., 2003; Resnick, 1985). Depending on the type of spinal curvature change in a given individual, the straight line measure from C2–C4 may be less representative of actual length or of overall body height.

Taken together, age-related spinal changes have the ability to either increase or decrease C2–C4 length in a given individual, suggesting that this measure may become less predictive of the “size of the system” and thus unable to adequately control for sex-based differences in hyoid excursion across the life span. The purpose of this investigation was to validate the use of an anatomical scalar in a mixed-age sample and confirm that C2–C4 eliminates sex-based differences in measures of hyoid movement across the life span using Molfenter and Steele’s (2014) methodology. We hypothesized that significant sex differences in hyoid excursion would be observed in millimeters and would be eliminated by converting to C2–C4 scaled units in a healthy mixed-age sample. We also hypothesized that scaled peak hyoid measures would eliminate more sex, age, and volume-related variation compared to displacement measures.

Figure 1. Peak anterior (X), superior (Y), and hypotenuse (XY) hyoid measures were captured on a single frame at the highest point of hyoid movement. Adapted from Molfenter and Steele (2014).

Method

Participants

All measurement and analysis were conducted on a master data set composed of two previously collected VF data sets, one comprising young adults (< 40 years old) and the other old adults (> 65 years old). All data were collected in accordance with institutional review board protocols, and participants provided written consent.

The data set of young healthy adults was originally collected by Molfenter and Steele (2014) to validate the C2–C4 scalar. As mentioned, this sample included VFs from 20 (10 men, 10 women) healthy young individuals ($M_{\text{age}} = 31.5$, $SD = 5.7$ years). The protocol included administration of 15 barium stimuli of varying consistencies and volumes. Of these, six of the boluses were extracted for this analysis: three trials of 22% w/v 5 ml thin liquid barium and three trials of 20 ml 22% w/v thin liquid barium (BraccoPolibar barium suspension diluted with water).

The data set of older healthy adults included VF studies from 44 participants (21 men, 23 women) 65 years old and older ($M_{age} = 76.9$ years, $SD = 7.1$ years), originally collected for separate analyses (Molfenter, Brates, Herzberg, Noorani, & Lazarus, 2018; Molfenter, Lenell, & Lazarus, 2019). Participants were healthy, community-dwelling volunteers with no history of neurological disease, head and neck cancer, or self-reported swallowing difficulties. The same VF protocol was followed as with the healthy young group, and the same six swallow trials were extracted for analysis: three trials of 5 ml thin liquid barium and three trials of 20 ml thin liquid barium. Due to discontinuation of Polibar barium suspension, a 20% w/v dilution of BraccoVaribar thin liquid barium suspension was used with the older cohort. All swallows were uncued and self-administered from 30-ml medicine cups. Both data sets were collected at 30 pulses per second (Toshiba Ultimix and GE Advantix fluoroscopes for the young and old data sets, respectively) and recorded at 30 frames per second on a Digital Swallowing Workstation (KayPentax). After combining the two samples above, the resulting master data set included 64 participants (31 men, 33 women). The height of each participant was measured in centimeters using a portable stadiometer to determine the correlation between the C2–C4 distance and overall body height and to compare this correlation between the young and older age groups.

Measurement and Data Analysis

ImageJ open source software (Schneider, Rasband, & Eliceiri, 2012) was used to measure hyoid peak positions and displacements on each of the six swallows per participant (3×5 ml and 3×20 ml), which were de-identified and randomized. These measures were previously measured on the young participants but were remeasured for the current analysis to ensure identical measurement methods across swallows. For peak position measurements (see Figure 1), the frame of maximum hyoid position during the swallow was located perceptually. Measurement points were placed on the anterior inferior corners of C2 and C4 and on the anterior inferior corner of the hyoid bone. These coordinates were run through an Excel macro via the Steele Swallowing Lab (Steele, 2018), which outputs the maximum position of the hyoid as a percentage of the C2–C4 distance relative to an origin at the anterior inferior corner of C4, with the C2 and C4 coordinates as the y-axis. Displacement measures (see Figure 2) were collected using the same methods, with the addition of the C2, C4, and hyoid bone coordinates from a postswallow rest frame. The rest frame was calculated by identifying the lowest point of the hyoid postswallow within 10 frames after the return of the epiglottis to vertical position, in keeping with previously reported methods (Molfenter & Steele, 2014). In the event of a secondary swallow ($n = 8$), we maintained this method for measuring the initial swallow.

This process resulted in six total hyoid measurements in %C2–C4 units (anterior, superior, and hypotenuse displacement and peak anterior, superior, and hypotenuse

Figure 2. Anterior (X), superior (Y), and hypotenuse (XY) hyoid displacement measures were determined by the difference between hyoid position at rest and at the height of the swallow. Adapted from Molfenter and Steele (2014).

position) on all six swallows per participant. All measures were then converted to absolute distance (millimeters). The C2–C4 distance and the diameter of a penny were captured in pixels on the perceptually identified rest frame in each individual study. The penny diameter was used to control for variable VF magnification across studies. This pixel-based measure was used as a standard scalar for conversion to millimeters. The diameter of a penny (19.05 mm) was divided by its diameter in pixels to determine the specific millimeters per pixel scale for each study.

The original rater and a trained lab assistant rated 15% of swallows in the older group to establish inter- and intrarater reliability on peak and displacement measures, penny diameter, and perceptual identification of peak and rest frame selection. Reliability ratings were previously established on the younger data set but were not conducted for the current analysis.

Statistical Analyses

SPSS Version 25 was used for all statistical analyses. Means and 95% confidence intervals for each hyoid measure were calculated in %C2–C4 and millimeters. Descriptive statistics were separated by age (young, old), sex (male, female), and bolus volume (5 ml, 20 ml). Pearson correlations of height (centimeters) and C2–C4 distance (millimeters) were calculated across the sample and by age group (young/old). Intraclass correlation coefficients (ICCs) were used to assess intra- and interrater reliability on 15% of the old healthy data set.

To first confirm the presence of a significant difference between male and female hyoid movement when measured in absolute units, we ran mixed-model repeated-measures analyses of variance (ANOVAs) with each of the six hyoid measures as the dependent variable (expressed in millimeters) and within-subject factors of age, sex, and

volume. Clinically relevant interaction terms were included. Mixed-model repeated-measures ANOVAs were then rerun with hyoid measures in %C2–C4 to determine whether anticipated effects of bolus volume and sex in millimeters would disappear with the use of scaled units. Bonferroni correction was applied to account for the three displacement values and three peak values that were analyzed, resulting in two-tailed p values of $< .016$ considered statistically significant. The magnitude of the difference between groups was calculated using Cohen's d ; values of 0.2–0.5 were considered to show small effects, values 0.5–0.8 were considered to show medium effects, and values > 0.8 were considered to show large effects (Kotrlík & Williams, 2003).

Results

The correlation between height and C2–C4 distance was higher for the young group ($r = .83$, $p < .001$) compared to the older group ($r = .40$, $p = .010$) but was significant across the overall sample ($r = .60$, $p < .001$; see Figure 3). ICC results for intra- and interrater reliability on peak and rest frame selection, all six hyoid measurements, and the penny diameter are reported in Table 1. Across all measures, raters achieved good-to-excellent reliability ($\text{ICC} > .7$; Fleiss, 1986).

Six swallow trials (3×5 ml and 3×20 ml) were extracted per participant (384 swallows total). Ultimately, 67 swallows were excluded due to poor visualization of structures or spinal coordinates being out of frame, resulting in 317 total swallows from 64 participants included in the final analyses. Descriptive statistics for all swallow measures in both millimeters and %C2–C4 by bolus volume and sex are reported in Table 2.

Mixed-model repeated-measures ANOVAs revealed significant differences in measures of absolute hyoid movements for all factors (sex, bolus volume, and age), as seen in the summary presented in Table 3. Specifically, there were significantly larger values for men compared to women in peak anterior, $F(1, 55.4) = 88.4$, $p < .001$, $d = 1.4$; peak

hypotenuse, $F(1, 54.5) = 47.3$, $p < .001$, $d = 1.4$; superior displacement, $F(1, 53.3) = 7.2$; $p = .010$, $d = 0.52$; and hypotenuse displacement, $F(1, 54.7) = 8.8$; $p = .013$, $d = 0.52$. Significantly larger peak positions were observed in the 20-ml condition compared to the 5-ml condition for peak superior, $F(1, 249.5) = 13.1$, $p < .001$, $d = 0.15$, and peak hypotenuse, $F(1, 249.7) = 8.3$, $p \leq .004$, $d = 0.14$, but these differences were not seen in peak anterior or in any of the displacement measures. Significantly larger measures of hyoid excursion were observed in young compared to older adults in peak anterior position only, $F(1, 55.4) = 9.5$, $p = .003$, $d = 0.49$. Hyoid movement was significantly greater in older adults in peak superior position, $F(1, 55.6) = 10.1$, $p = .002$, $d = 0.82$. No significant interactions were observed.

Summary results from the mixed-model repeated-measures ANOVAs using scaled units are reported in Table 4. When using %C2–C4, there were no significant differences in any hyoid measures as a function of sex. Significant differences as a function of bolus volume (20 ml greater than 5 ml) were found for all peak position measures (peak anterior: $F(1, 249.4) = 9.03$, $p = .003$, $d = 0.12$; peak superior: $F(1, 249.8) = 17.1$, $p \leq .001$, $d = 0.16$; peak hypotenuse: $F(1, 249.4) = 20.6$, $p < .001$, $d = 0.18$), but these differences were not seen for any of the displacement measures. All peak measures were significantly larger in the older adults compared to young adults (peak anterior: $F(1, 55.3) = 17.0$, $p < .001$, $d = 0.94$; peak superior: $F(1, 55.5) = 39.9$; $p < .001$, $d = 1.3$; peak hypotenuse: $F(1, 54.3) = 86.6$; $p < .001$, $d = 1.5$). This difference was also observed in superior displacement, $F(1, 53.2) = 19.4$, $p < .001$, $d = 0.80$, and hypotenuse displacement, $F(1, 55.1) = 22.3$, $p < .001$, $d = 0.90$.

Discussion

The primary goal of this study was to validate an anatomical scalar for measuring hyoid excursion across the life span. We found a weaker correlation between overall height and C2–C4 length in the older cohort compared to the

Figure 3. Height–spine correlations by age group.

Table 1. Intra- and interrater reliability of hyoid measurements in the old healthy cohort.

Reliability		Rest frame selection	Peak frame selection	Peak anterior (X)	Peak superior (Y)	Peak hypotenuse (XY)	Anterior disp. (X)	Superior disp. (Y)	Hypotenuse disp. (XY)	Penny diameter
Intrarater (ICC)	<i>M</i>	.99	.98	.99	.99	.98	.93	.85	.92	.92
	95% CI	[.99, .99]	[.96, .99]	[.99, 1.0]	[.99, .99]	[.96, .99]	[.86, .96]	[.71, .92]	[.84, .96]	[.85, .96]
Interrater (ICC)	<i>M</i>	1.0	.96	.99	.992	.96	.93	.93	.94	.87
	95% CI	[.99, 1.0]	[.92, .98]	[.99, 1.0]	[.69, .94]	[.91, .98]	[.86, .96]	[.87, .96]	[.88, .97]	[.74, .93]

Note. Disp. = displacement; ICC = intraclass correlation coefficients; CI = confidence interval.

younger cohort, which was expected given variable changes to the spine known to occur with aging. This effect can be visualized in Figure 3, in which greater variation in spine–height relationships can be seen in older adults. This finding demonstrates that cervical spine measurements may not change in predictable ways relative to height with aging and thus confirmed the need to validate the C2–C4 scalar in older individuals.

Effect of Scaling on Sex-Based Differences

The significant sex differences observed in absolute hyoid excursion are consistent with previous literature (Leonard et al., 2000; Logemann et al., 2000, 2002). The only hyoid measures that did not show an absolute sex effect were superior peak position and anterior displacement. Anterior hyoid displacement may be less related to a person's size compared to superior movement, though further research is needed to confirm this relationship. The nonsignificant superior peak position may be related to measurement magnitudes; in peak position measures, the superior dimension is typically of smaller magnitude than the anterior dimension, given the location of the C4 landmark from which it is measured.

Anatomically scaled hyoid measures effectively neutralized all sex-based differences observed in absolute units at an adjusted alpha level of .016. These findings indicate that %C2–C4 was an adequate scalar for measuring hyoid excursion in a mixed-age cohort. As a post hoc analysis, we ran all statistics on the old healthy data set to ensure that the effects of sex and bolus volume remained comparable to those seen across age groups, and all significant sex-based differences observed in millimeters were nullified in C2–C4 units in the older group alone. These results can be found in the Appendix. Similar findings have previously been reported on the young healthy group alone (Molfenter & Steele, 2014). Based on these findings, the C2–C4 scalar is recommended as best practice for measuring hyoid excursion, and it appears to be valid for collapsing results across males and females across the life span.

Effect of Scaling on Volume-Based Differences

A significant effect of bolus volume was found in unscaled peak superior and peak hypotenuse measures and in all C2–C4 scaled peak position measures. Larger boluses were significantly associated with increased magnitude

compared to 5-ml boluses. This effect was not observed in any of the displacement measures. Not only were peak measures sensitive to volume-related variation, the volume effect was retained and seemingly magnified in scaled units (given that a significant effect of volume only emerged in peak anterior measures after scaling), suggesting increased sensitivity of peak measures over displacement measures for volume-related analyses. Values for peak measures are larger than their displacement correlates because they measure a greater distance (see Figures 1 and 2). Therefore, volume-based differences in displacement values simply may not have been large enough to yield statistically significant results. It is unlikely that measurement error resulted in the lack of volume-related changes in displacement, given the high inter- and intrarater reliability of rest frame selection (see Table 1). Retaining the effect of volume in hyoid kinematic measurement is critical. Because this effect (increased excursion with increased volume) is established and well documented (Ishida et al., 2002; Kim & McCullough, 2008; Nagy et al., 2015), it is important for any measurement method to be sufficiently sensitive to capture it. Our findings indicate that peak position measures can be used to establish scaled norms for hyoid movement at different bolus volumes. Molfenter and Steele (2014) advocated for the use of peak over displacement measures in %C2–C4 units as the most accurate method for young, healthy individuals. This study confirms that peak measures capture differences in hyoid excursion by volume, and future research should include additional volumes.

Effect of Scaling on Age-Based Differences

The directional effect of age in absolute units was notably different from the effect of age in scaled units. In millimeters, young adults demonstrated significantly greater hyoid excursion in peak anterior position, but older adults had greater excursion in the peak superior position. No age effect in any other hyoid measures was observed. In scaled units, the effect of age followed a more consistent pattern. Older adults had significantly greater hyoid excursion in all measures except anterior displacement (no effect). The age-related effects in millimeters are difficult to interpret given the lack of a directional trend. However, this is in keeping with the mixed reports of the effect of age on unscaled hyoid excursion in the literature. Kendall and Leonard (2001) found that older women and older men had greater hyoid

Table 2. Descriptive statistics for hyoid excursion in absolute and scaled units.

Variable and statistic	Young healthy						Old healthy					
	5 ml			20 ml			5 ml			20 ml		
	Millimeters			Millimeters			Millimeters			Millimeters		
	Men	Women	%C2–C4	Men	Women	%C2–C4	Men	Women	%C2–C4	Men	Women	%C2–C4
Peak measures												
Peak anterior (X)												
<i>M</i>	61.3	49.1	130.8	62.2	48.4	133.8	56.6	45.4	150.1	57.0	46.2	154.0
95% CI	[58.9, 63.7]	[47.5, 50.6]	[127.5, 134.1]	[60.0, 64.4]	[46.9, 50.0]	[129.9, 137.7]	[54.9, 58.3]	[44.1, 46.7]	[145.7, 154.6]	[55.3, 58.8]	[44.8, 47.7]	[149.5, 158.5]
Peak superior (Y)												
<i>M</i>	28.4	26.4	65.0	28.7	30.3	71.7	37.2	36	107.8	37.4	36.7	109.9
95% CI	[24.0, 32.7]	[24.2, 28.7]	[59.8, 70.1]	[25.2, 32.3]	[28.0, 32.5]	[66.4, 77.0]	[33.1, 41.2]	[33.6, 38.5]	[102.1, 113.5]	[33.5, 41.3]	[34.2, 39.1]	[104.4, 115.5]
Peak hypotenuse (XY)												
<i>M</i> (%C2–C4)	68.5	56.0	147.6	69.2	57.4	153.3	68.8	58.4	187.2	69.2	59.5	191.6
95% CI	[66.4, 70.7]	[54.3, 57.7]	[145.1, 150.1]	[67.4, 71.1]	[56.4, 58.5]	[150.2, 156.3]	[66.4, 71.2]	[56.5, 60.4]	[182.9, 191.9]	[66.9, 68.5]	[57.5, 61.4]	[187.8, 195.4]
Displacement measures												
Anterior displacement												
<i>M</i>	10.5	9.0	23.0	10.8	9.37	24.6	10.4	9.5	29.5	9.9	10.1	30.2
95% CI	[9.2, 11.7]	[7.8, 10.1]	[21.1, 24.9]	[9.3, 12.2]	[8.5, 10.2]	[22.4, 26.7]	[9.2, 11.5]	[8.4, 10.5]	[27.1, 32.0]	[8.5, 11.4]	[8.6, 11.6]	[27.1, 33.3]
Superior displacement												
<i>M</i>	15.7	10.4	30.4	13.7	13.9	33.6	17.5	13.2	44.6	17.4	14.6	47.4
95% CI	[13.2, 18.1]	[8.2, 12.7]	[26.5, 34.3]	[11.6, 15.8]	[11.9, 15.9]	[30.0, 37.2]	[15.4, 19.7]	[11.8, 14.6]	[41.1, 48.0]	[15.1, 19.6]	[13.0, 16.2]	[43.6, 51.1]
Hypotenuse displacement												
<i>M</i>	19.2	14.7	39.9	17.8	17.0	42.5	20.9	16.7	54.9	20.7	18.5	58.5
95% CI	[17.0, 21.5]	[13.1, 16.3]	[36.9, 43.0]	[15.7, 19.9]	[15.2, 18.8]	[38.9, 46.0]	[18.9, 22.8]	[15.2, 18.2]	[51.5, 58.3]	[18.7, 22.8]	[16.9, 20.1]	[54.8, 62.1]

Note. CI = confidence interval.

Table 3. Contributions of sex, bolus volume, and age on hyoid excursion (in millimeters).

Variable	Sex		Volume		Age	
	Main effect?	Direction	Main effect?	Direction	Main effect?	Direction
Peak anterior (X)	Yes	M > F	No	—	Yes	Young > old
Peak superior (Y)	No	—	Yes	20 > 5	Yes	Old > young
Peak hypotenuse (XY)	Yes	M > F	Yes	20 > 5	No	—
Anterior displacement (X)	No	—	No	—	No	—
Superior displacement (Y)	Yes	M > F	No	—	No	—
Hypotenuse displacement (XY)	Yes	M > F	No	—	No	—

Note. Em dashes indicate no direction due to nonsignificant findings. M = male; F = female.

displacement compared to young men and women (only for 1-ml boluses), though this finding was only statistically significant in women. Kang et al. (2010) found greater magnitude of vertical (i.e., superior) hyoid movement in older adults compared with young adults, though they did not separate males and females in their analysis. In two studies following identical protocols, Logemann et al. (2000) found that older men had significantly greater hyoid movement compared to younger men, but older women (Logemann et al., 2002) had lesser hyoid movement compared to young women (though not significantly so). Given the lack of any significant interactions in this study, it does not appear that the observed age effects were influenced by sex or volume. One potential explanation for our results in millimeters is that younger individuals have greater functional reserve and more flexibility than older counterparts and therefore exhibit movement that extends beyond the minimum needed to adequately accomplish a task (Logemann et al., 2000). Decreases in this functional reserve with aging due to neuromuscular degeneration may have contributed to our findings. The anomalous finding of greater excursion in older adults in peak superior position may be the result of functional compensation by older adults.

In contrast, anatomically scaled hyoid excursion was significantly greater in older adults in all peak position measures and in superior and hypotenuse displacement. The observation of greater scaled hyoid excursion in older compared to younger adults is substantiated by some evidence, as detailed above. Greater magnitude of excursion

has been attributed to functional compensation for a lower resting position of the hyolaryngeal complex with age (Logemann et al., 2002). However, this rationale is not sound in the context of peak position measures, for which the position of the hyoid at rest is irrelevant. A more compelling explanation is that larger scaled values with age are due to age-related spinal changes affecting the C2–C4 scalar. Reduced intervertebral space and vertebral body shortening with age results in a shorter C2–C4 distance in older individuals, magnifying the relative distance between the peak hyoid position and C4. Supporting this hypothesis, a post hoc one-way ANOVA comparing C2–C4 distance (in millimeters) between the young and old adults showed that young adults had significantly greater C2–C4 distances ($M = 38.2$ mm, $SD = 4.5$) compared to the older adults ($M = 33.7$ mm, $SD = 3.9$), $F(1, 58) = 14.4$, $p < .001$.

Height distribution by sex was analyzed for the older cohort because the sample was not collected with consideration for participant height, unlike the young healthy adults, and had the potential to impact the age comparison in scaled units. Older adult heights were found to be well distributed for both men and women (see Figure 4).

The observed age effect in scaled units highlights an important caveat to the use of the C2–C4 scalar. The scalar appears to inflate hyoid measurements in older adults, highlighting the importance of making comparisons to the correct age group. Hyoid excursion values that appear adequate for young adults could potentially fall outside acceptable levels for an older adult (see Table 2). Therefore,

Table 4. Contributions of sex, bolus volume, and age on hyoid excursion (in %C2–C4).

Variable	Sex		Volume		Age	
	Main effect?	Direction	Main effect?	Direction	Main effect?	Direction
Peak anterior (X)	No	—	Yes	20 > 5	Yes	Old > young
Peak superior (Y)	No	—	Yes	20 > 5	Yes	Old > young
Peak hypotenuse (XY)	No	—	Yes	20 > 5	Yes	Old > young
Anterior displacement (X)	No	—	No	—	No	—
Superior displacement (Y)	No	—	No	—	Yes	Old > young
Hypotenuse displacement (XY)	No	—	No	—	Yes	Old > young

Note. Em dashes indicate no direction due to nonsignificant findings.

Figure 4. Distribution of participant height by sex.

we recommend restricting comparisons to age-matched groups. Future research should focus on more specific age boundaries for hyoid excursion, given that adults between 40 and 65 years old were not sampled.

While we recommend measuring peak hyoid position in %C2–C4 units as best practice, researchers who are working with existing data or who choose to use displacement measures and/or absolute units can refer to these values and compare to scaled correlates for a given age group or bolus volume. It should be noted that a clear relationship between adequacy of hyoid excursion and swallowing impairment has yet to be firmly established, though there is evidence that reduced excursion in the anterior dimension is associated with increased risk of penetration–aspiration (Steele et al., 2011; Zhang et al., 2019). An important future direction is to establish cutoff values of hyoid movement that are associated with swallowing safety at age-specific thresholds. Lastly, further research is needed to confirm the application of this methodology to dysphagic populations and to replicate findings with other bolus volumes and viscosities.

Conclusion

Based on the ability of the C2–C4 scalar to control for sex-based differences in all parameters of hyoid excursion while retaining sensitivity to the effects of bolus volume on hyoid kinematics, expressing hyoid excursion as a percentage of the C2–C4 distance appears to be valid for use across the life span. This analysis provides evidence supporting the use of peak position rather than displacement measures for capturing hyoid excursion. Based on our findings, we recommend measuring peak hyoid position in %C2–C4 units while controlling for volume and age as best practice.

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Appendix (p. 1 of 2)

Contributions of Bolus Volume and Sex to Hyoid Excursion in Millimeters

Variable	Main effect	df	F	p	d
Association between measure and volume					
Peak anterior (X)	Yes	1, 37.9	53.57	< .001	1.46
Peak superior (Y)	No	1, 37.9	0.34	.563	—
Peak hypotenuse (XY)	Yes	1, 37.62	23.22	< .001	1.21
Anterior displacement	No	1, 38.5	0.04	.852	—
Superior displacement	Yes	1, 36.8	7.49	.010	0.64
Hypotenuse displacement	No	1, 37.9	0.54	.020	—
Association between measure and volume					
Peak anterior (X)	No	1, 156.5	3.57	.061	—
Peak superior (Y)	No	1, 155.4	4.57	.034	—
Peak hypotenuse (XY)	Yes	1, 155.7	7.52	.007	0.15
Anterior displacement	No	1, 157.7	0.03	.860	—
Superior displacement	No	1, 158.2	0.11	.743	—
Hypotenuse displacement	No	1, 158.2	0.54	.464	—

Note. Em dashes indicate no direction due to nonsignificant findings.

Contributions of Bolus Volume and Sex to Hyoid Excursion (in Millimeters) in C2–C4 Units

Variable	Main effect	df	F	p	d
Association between measure and volume					
Peak anterior (X)	No	1, 37.6	5.75	.022	—
Peak superior (Y)	No	1, 37.9	1.31	.259	—
Peak hypotenuse (XY)	No	1, 37.3	3.24	.152	—
Anterior displacement	No	1, 38.2	0.53	.473	—
Superior displacement	No	1, 37.0	2.44	.126	—
Hypotenuse displacement	No	1, 38.5	0.89	.352	—
Association between measure and volume					
Peak anterior (X)	No	1, 155.5	3.24	.074	—
Peak superior (Y)	No	1, 155.7	3.86	.051	—
Peak hypotenuse (XY)	Yes	1, 155.7	6.99	.009	0.20
Anterior displacement	No	1, 157.3	0.02	.879	—
Superior displacement	No	1, 159.3	3.13	.079	—
Hypotenuse displacement	No	1, 159.02	5.49	.312	—

Note. Em dashes indicate no direction due to nonsignificant findings.