Video Article

Coordinate Mapping of Hyolaryngeal Mechanics in Swallowing

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Abstract

Characterizing hyolaryngeal movement is important to dysphagia research. Prior methods require multiple measurements to obtain one kinematic measurement whereas coordinate mapping of hyolaryngeal mechanics using Modified Barium Swallow (MBS) uses one set of coordinates to calculate multiple variables of interest. For demonstration purposes, ten kinematic measurements were generated from one set of coordinates to determine differences in swallowing two different bolus types. Calculations of hyoid excursion against the vertebrae and mandible are correlated to determine the importance of axes of reference.

To demonstrate coordinate mapping methodology, 40 MBS studies were randomly selected from a dataset of healthy normal subjects with no known swallowing impairment. A 5 ml thin-liquid bolus and a 5 ml pudding swallows were measured from each subject. Nine coordinates, mapping the cranial base, mandible, vertebrae and elements of the hyolaryngeal complex, were recorded at the frames of minimum and maximum hyolaryngeal excursion. Coordinates were mathematically converted into ten variables of hyolaryngeal mechanics.

Inter-rater reliability was evaluated by Intraclass correlation coefficients (ICC). Two-tailed t-tests were used to evaluate differences in kinematics by bolus viscosity. Hyoid excursion measurements against different axes of reference were correlated. Inter-rater reliability among six raters for the 18 coordinates ranged from ICC = 0.90 - 0.97. A slate of ten kinematic measurements was compared by subject between the six raters. One outlier was rejected, and the mean of the remaining reliability scores was ICC = 0.91, 0.84 - 0.96, 95% CI. Two-tailed t-tests with Bonferroni corrections comparing ten kinematic variables (5 ml thin-liquid vs. 5 ml pudding swallows) showed statistically significant differences in hyoid excursion, superior laryngeal movement, and pharyngeal shortening ($p < 0.005$). Pearson correlations of hyoid excursion measurements from two different axes of reference were: $r = 0.62$, $r^2 = 0.38$, (thin-liquid); $r = 0.52$, $r^2 = 0.27$, (pudding).

Obtaining landmark coordinates is a reliable method to generate multiple kinematic variables from video fluoroscopic images useful in dysphagia research.

Video Link

The video component of this article can be found at <http://www.jove.com/video/51476/>

Introduction

The pharyngeal phase of swallowing is a complex process involving over twenty muscles and multiple skeletal elements to transfer a bolus from the oral cavity into the esophagus while protecting the airway. Preceding pharyngeal constriction, elements of the hyolaryngeal complex (hyoid bone, larynx, and associated structures including the upper esophageal sphincter) are displaced to convert a respiratory conduit into a digestive tract. The larynx is re-located anteriorly away from the trajectory of an oncoming bolus, and the upper esophageal sphincter is stretched open. Kinematic measurements taken from video fluoroscopic swallowing studies (also known as an MBS or Modified Barium Swallow Studies) are the primary research methodology for quantifying the multiple movements of the hyolaryngeal complex¹.

While quantitative video fluoroscopic measurements are useful for measuring swallowing function, different axes of reference and scalars of measurement result in findings that are incompatible among the various methods of kinematic measurements². The movement of the patient and fluoroscope under manual clinician control also confounds the accuracy of measuring this complex physiological process. More importantly, kinematic measurements do not necessarily reflect structure-to-function relationships important for evaluating disordered swallowing. Kinematics of the hyoid in particular have been designed to track movement in an anterior or superior direction in reference to an anatomical plane aligned with the vertebrae. However, this configuration does not represent the line of action of muscles that suspend the hyoid.

A two-sling mechanism of hyolaryngeal elevation in the pharyngeal phase of swallowing has been identified (**Figure 1**)^{3,4}. The suprahyoid muscles comprise the anterior muscular sling, and the long pharyngeal muscles comprise the posterior muscular sling. These muscles elevate various elements of the hyolaryngeal complex including the hyoid, larynx, and structures that form the upper esophageal sphincter.

Coordinate mapping of hyolaryngeal mechanics utilizes nine easily identifiable anatomical landmarks to map three skeletal levers and features of the hyolaryngeal complex representing attachment points of the anterior and posterior muscular slings (**Figure 2**). During swallowing, each skeletal lever and feature of the hyolaryngeal complex is in motion. By collecting coordinates, the system can be captured in any time frame. Trigonometric conversion of coordinates can be used to generate multiple kinematic measurements of hyolaryngeal movement during swallowing. Variables can be calculated for comparison with findings reported in the literature, or used to generate new measurements representing structure-to-function relationships of interest.

The primary aim of this paper is to demonstrate a method of generating multiple kinematic measurements calculated from a single set of anatomical landmark coordinates collected from Modified Barium Swallow (MBS) studies. We document the reliability of this method by using Intraclass correlation coefficients to determine the inter-rater reliability of 6 different investigators including one expert, three raters with experience, and two novices. From the kinematic results, differences in swallowing mechanics by bolus consistency are evaluated. Finally, the question proposed by Molefenter and Steele concerning the importance of the axis of reference used in measuring hyoid movement is addressed. To approach this question we compare measurements of hyoid excursion in reference to the vertebrae and in reference to the mandible, calculated from the same set of coordinates for both bolus types. If these two methods of measuring hyoid movement represent the same structure to function relationship, then the results should be strongly correlated.

For this study, 40 lateral view MBS studies were randomly selected from a collection of 139 normal studies under a research protocol approved by the Georgia Regents University Institutional Review Board and in research collaboration with the Evelyn Trammell Institute for Voice and Swallowing at the Medical University of South Carolina. To demonstrate the utility of this method, ten variables characterizing hyolaryngeal kinematics were calculated from the same set of coordinate data (**Table 1**). Seven of these calculated measurements have previously been used in the literature including: anterior and superior hyoid distance measurements in reference to the vertebrae⁵; anterior and superior hyoid displacement as a ratio of C2-4 length, also in reference to the vertebrae⁶; superior movement of the larynx in reference to the vertebrae⁷; hyolaryngeal approximation¹; and maximum hyoid excursion in reference to the vertebrae¹. In addition, three novel measurements were calculated: pharyngeal shortening approximating the attachments of the palatopharyngeus muscle, laryngeal elevation following a line of action representing the stylopharyngeus, and hyoid excursion approximating the attachments of the suprahyoid muscles^{4,8}.

An expert head and neck anatomist (WP), three investigators with limited experience taking measurements (CJ, SR, TT), and two novice investigators (RS, JT) obtained coordinate mapping data using the protocol described below. The expert (WP) trained the three raters with experience, and these in turn trained the two novice raters. Inter-rater reliability of coordinate data and results calculated from coordinates by subject was determined by Intraclass correlation coefficients⁹. Two tailed t-tests were performed on each variable to determine statistically significant differences in bolus types. A Pearson correlation coefficient and a coefficient of determination were used to evaluate agreement between results of hyoid excursion calculated with the vertebrae as an axis of reference versus hyoid excursion with the mandible as an axis of reference for the 5 ml thin-liquid swallow and 5 ml pudding swallow.

Protocol

1. Configuring a computer

1. For Macintosh, download the following open source or freeware software: ImageJ, MacX Video Converter Free Edition (Mac), and QuickTime (see table of material/equipment).
2. For a PC, download the following open source or freeware software: ImageJ, MPEG Streamclip (PC), and QuickTime (see table of material/equipment).

2. Preparing video clips

1. File conversion. Convert raw video files into .mov for data collection in ImageJ. Note: usable videos should include the mandible, hard palate, C1-C4 vertebrae, larynx and pharynx in the field of view. ImageJ processing tools can improve image quality issues.
 1. With a PC, use MPEG Streamclip, load the raw .avi video file via File >> Open Files and selecting the desired clip. Select File >> Export to QuickTime.
 2. With a Mac, use MacX Video Converter, click "Add File" and choose video(s) for conversion. Multiple videos can be converted at once using this application.
 3. In the Output Settings section, click the browse button and choose the desired location to save the converted file.
 4. Click on the "to MOV" tab. Make sure the Output Format under the "Video Settings" section is MOV. Click Start.
2. Editing clip length. Memory is limited with ImageJ. It is recommended that a file of each swallow be made.
 1. Open MOV. Video file created in step 2.1 using QuickTime (PC or Mac).
 2. Identify 5 ml thin-liquid and pudding swallows by audio queues or by swallow sequence outlined by the MBS protocol used during data collection.
 3. Select Edit >> Trim and adjust the trimming bar so that the entire 5 ml Thin Fluid swallow is visualized. Click trim.
 4. Select File >> Export and create a file name that will be used to link subject data (gender, age, etiology, bolus type) to coordinate mapping results.
 5. Repeat for the pudding swallow (or for any other bolus of interest).

3. De-identifying images

1. If a file contains any personal health information (PHI) and needs to be de-identified, upload the file using Image J (See 4.1 - 4.2).
2. Use the rectangle tool to frame the swallowing study to exclude PHI. Select Image >> Crop. Then Select File >> Save As >> QuickTime Movie.
3. Configure the dialogue box as follows: Compression >> Sorenson 3; Quality >> Maximum, enter the appropriate frame rate (usually 30 fps).

4. Preparing to measure

1. Open ImageJ. Click on the ">>" icon on the toolbar. Select >> Arrow Labeling Tools.
2. Uploading images. Click on QuickTime icon. Select "Open movie as a stack" from the drop down menu and locate edited QuickTime clip. Image J will not open the entire swallow study due to memory limits (see step 2.2). Memory can be minimally expanded by selecting Edit >> Options >> Memory & Threads.
3. Processing images to improve image quality. Select Process >> Math >> Add. Check the preview box and adjust numbers to desired image quality. Reply yes to process the entire stack of images.
4. Set measurements. Select Analyze >> Set Measurements from the ImageJ menu. At the dialogue box mark "Stack Position" and "Invert Y coordinates". Unmark everything else.
5. Select the multipoint tool from the toolbar. Click on anatomical landmarks in sequence (see 5.0)
6. Using the multipoint tool.
 1. Take a measurement of all points by selecting Analyze >> Measure from the menu or keyboard command+M (control+M for PCs).
 2. Remove all points with command+A (control+A for PCs).
 3. Remove single points by hovering over a point, then hold the command-option keys and click on the point to be removed.
 4. Move singular points by hovering over a point, clicking, dragging and dropping a point to a new location.
 5. Move all points together with arrow keys.

5. Mapping Landmarks

1. Begin at first frame and advance to a clear frame in the pre-oral phase. Observe position of the bolus on the anterior, superior margin of the tongue prior to initiation of oral transport of the swallow. Use this frame to set the first nine coordinates.
2. Use the ImageJ multi-point tool to map the first nine coordinates at the following anatomical landmarks (see **Figures 3a and 3b**)
3. Record first nine coordinates using command+M keys (control+M for PCs).
4. Advance frames until hyoid bone has reached maximum position in anterior and superior directions. Confirm maximum by advancing frames to insure descent of the hyoid begins on the following frame.
5. Relocate points 1 - 5 to their new positions. These new positions will be recorded as coordinates 10 - 14.
6. Relocate Point 9, which in turn becomes coordinate 18. Note: frames will likely vary for the next two steps.
7. Locate frame depicting maximum laryngeal elevation. Adjust points 7 and 8, which will serve as coordinates 16 and 17.
8. Find frame(s) representing the maximum excursion of UES, point 6 (coordinate 15). From maximum hyoid frame, locate frame where the bolus is impeded by the UES in the hypopharynx. Adjust coordinate point for UES from minimum frame to represent UES maximum coordinate 18.
9. Record second nine coordinates using command+M keys (control+M for PCs).
10. For coordinates 19 and 20 mark the edges of the scalar (a penny or 1.9 cm ring) at the axis representing the longest diameter of the radiopaque marker.
11. Record scalar coordinates using command+M keys (control+M for PCs).

6. Transform coordinate data into kinematic measurements of interest using a macro enabled Excel file (the instructions for this macro are included on the file)

Note: Trigonometric calculations imbedded in the macros calculate kinematic measurements (**Figure 4**).

1. Download "CoordinateMapping.xlsm" from the JoVE article page.
2. Follow instructions on the spreadsheet to initialize the file. The initialization macro will create three sheets including: results, data, and input sheet. Note: Macintosh users must enable developer tools in Excel to run macros.
3. Copy coordinates from the ImageJ results window and paste into the designated cell in the "input sheet". Run the "datacaptureline" macro.
4. Results will appear on the "results" sheet. Lines of coordinate data will appear on the "data" sheet.

Representative Results

Intraclass correlation coefficients (ICC) of coordinates collected by six investigators who independently analyzed 80 video fluoroscopic files (two bolus trial from 40 subjects) ranged from ICC = 0.90 - 0.97. A breakdown of ICC's of coordinates by group is as follows: coordinates #1 - 5 (skeletal elements at minimum hyolaryngeal excursion) mean = 0.93, 0.91 - 0.95, 95% CI; coordinates #6 - 9 (hyolaryngeal complex at minimum hyolaryngeal excursion) mean = 0.94, 0.92 - 0.96, 95% CI; coordinates #10 - 14 (skeletal elements at maximum hyolaryngeal excursion) mean = 0.93, 0.91 - 0.95, 95% CI; and, coordinates #15 - 18 (hyolaryngeal complex at maximum hyolaryngeal excursion) mean = 0.96, 0.94 - 0.97, 95% CI. These results indicate that strong reliability between judges is achievable using coordinate mapping.

ICC's of ten variables calculated from coordinates collected from six independent raters by subject and bolus swallow revealed a single subject with an ICC=0.54 for the 5 ml thin-liquid swallow and ICC=0.47. Visual examination of this MBS study confirmed poor image quality. Excluding this subject, the mean of all ICC's and 95% confidence intervals is 0.91, 0.84-0.96 for the remainder of MBS files analyzed. These results indicate that inter-judge reliability of variables is useful to determine if image quality of particular files is acceptable.

A comparison of 5 ml thin-liquid swallows and 5 ml pudding swallows by calculated variable using a two-tailed t test produced the following p-values with all measurements included ($n = 234$): Ant. Hyoid Movement $p = 0.82$, Sup. Hyoid Movement $p = 0.0001$, Hyoid Excursion (mandible) $p = 0.09$, Hyoid Excursion (vertebrae) $p = 0.0005$, Sup. Laryngeal Movement $p = 0.003$, Hyolaryngeal Approximation $p = 0.42$, Laryngeal Elevation $p = 0.02$, Pharyngeal Shortening $p = 0.0000$, Hyoid Excursion (mandible, C2 - C4) $p = 0.06$, Laryngeal Elevation (C2 - 4) $p = 0.01$ (**Figure 5**) (**Table 2**). These results show what kinematic variables differ by bolus viscosity in this random sample.

A Pearson correlation coefficient and a coefficient of determination of hyoid excursion calculated with the vertebrae as an axis of reference versus hyoid excursion compared with the mandible as an axis of reference for the 5 ml thin-liquid and 5 ml pudding swallows is as follows: $r = 0.621$, $r^2 = 0.37$ (5 ml thin-liquid), and $r = 0.49$, $r^2 = 0.24$ (5 ml pudding). This results shows that hyoid movement is multifactorial; if suprahyoid muscles solely displaced the hyoid, then these measurements would be strongly correlated (> 0.90).

Figure 1. Illustration of the muscular slings that suspend and elevate elements of the hyolaryngeal complex including the hyoid, larynx, thyrohyoid (TH), and upper esophageal sphincter (UES): anterior muscular sling 1.) geniohyoid 2.) anterior digastric 3.) mylohyoid 4.) stylohyoid 5.) posterior digastric; posterior muscular sling 6.) palatopharyngeus 7.) salpingopharyngeus 8.) stylopharyngeus.

Figure 2. Nine coordinates (in blue) map the mandible, cranial base, and vertebrae (in red) and elements of the hyolaryngeal complex (in green).

Figure 3a. Landmarks for five coordinates mapping the three skeletal levers as visualized on MBS (# 1= mandible, where the inferior line of the body of the mandible meets the symphyseal outline of the mandible, # 2 = posterior edge of the hard palate where it crosses the anterior edge of the ramus of the mandible, # 3 = anterior tubercle of the atlas (C1), # 4 = anterior inferior edge of C2 vertebra, # 5=anterior inferior edge of C4 vertebra).

Figure 3b. Landmarks for four coordinates mapping the elements of the hyolaryngeal complex including the hyoid, larynx, and upper esophageal sphincter (# 6 = inferior air column of hypopharynx proximal to the upper esophageal sphincter, # 7 = posterior, inferior margin of the cricoid cartilage at the tracheal air column (posterior larynx), # 8 = anterior, inferior margin of the cricoid cartilage at the tracheal air column (anterior larynx), # 9 = anterior inferior edge of the hyoid bone).

Figure 4. Trigonometric transformation of coordinate data: To track movement of a landmark (ex. Hyoid) against a lever as axis of reference (ex. vertebrae represented by C1-C4) first designate x,y coordinates: 1 = C1, 2 = C4, 3 = hyoid. So then, b = axis of reference, C = angle of interest, a = hypotenuse. *Any distance between coordinates is derived using Pythagoras' theorem as demonstrated by length a. ** Any angle of interest is derived using the law of cosines as demonstrated by angle C. Anterior displacement of # 3 in reference to the axis of reference (line b) is $i' - i$, where $i' = \sin(C')a'$ and $i = \sin(C)a$. Superior displacement of # 3 in reference to the axis of reference is $ii - ii'$, where $ii = \cos(C)a$ and $ii' = \cos(C')a'$. These formulas can be converted to accommodate various axis of reference representing one of the three skeletal levers of the swallowing apparatus.

Figure 5. Results comparing a slate of kinematic variables calculated from coordinate comparing 5 ml thin-liquid vs. 5 ml pudding MBS swallows ($n = 39$). AH = anterior hyoid movement, SH = superior hyoid movement, HE_m = hyoid excursion in reference to the mandible, HE_v = hyoid excursion in reference to the vertebrae, SupLx = superior laryngeal movement, HyLx = hyolaryngeal approximation, LxEl = laryngeal elevation (towards the cranial base), PhxSh = pharyngeal shortening, HE_m* = hyoid excursion in reference to the mandible with a C2 - 4 scalar, LxEl* = laryngeal elevation with a C2 - 4 scalar.

Measurement Variable	Axis of reference	Scalar	Description
Anterior hyoid movement	Vertebrae	cm	Described by Kim and McCullough 2008, calculates the displacement of the hyoid (coordinate 9) away from a line approximating the vertebrae (line connecting coordinates 3 and 5, representing C1 and C4 respectively)
Superior hyoid movement	Vertebrae	cm	Described by Kim and McCullough 2008, calculates the displacement of the hyoid (coordinate 9) in a direction parallel to a line approximating C1-C4 vertebrae.
Hyoid excursion (mandible)	Mylohyoid line of the mandible	cm	Calculates the displacement of the hyoid towards a line approximating the mylohyoid line of the mandible (Coordinates 1&3). This measurement approximates the function of the suprahyoid muscles.
Hyoid excursion (vertebrae)	Vertebrae	cm	Describe by Leonard et al., 2000, resolves the anterior and superior vector of movement of the hyoid away from a line approximating C1-C4 vertebrae
Superior laryngeal movement	Vertebrae	cm	Described by Logemann et al., 2000, calculates the displacement of the larynx (coordinate 8)

			in a direction parallel to a line approximating the vertebrae
Hyolaryngeal approximation	n/a	cm	Described by Leonard et al., 2000, calculates the approximation of the hyoid (coordinate 9) and larynx (coordinate 8)
Laryngeal elevation	n/a	cm	Calculates the displacement of the posterior larynx (coordinate 7) toward C1 (coordinate 3) approximating the attachments of the stylopharyngeus.
Pharyngeal shortening	n/a	cm	Calculates the displacement of the UES (coordinate 6) toward the hard palate (coordinate 2) approximating the attachments of the palatopharyngeus.
Hyoid excursion (mandible)	Vertebrae	C2-4	Described above, but uses C2-C4 scalar (coordinates 4 and 5) described by Steele et al., 2011
Laryngeal elevation (vertebrae)	Vertebrae	C2-4	Described above, but uses the C2-C4 scalar (coordinates 4 and 5) described by Steele et al., 2011

Table 1. Descriptions of displacement measurements.

Measurement Variable	5 ml Thin Liquid (n=234 measurements)		5 ml Pudding (n=234 measurements)		p-values (2 tailed T-test)
	Mean	SD	Mean	SD	
Anterior hyoid movement	1.10	0.41	1.11	0.40	0.82
Superior hyoid movement	1.49	0.66	1.76	0.75	0.0001
Hyoid excursion (mandible)	1.37	0.48	1.45	0.48	0.09
Hyoid excursion (vertebrae)	1.93	0.57	2.15	0.69	0.001
Superior laryngeal movement	3.32	0.88	3.60	1.03	0.003
Hyolaryngeal approximation	1.10	0.57	1.14	0.55	0.42
Laryngeal elevation	2.53	0.67	2.70	0.76	0.02
Pharyngeal shortening	1.30	0.62	1.66	0.65	0.0000
Hyoid excursion (mandible)	0.36	0.12	0.38	0.13	0.06
Hyoid excursion (vertebrae)	0.67	0.16	0.71	0.19	0.01

Table 2. Means, standard deviations, and p-values of 5 ml thin liquid vs. 5 ml pudding.

Discussion

This study demonstrates the usefulness of a method using coordinate data of anatomical landmarks to calculate multiple kinematic measurements of hyolaryngeal movement in swallowing. Inter-rater reliability of six raters, including two novice raters, for coordinates and calculated variables was strong (ICC > 0.90). Representative results from a random sample of healthy non-dysphagic adults showed differences in several kinematic variables in response to two bolus types. We also found that using different axes of reference for calculating the excursion of the hyoid bone produced results that were not strongly correlated.

Collecting anatomical landmark data reduces time and removes variability introduced by multiple measurements used in other methods^{1,5-7}. A full complement of kinematic measurements can be calculated and used in a factor analysis or principal components analysis if all coordinates are visible. Alternatively, if a research question involves fewer variables, fewer coordinates may be needed to calculate a smaller slate of distance measurements. The initialization macro will determine which of the coordinates needs to be collected. This technique was developed

using open source or readily available software in order to encourage wide use in dysphagia research. These multiple steps could be incorporated into commercially available software that could potentially make this technique feasible in a clinical setting.

Modifications to the protocol can be made to accommodate computing preferences. ImageJ can read .avi files among others. QuickTime was chosen to retain the greatest image resolution with the smallest file size. The macro enabled excel file is in its first version. As limitations or problems are identified and repaired in the code, newer versions will be uploaded. One known problem is that v1.0 does not allow for missing data. A current limitation is that results cannot be generated in SI (reported in centimeters) and anatomical units (reported as C2 - C4 distance) at the same time. A current solution is to initialize one excel workbook to report SI units and another to report anatomical units using the same data collected using ImageJ. These and other issues will be addressed over time by the authors (FO,WP).

Critical to validity and reliability in this method is consistency in: coordinate mapping of anatomical landmarks, and frame selection for minimum and maximum recoding of coordinate. It is important to mark anatomical landmarks consistently. Since most kinematic measurements are calculated as a difference in distance in the minimum and maximum measurements, consistency will ensure that kinematic measurements represent swallowing function of interest. Frame selection can be confounded by poorly controlled data collection in the fluoroscopy suite where the minimum frame as described in step 5.1 is not imaged. Coordinates collected at maximum can also be confounded if camera and patient movement is sudden. Hyoid and larynx maximums are usually achieved near the same frame, however UES maximums (representing pharyngeal shortening) can vary. Each frame represents 30msec in time. In cases where many frames separate maximum excursion of landmarks 6 - 9, it is important to be sure that landmarks numbered 1 - 5 remain in place.

Other limitations of this technique arise from using imaging data. This technique infers three-dimensional spatial relationships from two-dimensional data. Fluoroscopic images, like radiographs, are also subject to magnification and distortion, which may impact the validity of these measurements. Achieving inter- or intra- rater reliability with poor image quality is difficult. Finally there is a learning curve associated with attaining reliability.

In the current study, reliability was tested by comparing coordinates measured by six raters; including two novice raters, three raters with experience and one expert. We found that training influences reliability. Agreement between the novice raters was ICC = 0.88 whereas agreement between more experienced and expert raters was ICC = 0.95. A recurring theme in reliability training was frame selection, underscoring the importance of clear operational definitions of minimum and maximum hyolaryngeal excursion to improve reliability. Finally, image quality affects reliability. By comparing a string of variables subject by subject, ICCs were used to identify MBSs with poor image quality. For research purposes we propose rejecting images with an inter-rater agreement of ICC < 0.70. In our cohort, a subject with an ICC = 0.54 for the 5 ml thin-liquid swallow and ICC = 0.47 for the 5 ml pudding was identified. Visual inspection of the MBS confirmed that poor image quality could be identified by statistical analysis.

Our representative results were used to demonstrate how questions important to swallowing could be addressed such as differences in kinematic variables associated with different bolus viscosities. In this sample, for example, the more viscous bolus elicited an increase in pharyngeal shortening. Conclusions should not be drawn from these particular results since variables such as age and gender were not accounted for, however studies can be constructed using this method to address various questions important to dysphagia research.

This technique allows for evaluation of variation in the calculation and interpretation of kinematic measurements². Of special interest in dysphagia research is how the movement of the hyoid is measured and interpreted. Hyoid excursion calculated from different axes of reference was not highly correlated. The coefficient of determination shows that hyoid movement measured against the vertebrae only predicts 37% of the variance of hyoid movement measured against the mandible as an axis of reference in 5 ml thin-liquid swallows and 24% in 5 ml pudding swallows. This indicates that other movement accounts for hyoid movement. The hyoid bone is attached to the mandible and cranial base by the suprahyoid muscles. Since the mandible remains relatively fixed during swallowing, the hyoid approaching the mandible is representative of the concentric contraction of the suprahyoid muscles. When measuring hyoid movement against the vertebrae, it is likely that movement of the atlanto-occipital joint (head extension or flexion) is conflated with hyoid movement attributable to suprahyoid function.

Measuring hyoid excursion in reference to the mandible by design more accurately represents the underlying functional anatomy⁸. Two studies associating diminished hyoid movement and risk for aspiration found differing results; one associated diminished superior movement of the hyoid and the other found anterior movement^{6,10}. Both measured hyoid movement in reference to the vertebrae. To determine if hyoid movement is a biomarker of aspiration, we argue that studies should measure hyoid movement in relationship to the skeletal levers to which muscles displacing the hyoid attach, rather than in relationship to the vertebra to which they do not attach.

When using displacement measurements in research it important to define the anatomic correlates of interest. The finding that hyoid excursion calculated from different axes of reference are not highly correlated underscores the need to consider what kinematic measurements actually represent. Hyoid excursion in reference to the vertebrae represents the covariant function of head and neck extension and suprahyoid contraction. If understanding the underlying function of the suprahyoid muscles is more important, then hyoid excursion measured in reference to the mandible is more accurate^{3,8}. The proposed laryngeal elevation and pharyngeal shortening variables correlate to the long pharyngeal muscles, a posterior sling of muscles that elevate the larynx innervated by cranial nerves IX and X^{3,4}. However, other muscles aid in laryngeal elevation and pharyngeal shortening. Coordinate mapping allows investigators to measure an array of selected variables, but variables should be chosen in the context of a particular research question. It is therefore important to acknowledge the covariant function of muscles that underlie these measurements.

Coordinate mapping data can be used in morphometric analysis to evaluate covariant shape changes in normal and abnormal swallowing¹¹. Morphometric analysis of the hyolaryngeal apparatus indicates musculoskeletal adaptations to various conditions including swallowing impairment. The morphometric analysis of coordinates mapping swallowing function may ultimately provide more useful information about the biomechanics of swallowing and swallowing impairment than kinematics alone. Future directions include developing a database of coordinates to phenotype swallowing and swallowing impairment using kinematic results and morphometric analysis. Such a database would allow us to determine underlying functional anatomy of swallowing and swallowing impairment associated with various etiologies of dysphagia. A coordinate strategy could also be applied to other imaging modalities where coordinates can be obtained such as dynamic MRI or 320-detector-row Multi-slice CT¹².

In sum, coordinate data is useful for calculating multiple reliable kinematic measurements of hyolaryngeal movement in swallowing. Kinematic measurements must be understood within the context of the research question and the underlying anatomy. Some of displacement variables are coupled with specific muscle group function and some are not. Coordinates can also be used in morphometric analysis of swallowing.

Disclosures

The authors declare that they have no competing financial interests.

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