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The Effect of Bolus Consistency on Hyoid Velocity in Healthy Swallowing

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Abstract

The aim of this study was to determine whether measures of hyoid velocity increase when swallowing liquids of thicker consistency at a constant volume. A gender-balanced sample of 20 healthy young participants (mean age 31.5) each swallowed 3 boluses of 5ml volume in 3 consistencies (ultrathin, thin, and nectar-thick barium). Using frame by frame tracking of hyoid position, we identified the onset and peak of the hyoid movement and derived measures of velocity (i.e., distance in anatomically normalized units, i.e., % of the C2–4 vertebral distance, divided by duration in ms) for the X, Y and XY movement directions. Peak hyoid velocity was also identified for each movement direction. Where significant differences were identified, the component measures of hyoid movement distance and duration were further explored to determine the strategies used to alter velocity. The results showed increased velocities and higher peak velocities with the nectar thick stimuli compared to thin and ultrathin stimuli. This was achieved by a primary strategy of larger hyoid movement distances per unit of time when swallowing nectar-thick liquids.. These results point to one mechanism by which thickened liquids may contribute to improved airway protection, by facilitating more-timely laryngeal vestibule closure.

Keywords

Deglutition; deglutition disorders; swallowing; hyoid; kinematics

INTRODUCTION

Safe deglutition is associated with timely coordination of laryngeal elevation and laryngeal vestibular closure; both events are dependent on the biomechanics of hyoid motion [1–3].

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Hyoid movement in swallowing is achieved by contracting the floor of mouth suprahyoid muscles against a stabilizing resistance provided by the infrahyoid strap muscles and the middle pharyngeal constrictor muscle [4]. Contraction of the mylohyoid muscle is thought to contribute primarily to elevation of hyolaryngeal structures, while contraction of the geniohyoid muscle is thought to contribute to anterior movement [4]. The term hyoid kinematics refers to measurements of hyoid movement, which can be derived from frame-by-frame hyoid position tracking across the movement trajectory [5]. Normalization of these hyoid measurements to the size of the system allows for uniform anatomical scaling and permits comparison across individual patients or study participants [6].

Clinicians frequently evaluate the adequacy of hyoid excursion in swallowing and consider reduced hyoid movement to be a factor contributing to aspiration or residue [7–11]. However, recent studies have found a wide range in hyoid movement distance in the healthy population, and have failed to find a clear relationship between aspiration and reduced hyoid movement [12, 13]. Consequently, attention has been redirected to other parameters of hyoid movement, including hyoid velocity, i.e., the rate of change in hyoid position over time, measured in a single plane (e.g. superior, anterior). Several recent studies suggest that hyoid velocity may differ between healthy and pathological swallows, with the latter having significantly reduced velocity [5, 8, 14–16]. Another parameter of potential clinical relevance is *peak* hyoid velocity, defined as the maximum rate of position change within a single plane of hyoid movement (Y: superior-inferior; or X: anterior-posterior). Peak speed is the term used to describe the corresponding parameter measured in an integrated two dimensional vector (XY) [8]. In the motor control and movement kinematics literature, measurements of peak velocity or peak speed are frequently interpreted to reflect power [17–19]. Nagy and colleagues [14] have recently reported that the moment of peak hyoid speed corresponds very closely in time with the moment of achieving laryngeal vestibule closure via arytenoid cartilage contact with the undersurface of the epiglottis in healthy thin liquid swallowing. This suggests that the speed (and power) of hyoid movement may be governed by the functional goal of closing the laryngeal vestibule in a timely manner.

Relatively little data are available regarding normal hyoid velocity or peak velocity in swallowing. Nagy and colleagues [14] have recently reported stability in hyoid velocity in healthy swallowing of “ultrathin” 20% w/v liquid barium across bolus volumes from 5 to 20 ml. Peak velocity, by contrast, was significantly higher for a 20 ml volume compared to 5 and 10ml boluses. Similarly, Ueda et al. [16] studied a sample of 21 healthy young adults and reported that peak hyoid speed along the XY hypotenuse was significantly higher for 20 ml liquid barium stimuli compared to volumes of 10 ml or smaller. An understanding of whether and how these parameters vary in response to differences in bolus consistency is currently lacking. Inferences can, however, be made based on reported data regarding hyoid movement distance and duration. In a study by Dantas and colleagues [20], the effect of bolus consistency on the duration and distance of hyoid motion was evaluated in healthy young male subjects using high viscosity paste and low viscosity liquid barium. The results showed significantly greater anterior hyoid movement distance for the paste stimulus. Perlman and colleagues [2], however, used anatomically scaled measures of hyoid movement in male patients with dysphagia and failed to find differences in movement distance between liquid and paste consistency barium. Furthermore, Lof & Robbins [21] failed to find differences in several durational measures of hyoid movement in healthy adults between liquid and semi-solid consistencies. The purpose of the current manuscript is to explore the influence of liquid bolus consistency on measures of hyoid velocity and peak velocity in swallowing, based on retrospective analysis of a previously acquired data set of swallowing from healthy young adults [22]. Given that measures of hyoid velocity are derived from component measures of hyoid movement distance and duration, these parameters were also explored in post-hoc analyses so that the mechanisms behind differences in velocity might be appreciated. Based on the available literature showing a relative lack of significant differences in hyoid movement distance or duration as a function of viscosity [2, 20, 21], our hypotheses were that thicker bolus consistencies would elicit no difference in measures of hyoid velocity and peak velocity.

MATERIALS AND METHODS

The data for this study were collected in an experiment designed to determine the nature and extent of systematic differences in swallowing kinematics in healthy adults, given planned variations in bolus volume and consistency and methodological control for anthropometric variations in height and pharyngeal size between 10 male and 10 female participants with a mean age of 31.5 years (SD 5.7 years) [22]. The data for the current analysis comprised 9 boluses of 5 ml volume per participant, organized in blocks of 3 boluses at each of 3 consistencies: nectar-thick, thin and ultrathin liquid barium. The flow characteristics of these stimuli are illustrated in Figure 1. The nectar thick liquid barium was prepared in a 40% w/v barium concentration by mixing EZ-HD powder into a xanthan-gum-thickened liquid. This product had an apparent viscosity of 236 mPa.s at a shear rate of 50 reciprocal seconds, which is the rate conventionally used for describing the viscosity of dysphagia thickened liquids [23]. The thin liquid barium was prepared in a 40% w/v concentration by diluting Liquid Polibar® (Bracco Diagnostics Inc., Monroe Township, New Jersey) with water, to an apparent viscosity of 30 mPa.s. The “ultrathin” liquid barium [24] was prepared by diluting Liquid Polibar® with water to a 22% w/v barium concentration, with an apparent viscosity of 11 mPa.s. The ultrathin liquid was included based on a study [24] that suggests that this concentration of barium represents a true thin liquid more closely than 40% w/v barium. For reference, water, as a true thin liquid would have constant Newtonian viscosity rather than the shear-thinning properties seen for the three barium stimuli and would appear as a horizontal straight line at a coordinate of 1mPa.s across the x-axis of Figure 1. Boluses were self-administered from 30ml volume medicine cups and the order of bolus consistency blocks was randomized. Swallows were captured in lateral view at 30 pulses per second, and recorded at 30 frames per second on the KayPENTAX Digital Swallow Workstation.

Data processing involved splicing of the videofluoroscopy recordings into clips capturing a time interval beginning 30 frames prior to the first bolus of each block passing the mandibular ramus until 30 frames after the hyoid returned to rest after the 3rd bolus in the block. Data analysis involved frame-by-frame tracking of hyoid position in ImageJ freeware, using a coordinate system with an origin defined at the anterior-inferior corner of the C4-vertebrae, and the vertical axis defined by a line running from the origin upwards through the anterior-inferior corner of the C2-vertebrae (see Figure 2). The pixel-distance between the anterior-inferior corners of the C2 and C4 vertebrae was also measured as an anatomical scalar to enable us to control for differences in the size of the system (i. e. oropharynx and cervical spine) across participants during measurements of hyoid movement distance [6]. Using the frame-by-frame position history data, an algorithm in Microsoft Excel VBA software was used to index the onset and end positions of the anterosuperior hyoid movement for each swallow. The onset positions were defined as the lowest positions between the start of marking (10 frames before observed hyoid movement) and the peak hyoid position, and were identified in both the X and Y directions. Similarly, the end positions of the hyoid movement were defined as the peak of maximal hyoid position within the hyoid position history, and were identified in both the X and Y directions. This permitted the derivation of measures of hyoid movement distance (maximum position minus onset position, in % C2–4 units), maximum hyoid displacement position (in anatomically normalized units, i.e., % of the C2–4 vertebral distance). The time lapse between the frames of onset and end hyoid position were used to calculate movement duration (ms) and the velocities (X, Y) and speed (XY) of hyoid movement were calculated as the distance travelled divided by movement duration (in mm/s). The peak velocities (X,Y) and speed (XY) in (mm/s) were also identified within each movement trajectory. As reported elsewhere, strong inter and intra-rater reliability (i.e., intra-class correlation coefficients > 0.79) were obtained for superior and hypotenuse hyoid measurements based on repeat rating of a random selection of 10% of the recordings [6, 22]. Intra-class coefficients for inter- and intra-rater reliability of anterior hyoid displacement measures were slightly lower at 0.59 and 0.61, respectively. Statistical analyses were performed using IBM SPSS Statistics version 21. A mixed model analysis of variance (ANOVA) with a within-participant repeated factor of trial-within-bolus-consistency was performed to identify the impact of bolus consistency on the study parameters. Post-hoc Sidak tests and Cohen's *d* effect size measures were used to further understand the nature and magnitude of significant pairwise comparisons. Cohen's *d* measures of 0.2 to 0.49 can be interpreted as showing a small effect, while values of 0.5 to 0.79 and ≥ 0.8 reflect medium and large effect sizes, respectively [25].

RESULTS

Descriptive statistics for the hyoid kinematic parameters of interest are found in Table 1.

Hyoid Velocity

Significantly faster anterior hyoid velocities were found with the nectar-thick consistency compared to the thin and ultrathin stimuli [$F(2, 159.08) = 6.24$, $p = 0.002$, $d = 0.61$]. Along the XY hypotenuse, significantly faster hyoid speeds were also seen with the nectar-thick consistency [$F(2, 158.52) = 6.03$, $p = 0.003$, $d = 0.53$], as illustrated in Figure 3. No significant differences in hyoid velocity were seen in the superior direction.

Peak Hyoid Velocity

With respect to the peak velocities achieved during the hyoid movement, we found significantly higher values for the nectar-thick liquid and thin stimuli compared to the ultrathin liquid for anterior movement [$F(2, 157.98) = 4.12$, $p = 0.018$, $d = 0.42$].

Significantly higher peak velocities were also found for the nectar-thick compared to the ultra-thin liquid for superior movement [$F(2, 158.78) = 6.85$, $p = 0.001$, $d = 0.62$], and for XY movement with the nectar-thick and thin stimuli compared to the ultrathin liquid [$F(2, 158.39) = 6.1$, $p = 0.003$, $d = 0.52$]. These results are illustrated in Figures 4 a, b and c, and all point to a pattern of faster peak velocity for thicker consistency liquids.

Mechanisms of Increased Velocity

Post-hoc analyses revealed that the increased velocities seen with nectar-thick liquids for anterior hyoid movement involved significantly larger hyoid movement distances (hyoid onset to peak hyoid position) compared to those seen with the thin and ultra-thin liquids [$F(2,157.61) = 3.37$, $p = 0.037$, $d = 0.32$]. These greater anterior hyoid movement distances were achieved in combination with significantly shorter movement durations for the nectar-thick consistency compared to the ultrathin liquid [$F(2, 156.42) = 3.465$, $p = 0.034$, $d = 0.4$]. Similarly, significantly larger XY movement distances were found for the nectar-thick liquid compared to the ultrathin liquid [$F(2, 158.07) = 4.17$, $p = 0.017$, $d = 0.38$]. XY movement durations showed a non-significant trend towards being shorter as the bolus progressed from ultrathin to thin to nectar-thick consistency [$F(2, 157.15) = 2.92$, $p = 0.057$, $d = 0.21$] Overall, these results point to a primary strategy of the hyoid covering a greater movement distance per unit time as the mechanism by which increased velocity is achieved with thicker liquids.

DISCUSSION

The study adds to the current understanding of swallowing dynamics and the adaptive physiological mechanisms that take place when accommodating liquids of differing consistency. The analysis reveals a clear influence of bolus consistency on the velocity of anterior and XY hypotenuse hyoid movement, reflected by increased, i.e., faster hyoid movement velocities for the nectar-thick consistency compared to thin and ultra-thin liquid stimuli. This increase in velocity appears to be achieved using a primary strategy of increasing the hyoid movement distance covered per unit of time. The confirmation of consistency influences on hyoid kinematics is in contrast to the relative lack of bolus volume effects reported by Nagy et al. [14] who found that a 20 ml volume bolus of ultrathin liquid elicited a higher vertical peak hyoid velocity and greater XY displacement than 5 and 10 ml volumes, while other parameters of hyoid movement remained stable across manipulations of bolus volume.

The results of this study are consistent with previous evidence of greater hyoid movement distances for paste versus liquid barium described by Dantas and colleagues [20], but are seen with a narrower contrast between nectar-thick and thin liquids. The result of increased hyoid movement velocity and peak velocity with nectar-thick liquids is contrary to our hypothesis, which was based on the relative lack of evidence pointing to viscosity-dependent differences in hyoid movement distances or durations in the literature [2, 21]. The use of anatomically scaled measures of hyoid movement may be partly responsible for the emergence of consistency-based findings in this study in contrast to previous research where these differences have not been seen. Additionally, previous literature has focused exclusively on elderly participants [21] or adults referred for swallowing examination [2] in contrast to the present data, which were obtained from a sample of healthy young adults.

Nagy et al. [14] have recently suggested that peak hyoid velocity may be associated with the functional goal of timely laryngeal vestibule closure in liquid swallowing. This relationship was not specifically evaluated in the current study; however, given that thicker consistencies flow more slowly, it would be reasonable to posit that nectar-thick liquids create a context in which there is less urgency to achieve laryngeal vestibule closure, and that lower peak hyoid velocities might be expected accordingly. The observed result of faster hyoid velocities and peak velocities with nectar-thick liquids is opposite to this prediction, but does not negate the possibility of a functional connection between hyoid velocity and laryngeal vestibule closure. The current results may point to an as-yet unappreciated mechanism by which thickened liquids facilitate safe swallowing, in addition to their slower flow, in the form of eliciting more timely laryngeal vestibule closure. This possibility requires further investigation.

In the current analysis, we found no significant differences in hyoid velocity in the superior direction across the stimulus consistencies tested (mean: 70% of the C2–4 distance/s; 95% confidence interval: 64–77% C2–4/s). The observed consistency effects were restricted to the anterior and XY planes of movement. These observations are consistent with the report of stable, non-varying superior hyoid velocity across increasing bolus volume with ultrathin barium in the Nagy et al. study [14]. Consequently, superior hyoid movement velocity may be expected to fall within specified ranges in healthy young adults; this may be of use in discriminating healthy from pathological swallows. Further exploration of changes in hyoid velocity measures in healthy aging is warranted to define the boundaries between healthy and impaired swallowing.

An important limitation to acknowledge regarding this study is the possibility that the differences we are attributing to viscosity may also reflect other characteristics of the stimuli that we used. Although we attempted to control for other influences, our stimulus array also included a contrast with respect to barium density between the ultrathin stimulus and the thicker stimuli. Additionally, the nectar-thick liquid in this study was raspberry-flavored, so we cannot entirely rule out the possibility that the difference in flavor across stimuli contributed to the patterns seen.

CONCLUSION

Earlier studies by Van Daele and colleagues and Paik et al. [5, 8] suggest that reduced peak velocity of hyoid movement may be a parameter that is characteristic of impaired swallows. This analysis provides preliminary descriptive statistics on hyoid kinematics for healthy swallowing of liquid boluses in the apparent viscosity range of 11–236 mPa. s. Interestingly, our data show that a nectar-thick bolus elicits faster velocities and higher peak velocities of hyoid movement in healthy young adults. Thus, one mechanism by which thicker liquids may contribute to improvements in swallowing function may be their tendency to elicit higher velocities of hyoid movement. Future studies on hyoid kinematics exploring both finer gradations and a wider range of viscosities, extending into the honey- and spoon-thick consistency ranges would more clearly elucidate the relationships between bolus consistency, hyoid velocity and airway protection that are suggested by the current results.

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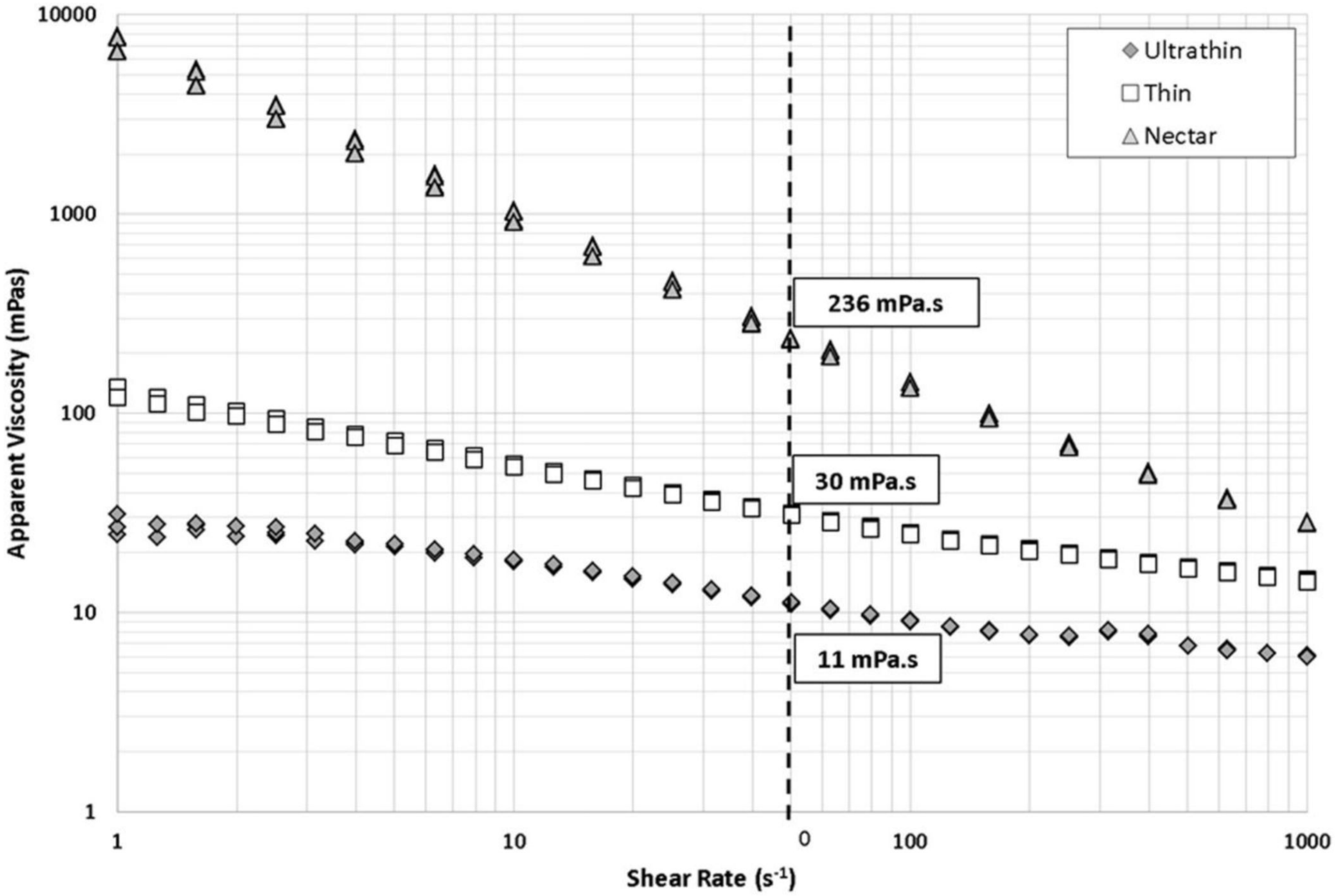

Figure 1.

Graph showing the apparent viscosity of the three different stimuli used for the current analysis.

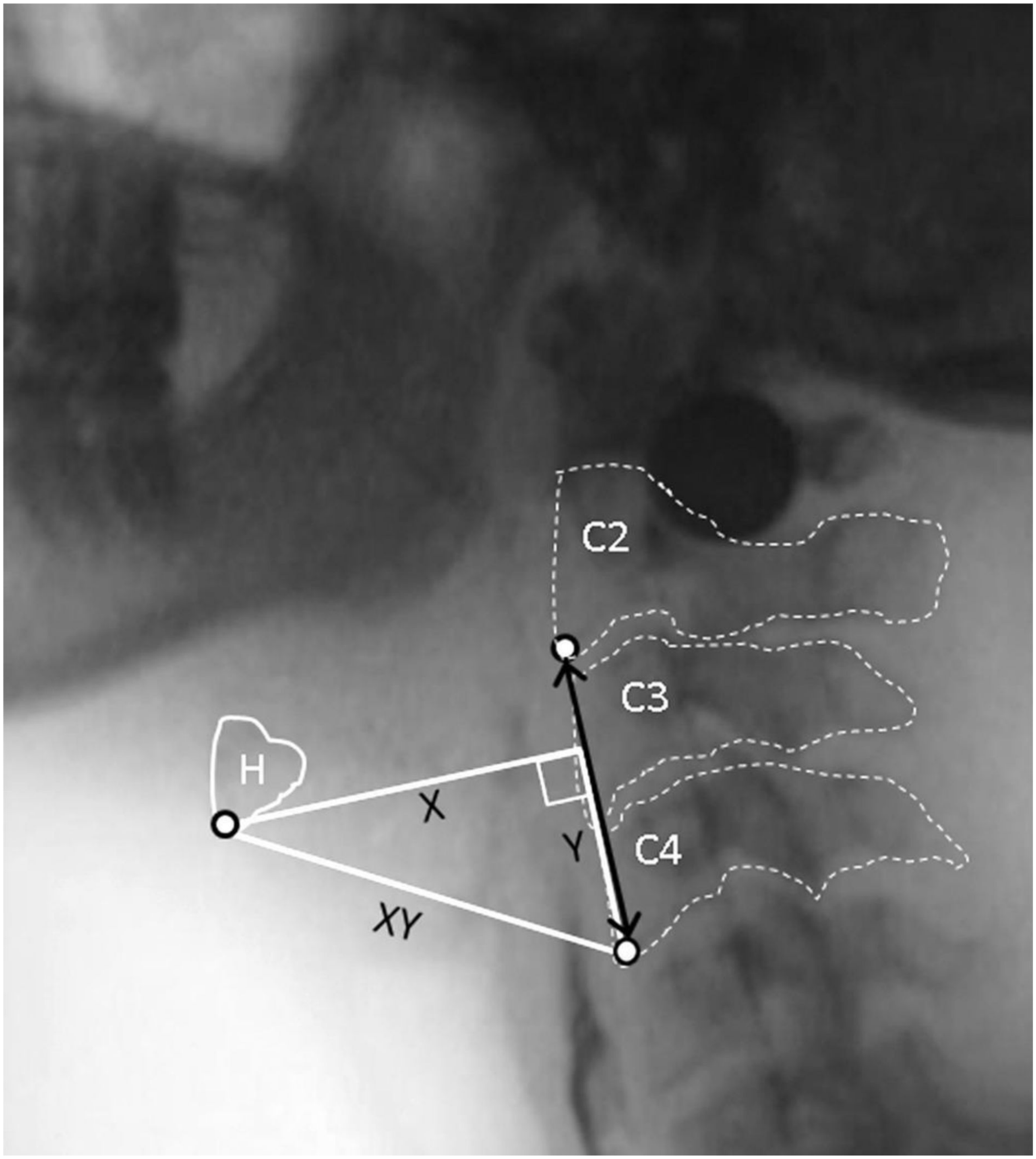

Figure 2.

Lateral view videofluoroscopic image, showing the hyoid (H) at maximum excursion, and the anatomical points used for measurement in a coordinate system with the origin located at the anterior-inferior corner of C4 and the vertical (Y) axis running in a line up from the origin through the anterior-inferior corner of C2.

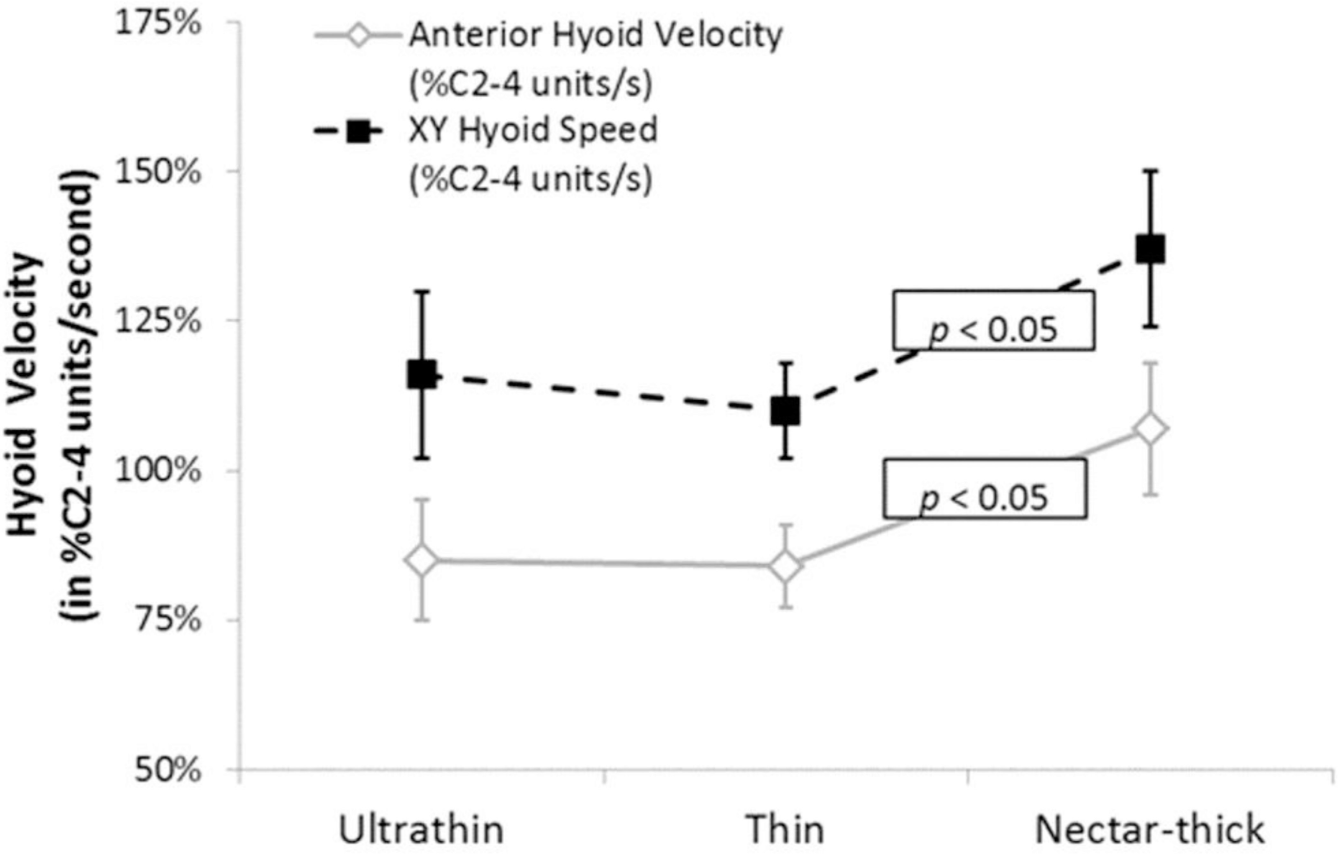
Anterior Hyoid Velocity
(%C2-4 units/s)
XY Hyoid Speed
(%C2-4 units/s)
Hyoid Velocity
(in %C2-4 units/second)
175%
150%
125%
100%
75%
50%
$p < 0.05$
$p < 0.05$
Ultrathin
Thin
Nectar-thick

Figure 3.

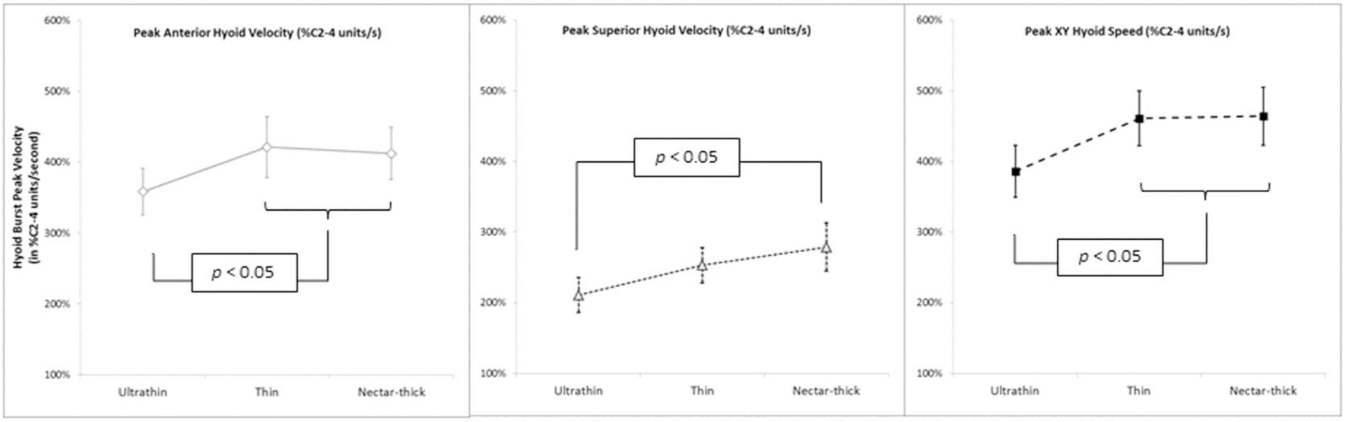
Peak Anterior Hyoid Velocity (%C2-4 units/s)
Hyoid Burst Peak Velocity (in %C2-4 units/second)
600%
500%
400%
300%
200%
100%
Ultrathin
Thin
Nectar-thick
$p < 0.05$
Peak Superior Hyoid Velocity (%C2-4 units/s)
600%
500%
400%
300%
200%
100%
Ultrathin
Thin
Nectar-thick
$p < 0.05$
Peak XY Hyoid Speed (%C2-4 units/s)
600%
500%
400%
300%
200%
100%
Ultrathin
Thin
Nectar-thick
$p < 0.05$

Figure 4.

Table 1

Descriptive statistics for hyoid kinematics by liquid bolus consistency

	Ultrathin			*Thin*			*Nectar-thick*		
		95% Confidence Interval			**95% Confidence Interval**			**95% Confidence Interval**	
	Mean	**Lower Bound**	**Upper Bound**	**Mean**	**Lower Bound**	**Upper Bound**	**Mean**	**Lower Bound**	**Upper Bound**
Anterior Hyoid Velocity (%C2–4 units/s)	85	75	95	84	77	91	107	96	119
Superior Hyoid Velocity (%C2–4 units/s)	70	56	83	66	57	74	78	66	90
XY Hyoid Speed (%C2–4 units/s)	116	102	130	110	102	118	137	124	151
Peak Anterior Hyoid Velocity (%C2–4 units/s)	358	325	391	421	378	464	412	376	449
Peak Superior Hyoid Velocity (%C2–4 units/s)	211	186	236	253	227	278	279	246	313
Peak XY Hyoid Speed (%C2–4 units/s)	386	349	423	461	422	500	464	424	505
Anterior Hyoid Movement Distance (%C2–4 units)	37	34	39	36	32	40	41	37	44
Superior Hyoid Movement Distance (%C2–4 units)	42	38	46	43	38	49	41	34	47
XY Hyoid Movement Distance (%C2–4 units)	49	46	51	49	46	53	54	50	58
Duration of Anterior Hyoid Movement (ms)	495	454	536	446	405	487	440	407	473
Duration of Superior Hyoid Movement (ms)	432	386	479	427	377	477	362	328	395
Duration of XY Hyoid Movement (ms)	477	434	520	449	407	490	417	387	447