A PROOF-OF-CONCEPT STUDY TO QUANTIFY TYPICAL SWALLOWING AND RELATED ENDOSCOPIC EVENTS

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ALL INDIA INSTITUTE OF SPEECH AND HEARING MANASAGANGOTHRI,
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JUNE - 2026

CERTIFICATE

This is to certify that this dissertation entitled **"A Proof-Of-Concept Study To Quantify Typical Swallowing And Related Endoscopic Events"** is a bonafide work submitted as part of fulfilment of the degree of Master of Science Speech Language Pathology of the student with Registration Number P01II24S123034. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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This is to certify that this dissertation entitled "A Proof-Of-Concept Study To Quantify Typical Swallowing And Related Endoscopic Events" has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled "A Proof-Of-Concept Study To Quantify Typical Swallowing And Related Endoscopic Events" is the result of my own study under the guidance of Dr. Gayathri Krishnan, Assistant Professor of Speech/Language Pathology, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

Mysuru
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CHAPTER 1

INTRODUCTION

Swallowing is a basic, highly coordinated sensorimotor process that enables food, liquids, and saliva to be transported safely from oral cavity to stomach without airway intrusion. The act of swallowing plays a major role in maintaining nutrition and hydration necessary for overall health and well-being. On a daily basis, the process of typical swallowing is effortless, though it involves fine coordination of numerous anatomical structures, including the pharynx, larynx, and esophagus. The perfect orchestration of these structures is crucial to ensure safe and efficient swallowing. A complex neural network involving cortical and subcortical regions of the brain, brainstem central pattern generators, and multiple cranial nerves mediates the process of swallowing.

Swallowing is explained through several physiological models reflecting the complexity of bolus transportation through the oro-pharyngeal system. Traditionally, swallowing is described using a three-stage model of oral, pharyngeal, and esophageal stages, the three-stage model was later expanded into Four-Stage Model to incorporate oral preparatory, oral propulsive, pharyngeal, and esophageal phases (Dodds, 1989; Feinberg, 1993; Linden et al., 1989). These models were applicable primarily for liquid swallowing and did not explain the solid bolus swallow dynamics. The process model of swallowing described the stages of solid bolus transport through the oral cavity before initiating the pharyngeal swallow (Hiiemae, & Palmer, 1999; Palmer, 1998; Palmer et al., 1992, 1997). These models illustrated swallowing as not a single event but a series of shared physiological processes that is adaptive in nature. Interaction of these physiological events with afferent sensory feedback is critical for effective airway protection and clearance. Interruption at any level of this complex network can cause swallowing difficulty.

A disruption in the swallowing process can make swallowing effortful, inefficient, and unsafe, leading to bolus residue (Labeit et al., 2022), choking (Yang et al., 2023), aspirations (Butler et al., 2009), insufficient nutrient intake, malnutrition, and dehydration (Clavé & Shaker, 2015), thereby reducing health as well as quality of life (Baijens et al., 2016; Eslick & Talley, 2008). Dysphagia has been defined in various ways by professional groups depending on the clinical perspective and scope of evaluation. Logemann (1983) described dysphagia as an impairment in the efficiency or safety of bolus transfer from the mouth to the stomach, resulting from abnormalities in the swallowing mechanism. Leonard and Kendall (2008) defined dysphagia as a disorder affecting bolus preparation, propulsion, and airway protection mechanisms during swallowing. The American Speech-Language-Hearing Association [ASHA] defines dysphagia as a disorder of swallowing involving dysfunction in any stage of the swallowing process that may compromise airway protection, nutrition, hydration, or quality of life (American Speech-Language-Hearing Association, n.d., Dysphagia). The World Health Organization (2001) identified swallowing disorders under the International Classification of Diseases (ICD-10) and International Classification of Functioning, Disability and Health, stressing the functional and health-related effects of swallowing impairments. Hence, dysphagia is widely designed as a deviation in swallowing physiology that affects either swallow safety (airway protection) or swallow efficiency (bolus transport and clearance).

Dysphagia is widely recognized as a global health concern due to the globally aging population and the increasing survival rates with chronic illnesses. A systematic review estimated the global prevalence of oropharyngeal dysphagia to be approximately 43.8% across various clinical populations (Wirth et al., 2016). In community-dwelling adults over the age of 50 years, dysphagia prevalence is estimated to range between 15% and 22%, while in institutionalized populations such as nursing homes, the prevalence may exceed 60% (Huckabee & Leonard, 2018; Wirth et al., 2016). Neurological disorders are one of the most frequent causes of dysphagia. For instance, dysphagia occurs in 29–64% of stroke patients, depending on the diagnostic method used. A meta-analysis reported that post-stroke dysphagia affects approximately 42–46% of patients (Smithard et al., 1996). Dysphagia prevalence may reach 11–81% in Parkinson's disease, 27–30% in traumatic brain injury, and up to 91.7% in patients with pneumonia. Epidemiological studies also indicate that dysphagia is highly prevalent in patients with neurodegenerative diseases, Head and neck cancers, critical illness, and aging-related physiological decline (ASHA, n.d.), An epidemiological survey of nearly 6000 individuals reported dysphagia in 39.4% of participants, including 51% of stroke patients, 34% of head and neck cancer patients, and 48% of individuals with neurodegenerative disorders (Wirth et al., 2016).

Dysphagia may occur due to neurological, structural, or systemic disorders, and the processes of one or more phases of swallowing may be affected, resulting in inefficient bolus transport, airway invasion, or impaired clearance of swallowed material. Dysphagia can be a symptom or consequence of various neural (eg: stroke, neuro-degenerative conditions), muscular (eg: myopathies, atrophy), structural (eg: surgical reconstructions, hypoplasia), behavioural (eg: Avoidance/Restrictive Food Intake Disorder), sensory-motor (eg: sensory intolerance, chewing difficulties), metabolic (eg: lactose intolerance), and sometimes psychological disorders (eg: phagophobia) (Clavé & Shaker, 2015; Dodds et al., 1990). The comprehensive assessment of dysphagia is essential to identify, diagnose, and explore the cause, associated factors, impact, and develop the most efficient treatment plan. Standardized methods of screening and diagnosis facilitate effective communication between healthcare professionals and also help in evidence based practice (Clavé & Shaker, 2015; Dziewas et al., 2020; Logemann, 1998).

Dysphagia can be classified in several ways on the basis of affected phase, etiology, age of onset etc. These classifications are essential for meaningful clinical assessment and management. From a physiological perspective, dysphagia may involve the oral, pharyngeal, or oesophageal phases of swallowing. Oral dysphagia is the impairment of the oral preparatory or oral transit stage, which results in difficulty in mastication, bolus formation, and anteroposterior transit of the bolus (Logemann, 1998; Matsuo & Palmer, 2005). Pharyngeal dysphagia refers to impairment during the pharyngeal phase and is associated with delayed swallow initiation, reduced pharyngeal constriction, aspiration, and pharyngeal residue (Langmore, 2001; Logemann, 1998). Oesophageal dysphagia occurs when bolus transport through the oesophagus is compromised due to motility disorders or structural obstruction (Kahrilas & Pandolfino, 2018; Logemann, 1998). Dysphagia can also be categorized according to etiology, such as neurogenic dysphagia that disrupt neural control of swallowing (Dziewas et al., 2020; Suttrup et al., 2017); mechanical or structural dysphagia caused by anatomical abnormalities (Langmore, 2001; Logemann, 1998); functional dysphagia that perceives a difficulty in swallow despite the absence of structural or neurological abnormalities (Clavé & Shaker, 2015); and psychogenic dysphagia, wherein swallowing difficulties arise due to psychological or emotional factors without identifiable physiological impairment (Alzuabi et al., 2023). Additionally, dysphagia may originate as age-related changes termed 'presbyphagia'. The presbyphagic changes in swallowing performance may increase the vulnerability to dysphagia and aspiration (Nicosia & Robbins, 2001). Such multidimensional classification is clinically relevant for speech language pathologists (SLPs) and facilitates identification of the underlying mechanism of swallowing impairment based on which clinical decisions are made. Evidence based decision making further improves patient outcomes.

Dysphagia is associated with significantly more adverse medical complications affecting health outcomes and quality of life. Individuals with dysphagia are at increased risk for malnutrition and dehydration due to inadequate oral intake (Leonard & Kendall, 2019), as well as aspiration and its sequelae (ASHA, n.d.). Aspiration pneumonia is one of the most serious and potentially life-threatening complications of swallowing disorders. Epidemiological studies have shown that patients with dysphagia experience higher rates of respiratory infections, prolonged hospital stays, increased healthcare costs, and greater morbidity and mortality compared to individuals with normal swallowing function post-stroke (Attrill et al., 2013; Clavé & Shaker, 2015; Logemann, 1993; Takizawa et al., 2016). The fourfold increase in the risk of pneumonia and mortality in post-stroke dysphagia compared to those without swallowing impairment post-stroke emphasizes the need to prioritize dysphagia management (Martino et al., 2005). Chronic dysphagia contributes to reduced nutritional status, impaired immune function, and delayed functional recovery (Cichero & Murdoch, 2006; Clavé et al., 2012) and overall deterioration in the quality of life (Baijens et al., 2016; Clavé & Shaker, 2015). Timely identification of swallowing impairment and implementation of appropriate management strategies should hence be critical components of patient care. Evidence suggests that early screening, accurate assessment, and prompt intervention significantly reduce the risk of aspiration, pneumonia, and other complications associated with dysphagia (Dziewas et al., 2021; Hinchey et al., 2005).

A comprehensive evaluation of swallowing function is critical for effective management (Attrill et al., 2018; Logemann, 1998; Matsuo & Palmer, 2008). SLPs rely on clinical, subjective, and instrumental evaluations for this purpose. A clinical or bedside swallowing assessment involves detailed case history taking, assessment of oral sensory-motor functions, cognitive, respiratory and laryngeal function assessments before oral bolus trials are performed to evaluate the presence, nature, impact and factors associated with dysphagia. The signs and symptoms of dysphagia are correlated with the case history to arrive at the most probable diagnosis. Various protocols are available in the literature for guiding the SLP through this process**,** such as the Mann Assessment of Swallowing Ability (MASA), the Gugging Swallowing Screen (GUSS), and clinical swallowing examination protocols (Daniels et al., 1997; Massey & Jedlicka, 2002; Trapl et al., 2007). However, the clinical subjective evaluation results most often are useful in identifying patients who may require further assessment, as these procedures have been shown to have moderate variability, limited predictive values, and high dependency on clinician skills (McCullough et al., 2000).

The sensitivity of subjective clinical examination ranges from 21-93% and specificity from 46-93%, suggesting moderate diagnostic accuracy when conducted by expert professionals (Bours et al., 2009; Daniels et al., 1997). Large variability in the psychometric measures of this procedure suggests the variations in its components and differences in its validity across different populations (Martino et al., 2000). Compared with instrumental evaluation, Leder et al. (2017) reported its inability to accurately detect silent aspiration and higher sensitivity (77% and 86%) compared to specificity (52% and 65%). Therefore, while clinical examination by the professional is non-negotiable, instrumental assessments are often required to accurately identify and diagnose persons with dysphagia before making management decisions. Instrumental evaluations are recommended to detect silent aspiration and to confirm the results of a comprehensive clinical swallow examination before an accurate diagnosis of dysphagia is made.

Instrumental assessments can be further classified into imaging and non-imaging and invasive and non-invasive methods (Langmore, 2001; Logemann, 1998). The non-imaging techniques do not provide visualization of swallow or its consequences, such as penetration and aspiration risk, and do not provide information regarding the timing and coordination of swallowing events (Kahrilas & Pandolfino, 2005; Omari et al., 2014; Steele & Huckabee, 2007).

The gold-standard assessments for dysphagia include the Videofluoroscopic Swallow Study (VFSS) and Flexible Endoscopic Evaluation of Swallowing (FEES). Both are imaging procedures that provide invaluable information about the physiological components of swallow, which are otherwise not accessible for direct visualization during the clinical swallowing assessment. The VFSS is a dynamic radiographic visualization of swallowing physiology that allows the clinician to observe, analyze, and derive the pathophysiology of dysphagia presented. VFSS provides the clinician with dynamic data related to oral, pharyngeal, and cervical oesophageal physiology as visualized in the lateral and anterior-posterior views. However, the demand for specialized infrastructure, patient mobilization, and exposure to radiation limits the access and affordability of this evaluation in many healthcare setups.

Flexible Endoscopic Evaluation of Swallowing (FEES), introduced by Langmore et al. (1988), is an alternative method for assessing swallowing physiology. The procedure involves transnasal insertion of a flexible endoscope to visualize the nasopharynx, oropharynx, hypopharynx, and larynx before and after swallowing. FEES offers several advantages in swallowing assessment, including direct visualization of the swallow and its consequences, including airway penetration, aspiration, and residue. Unlike VFSS, FEES evaluations provide bilateral information in a single study. The feasibility of performing repeated evaluations without radiation exposure and the advantage of portability of the system to the bedside of medically fragile individuals have made FEES a first choice among SLPs for clinical and research purposes. Though VFSS has long been considered the 'gold standard' for dysphagia evaluation, the undemanding nature of the FEES procedure in terms of radiation risk, time restrictions, patient comfort, patient transportation requirements, and special infrastructure has made FEES an equally valuable diagnostic procedure in dysphagia. In recent years, the technology of FEES has been of great academic, clinical, and research interest among professionals.

The procedure of FEES is a well-established diagnostic procedure for diagnosis, treatment planning, and monitoring of oropharyngeal dysphagia at bedside, inpatient, outpatient, and/or long-term care settings (Dziewas et al., 2021; Giraldo-Cadavid et al., 2017; Langmore, 2001, 2017). Langmore et al. (1991) compared VFSS and FEES in individuals with dysphagia and reported significant concordance between both procedures. The FEES procedure had high sensitivity in the detection of airway intrusion. The study suggested FEES as valid and reliable as VFSS in the evaluation of the risk of aspiration. The American Speech and Hearing Association also recommended FEES evaluation as a safe and validated procedure for dysphagia evaluation in children and adults when performed by a trained and registered professional (Langmore, 2017).

Through a detailed protocol for assessment, FEES evaluations involve assessing the movement of the velum, base of the tongue, posterior pharyngeal wall, vocal folds, and epiglottis during phonation, breath holding, and swallowing tasks. The swallowing tasks are repeated on a variety of bolus consistencies, volumes, feeding strategies, positions, and many other factors to arrive at the diagnosis and management decisions (Dziewas et al., 2021; Langmore, 2001; Logemann, 1999; Murray, 2019) The procedure of FEES is generally well tolerated by persons with dysphagia (Kelly et al., 2007; Langmore, 2017) and has been shown to have excellent clinical application in the practice of SLPs (Dziewas et al., 2021; Langmore, 2001). A narrative literature review that focused on the application and evolution of FEES revealed that it is a safe and well-tolerated procedure and offers a valid assessment of swallowing function in a diverse population, which plays a critical role in evaluating the severity of dysphagia aspiration (Dziewas et al., 2021; Langmore, 2017). It can be performed at the bedside without any radiation exposure and can be useful in monitoring the progress of therapy, making it a functional diagnostic tool (Mari et al., 2025). A study by Schindler et al. (2022) supported FEES as the first choice of assessment technique. FEES is becoming increasingly popular because of its usefulness, safety, low costs, wide applicability, and feasibility in different clinical settings. The direct effect of therapeutic interventions can be evaluated using FEES, contributing to management planning beyond its diagnostic application. Standardization of FEES protocols and metrics is still underway. Technological innovation regarding image resolution, frame rate frequency, endoscopic light source specifications, and endoscopic rotation range has contributed to an increased diagnostic accuracy.

The procedure of FEES has evolved as a critical and versatile tool with its application in difficult-to-test populations. Its portability, repeatability, and ability to be performed at the bedside have made this procedure widely popular in medically fragile, non-ambulatory, or behaviorally complex populations, such as in intensive care units and individuals on ventilator support and/or with reduced levels of consciousness. FEES is also being increasingly implemented in pediatric feeding and swallowing assessment (Krug et al., 2023; Pazinatto et al., 2024). The advantages of portability, absence of hazardous radiation, and repeatability are particularly valuable in the assessment of fragile infants. Further, it can be adapted to accommodate behavioral and sensory difficulties commonly seen in pediatric populations, making assessment more naturalistic in the feeding contexts, including breastfeeding or caregiver-assisted feeding. Beyond clinical swallow examination, FEES has been reliably identified to detect silent aspiration (Chang et al., 2024; Dziewas et al., 2019), facilitating timely intervention in acute and intensive care settings (Brodsky et al., 2019).

Evidence for the clinical utility of FEES across diverse and complex clinical populations such as neurological disorders, head and neck cancers, and chronic pulmonary conditions is available in the literature (Bours et al., 2020). Comparison of endoscopic studies pre- and post-intervention was useful in reporting the effectiveness of intervention in secretion management, residue patterns, and airway protection (Dziewas et al., 2019; Patterson et al., 2019; Warnecke et al., 2021). The respiratory-swallow incoordination in chronic pulmonary disease could be examined with FEES, while the laryngeal function was not accurately visible in VFSS (American Speech-Language-Hearing Association [ASHA], 2024a, 2024b; Langmore et al., 1988). These applications highlight the role of FEES in a wide range of clinical populations with dysphagia where VFSS may be contraindicated, inaccessible, or poorly tolerated.

FEES allows for direct visualization of the pharyngeal and laryngeal structures. Direct assessment of functions such as secretion management, airway closure, and residue patterns across bolus types enables more accurate identification of dysphagia and timely, individualized interventions (Brodsky et al., 2019; Kelly et al., 2006; Langmore, 2001; Murray et al., 1996; Warnecke et al., 2021). This direct visualization of swallowing performance is particularly critical in populations with communication impairment, as they may not reliably report symptoms. Table 1 compares the VFSS procedure to that of the FEES procedure in various properties and components.

Table 1

A comparison between VFSS and FEES procedures

Domain	FEES	VFSS
Primary Purpose	Direct visualization of pharyngeal and laryngeal structures during swallowing	Dynamic visualization of oral, pharyngeal, and oesophageal phases
Clinical Focus	Airway protection, secretion management, pharyngeal residue	Bolus flow, timing, and coordination across all phases
Best Use	Medically fragile/bedside assessment, repeated evaluations	Comprehensive biomechanical analysis
Visualization	Direct anatomical view	Indirect radiographic view

Phases Assessed	Primarily pharyngeal phase	Oral preparatory, oral transit, pharyngeal, and upper oesophageal
Procedure	Flexible endoscope inserted transnasally to view the pharynx and larynx	The patient swallows a barium-coated bolus under continuous X-ray
Set up	bedside**,** seated or supine	radiology suite, seated/standing
Bolus Type	Real food dyed for contrast	Barium-mixed food/liquids
Radiation Exposure	None	Present
Secretion management assessment	Excellent	Limited
Airway Protection	Direct observation of penetration/aspiration before & after swallow	Indirect visualization of penetration/aspiration before, during and after swallow
White-out Phase	Present	Absent
Timing Measures	Not known	High temporal accuracy with frame-by-frame analysis
Quantitative Measures	Mostly ordinal, limited objective quantification	Temporal (ms), spatial (mm), and kinematic measures are possible
Residue Assessment	Direct visualization of residue location and amount	Estimated based on radiographic contrast
Sensory Testing	Possible	Not possible

Patient Tolerance	May cause mild discomfort, but is generally well-tolerated	May be difficult in critically ill patients
Repeatability	High	Limited to the critical radiation exposure limit
Ecological Validity	High	Moderate
Interpretation Approach	Visual-perceptual, clinician-dependent; focuses on safety & efficiency	Combines visual-perceptual + objective kinematic analysis

Note: FEES- Flexible Endoscopic Evaluation of swallowing, VFSS- Videofluoroscopic Swallowing Study.

Despite the wide applicability of FEES in complex populations, there is considerable variability in findings across professionals due to the lack of standardized approaches to observation, interpretation, and reporting. This contributes to inconsistencies in clinical judgment. Acceptable inter- and intra-rater reliability among SLPs was possible only with standardized rating scales (Rosenbeck et al., 1996) and with structured training and feedback (Butler et al., 2009; Kelly et al., 2007; Pilz et al., 2016). The professional using FEES requires advanced competencies in endoscopic handling, precise anatomical identification, and real-time analysis of swallowing physiology. Feedback-based learning with systematic case review and scoring has been shown to improve diagnostic accuracy and minimize subjective differences in interpretation with systematic training only (Martin-Harris et al., 2008; Preisser et al., 2019). While training may improve the reliability, the procedure may be relatively time-consuming and subjective.

As mentioned in Table 1, inferring relevant information from FEES for swallowing assessment relies on subjective assessment of the direct visualization of physiological components. Interpretation of FEES examinations relies primarily on visual-perceptual analysis of swallowing events. There are varied scales that are employed by clinicians to rate the output of a FEES evaluation. For example, the SLP derives information about the 'safety' of a swallow by evaluating the events of airway penetration and/or aspiration and the 'efficiency' of a swallow by evaluating the proportion of bolus remaining in the oral and pharyngeal cavity post-swallow. These are traditionally obtained using standardized rating scales such as the penetration-aspiration score (Rosenbek et al., 1996) and the pharyngeal residue scale (Neubauer et al., 2015). Table 2 provides a list of rating scales that are commonly employed with the FEES procedure for inferences and clinical decision-making.

Table 2

Subjective assessment scales for Flexible Endoscopic Evaluation of Swallowing (FEES)

Assessment scale	Author and Year	Components	Pros	Cons
Penetration Aspiration Scale (PAS)	Rosenbek et al., 1996	Penetration or Aspiration. 8-point ordinal scale	Popular and good inter-rater reliability. Both depth and response to airway penetration were assessed	Certain components of aspiration are not visible in FEES; hence, item-wise reliability is questionable
Modified Penetration Aspiration Scale	Rosenbek et al., 1996	It is a modified version of PAS, which also has an 8-	Simple, standardized, and widely used and	Does not assess the residue, and

		point ordinal scale. Modified version regroups levels based on clinical context for easy evaluation.	validated rating scale.	poor inter-rater variability also requires training and expertise.
Penetration-Aspiration-Residue Combination (PARC)	Neubauer et al., 2015	Incorporates both airway invasion and pharyngeal residue. It is semi-quantitative and combines the PAS ordinal scale and the residue assessment.	More comprehensive.	Not validated, less clinically used may require extensive training
Yale Pharyngeal Residue Severity Rating Scale (YPRSRS)	Neubauer et al., 2015	Location and amount of residue on a 5-point ordinal scale.	Easy to use and describes both where the residue is and the quantity.	Subjective visual perception of residue makes the scaling variable across clinicians
Boston Residue and Clearance	Kaneoka et al., 2014	It assesses the amount, location of	It assesses different	It requires more time and

Scale (BRACS)		residue, spontaneous clearing, and effectiveness of clearing. 11-point rating scale.	aspects of residue, and it has high reliability and validity and is also used in real-world clinical setups.	is complex, and expertise is also required.
Murray Secretion Scale	Murray et al., 1996	Location and extent of secretion pooling on a 4-point scale.	Easy to use Claims to identify the risk of aspiration from bodily secretions.	Validated only for secretions.
Secretion Severity / Laryngeal Secretion Scale	Belafsky et al., 2008	Secretions on vocal folds in a 0-3 or 4 rating scale.	Useful for assessing aspiration risk and focusing on the clearance status of the vocal folds.	Limited data and scope in dysphagia
Pooling Score (P-Score)	Farneti et al. 2014	It assesses the 3 parameters, like site and amount of residue, and the	It is a standardized, simple scoring system that can be	It does not assess the functional impact, and

		management of residue. It will have a minimum of 4 and a maximum of 11 scores.	used for different consistency boluses.	training is required.
Residual Ordinal Rating Scale (RORS)	Allen et al., 2017	It assesses residue in 2 different sites, that is, the valleculae and the pyriform sinus.3-point ordinal scale.	High intra-rater reliability, easy to use, and minimal steps to score.	Low inter-rater reliability, and cannot be used in the evaluation of management.
Dynamic Imaging Grade of Swallowing Toxicity-Flexible Endoscopic Evaluation of Swallowing (DIGEST-FEES)	Starmer et al., 2021	It includes 3 components: 1. Safety Grade (DIGEST-S) based on PAS. 2. Efficiency Grade (DIGEST-E) Evaluates the pharyngeal residue amount. 3. Global DIGEST Score combines safety and efficiency, which	It includes safety and efficiency, has clear definitions, and a manual that improves reliability after training.	Training and expertise are required; evaluation of residue in FEES is less than that of VFSS.

		includes 5 5-point rating scale.		
Visual Analysis of Swallowing Efficiency and Safety (VASES)	Curtis et al., 2021	It includes 4 components. Pharyngeal residue penetration and aspiration anatomical and temporal boundaries, and trial-level analysis. It uses a 100-point visual analog scale.	It improves transparency, reliability, and standardization of the interpretation. Improves clinical and research efficiency.	Its visual scale is complex, training is required, and subjectivity is also present in the rating.

Need for the study

Despite the multitude of tools that are available to assist a clinician in making clinical decisions, the interpretation of these tools is largely subjective and perceptual. There is a heavy reliance on the clinician's experience, judgment skills, and expertise (Langmore, 2001; Leonard & Kendall, 2019). Most of the tools listed in Table 2 categorize the FEES observations into broad categories of dysphagia symptoms 'present' or 'absent'. Similarly, the penetration-aspiration scale provides a perceptual rating method for inferring the safety of swallowing performance as observed on FEES. This does not directly help imply the physiological impairment that caused aspiration, limiting its applicability in management decisions. The clinician often needs to combine the subjective FEES evaluation judgment with the clinical subjective observations to make management decisions. This may dilute the clinical decisions and make management less precise and effective. The subjectivity in these scoring and assessment systems makes the information less reliable, more variable, and non-transferable across professionals. Further, most FEES evaluation scales are ordinal, with variable intervals between rating scores. This makes subtle changes in the functional status invisible and neglected, even when the functional reports say otherwise (Langmore, 2001; Logemann, 1999; Moloney et al., 2023; Wilmskoetter et al., 2019).

Comparisons between FEES and VISS themselves demonstrate only moderate agreement in detecting aspiration and residue, with each modality offering an advantage and sensitivity to different components of swallowing (Dziewas et al, 2021; Kelly et al, 2015) Studies using FEES registries have emphasized the need for repeat instrumental evaluations after clinical management, underscoring the limitations of relying solely on PROMs (Dzirwas, et al, 2019). Patient-reported outcome measures (PROM's) and instrumental evaluations evaluate different, but complementary aspects of swallowing disorders. PROMs give information about the individual's interpretation of their swallowing difficulties based on the impact of dysphagia in their daily living. Instrumental evaluation provides objective information about swallowing physiology and the function. Therefore, differences between these measures are not common but anticipated. This emphasizes the importance of implementing an extensive multidimensional evaluation approach that incorporates both subjective and objective evaluations. Depending on one type of measure may give incomplete information of the swallowing disorder which leads to misinterpretation and makes the research findings difficult to compare across studies and clinical settings.

Emerging research suggests that interpretation of FEES is subject to several limitations, majorly in terms of reliability and objectivity. Several studies have demonstrated variability in both inter-rater and intra-rater agreement across commonly used FEES rating scales. These studies clearly indicate that FEES interpretations are clinician-dependent and that the visual–

perceptual judgments remain a significant source of inconsistency. Butler et al. (2015) reported only moderate inter-rater reliability when clinicians applied the Penetration–Aspiration Scale (Rosenbeck et al., 1996), suggesting that even trained professionals may differ in their interpretation of airway invasion events. Another scale, the pharyngeal residue scale (Neubauer et al., 2015), also indicated variability, suggesting individual differences in image interpretation (Steele et al., 2019). Comparing various residue rating systems, Messina et al. (2024) demonstrated higher reliability but moderate variability across all residue rating scales for FEES measurement.

They also expressed their concern regarding the feasibility and time efficiency of certain tools. Recently, it was demonstrated that clinician experience significantly influenced scoring accuracy; novice raters, despite brief training, showed inconsistencies in assigning scores, especially when the differences are subtle at the level of glottic function (Rocca et al., 2025). These reports highlight the need for an alternative method of FEES evaluation that is more structured, task-specific, and objective (Butler et al., 2015; Messina et al., 2024).

Despite these methodological limitations, FEES remains as a widely used and valuable tool in the evaluation and management of dysphagia across a wide clinical population. Its ability to provide direct visualization of pharyngeal and laryngeal structures provides clinicians with information about swallowing function in difficult-to-test populations. The direct observation of key physiological features such as penetration, aspiration, pharyngeal residue, and airway protection mechanisms improves the clinical utility of the procedure. Research suggested that FEES exhibits high sensitivity for detecting aspiration and residue, with diagnostic performance comparable to Videofluoroscopic, Swallow Study (Helliwell et al., 2023). Another advantage is the real-time evaluation of compensatory strategies, including postural adjustments and dietary modifications, supports individualized treatment planning (Dziewas, et al., 2024). Latest systematic and scoping reviews further highlighted the expanding role of FEES in clinical practice and research, including its importance in treatment monitoring, outcome evaluation, and investigation of swallowing physiology (Dziewas et al., 2024; McSharry et al., 2022); however, these reviews also emphasize considerable heterogeneity in protocols, outcome measures, and reporting standards (Dziewas et al., 2024; Imaizumi, et al, 2024; McSharry et al., 2022). Such variation limits the integration of evidence and the development of standardized clinical guidelines. In such conditions, the implementation of quantitative approaches into FEES analysis has the potential to improve objectivity, improve reliability, and enable meaningful comparisons across populations and studies, thereby improving the scientific precision of dysphagia research.

Table 2 is a compilation of the most common perceptual rating scales that rely on the rating of airway invasion and pharyngeal swallowing events as visualized during FEES. These observable events are understood to reflect complex, multidimensional disruptions in swallowing physiology (Molfenter & Steele, 2013). While the identification of such events is clinically valuable for determining the presence or absence of impairment, these scales do not provide direct insight into the underlying physiological mechanisms responsible for the observed dysfunction. The feasibility and accuracy of measuring temporal events before, during, and after a swallow as visualized in a FEES examination are underexplored. The timing, latency, sequencing, and response duration of events visualized in FEES are rapid and may not be reliably captured through ordinal perceptual ratings. Various reports emphasize the essentiality of temporal parameters and coordination of swallowing physiology in determining the safety and efficiency of the function.

The support for considering temporal parameters of swallowing as one of the critical objective quantifications can be derived from the studies of swallows using instrumental modalities such as the Videofluoroscopic Swallow Study, ultrasonography, high-resolution manometry, and surface electromyography. Foundational work by Logemann (1998) using

VFSS established key temporal metrics, including oral transit time (OTT), pharyngeal transit time (PTT), and total swallow duration, which are considered clinically valid and critical for identifying delays in bolus propulsion. Subsequent investigations by Perlman et al. (1993) demonstrated that swallowing timing is influenced and modulated by bolus characteristics and individual physiological variability. According to the author, larger bolus volumes had earlier swallow initiation and adaptive pressure responses. Further, Kendall et al. (2000) delineated the temporal sequencing of discrete swallowing events such as the onset of the pharyngeal swallow, laryngeal elevation, and upper oesophageal sphincter (UES) opening. The team attempted to establish normative patterns and highlighted deviations in these sequences as indicative of impaired coordination. With further research, the scope of temporal analysis expanded to integrate physiological and biomechanical parameters. Steele and Van Lieshout (2004) reported that bolus consistency influenced oral phase timing, with thicker consistencies requiring prolonged and more controlled lingual movements. More recently, Steele et al. (2019) emphasized a comprehensive temporal–physiological framework, demonstrating that measures such as stage transition duration, airway closure duration, and UES opening duration are critical indicators of swallowing safety and efficiency.

Like VFSS, ultrasonography has also been popular for the objectification of swallowing measures. Ultrasonography emerged as a non-invasive modality capable of capturing temporal aspects of swallowing. After the feasibility of visualizing coordinated movements of the tongue, hyoid, and larynx was established by the work of Shawker et al. (1984), temporal analysis of the session movements was found to provide insights into the oral phase dynamics (Peng et al., 2000). Hsiao et al. (2012) further confirmed its utility in assessing dynamic events such as hyoid displacement and coordination patterns during swallow. However, ultrasonography provided more oral phase dynamic measures than the complex pharyngeal measures and stage shift-related measures.

High-resolution manometry quantifies the pressure events across the pharyngo-oesophageal segment to quantify the spatiotemporal characterization of swallowing physiology. Omari et al. (2011) demonstrated its precision in measuring the timing of pharyngeal contraction and UES relaxation. Similarly, Pandolfino et al. (2006) and Ghosh et al. (2006) highlighted the role of manometry in evaluating coordination between pressure generation and bolus transit, which are otherwise not measurable. Cook et al. (2012) emphasized the utility of the high-resolution manometry procedure in assessing timing and coordination across pharyngeal and oesophageal phases during swallow. Normative datasets established by Steele et al. (2015) further revealed that temporal and pressure variables vary systematically with bolus characteristics and implied the need for clinical reference standards.

Surface electromyography (sEMG) has a significant role in improving the understanding of swallowing timing and coordination by evaluating the activity of muscles required during swallowing mainly the submental and infrahyoid muscle groups. Early study by Reynolds et al. (1988) explained a close temporal relationship among muscle activation patterns and pressure events recorded during swallowing. Later Palmer et al. (1992) explained that submental muscle activity was strongly related to the progression from the oral to the pharyngeal phase of swallowing, with interruption in this trend reflected in impairment in the swallow coordination. Following these studies, normative temporal measures like onset latency time to peak activation and duration of the muscle activity were established that assists in differentiating between typical and atypical swallowing patterns (Vaiman et al.,2004, 2005).

Research has constantly indicated that individuals with swallowing difficulty exhibit prolonged delay and poor coordination between the muscles when compared with the healthy individuals (Crary et al., 2002; Huckabee & Steele, 2006). Recent study by Alvarenga et al. (2019) have confirmed these results by reporting delayed onset and prolonged duration of muscle activity in persons with dysphagia which highlights the importance of sEMG in identifying variation in swallowing timing and coordination.

From these evolutions in swallowing assessment across various instrumental measures, quantification represents a structured process of changing visual and perceptual examination into more objective, measurable parameters. In swallowing assessment, the physiological events should be transformed into numerical measures that are reliable, valid and clinically useful and reduce the human perceptual bias and interpretation errors. This procedure agrees with more extensive practices in clinical medicine, where quantification strengthens diagnostic accuracy, such as in neurophysiology (Kimura, 2013), cardiovascular function (Hall, 2016), and pulmonary physiology (West, 2012). The development of normative reference values and the monitoring ability change over time. They are important to monitor disease progression and evaluation of treatment outcomes. Extending such quantitative methodologies to FEES-based assessment holds significant potential to enhance objectivity, reproducibility, and clinical utility in dysphagia evaluation.

The VFSS and FEES are considered gold-standard assessments in dysphagia. Many researchers have attempted quantification of VFSS for swallowing evaluation (Logemann, 1999; Rosenbek et al., 1996; Martin-Harris et al., 2008; Steele & Cichero, 2014). In FEES evaluation, quantification may be interpreted as the transformation of a visualized dynamic image of swallowing physiology, extent and distribution of residue, airway intrusion depth, timing, and duration into systematically measured parameters. At this point, we may only assume that the subtle deviations in these measures from the expected may be critical diagnostic indicators of disorder. Regular monitoring of changes in these measures across time may be useful in studying the magnitude and direction of change over time. This can help the clinician to evaluate treatment efficacy and make data-driven modifications to intervention plans. Quantification of swallowing physiology, kinematics and consequences can support objective clinical decision-making by providing measurable indicators. Predictive models for aspiration risk and further decisions towards the need for alternative feeding methods require quantifiable data. Such developments in the field of deglutition science and research can facilitate early effective intervention, improve patient outcomes, and reduce healthcare burden (Logemann, 1999; Rosenbek et al., 1996; Martin-Harris et al., 2008; Steele & Cichero, 2014).

Although these advantages are recognized, the inclusion of quantitative methods into routine FEES analysis remains limited in scope. Validated and standard framework for the quantification of swallowing events are limited using FEES. This is a major gap in both clinical practice and dysphagia research. With the increase in widespread use and applicability of FEES as a primary instrumental assessment tool in dysphagia, there is a strong need to develop and validate methods for quantitative analysis of swallowing and related events observed during FEES examinations. Such advancements have the potential to improve diagnostic precision, improve the reliability of interpretation, support evidence-based clinical decision-making, and facilitate outcome measurement in dysphagia rehabilitation.

The last decade has witnessed the technology boom in artificial intelligence, machine learning, and tele-diagnostics and management. Translation of this technology into the rehabilitation sector requires exploration and systematically generated data. In this direction, the development of objective measures may be a step towards automatization of diagnostics. Therefore, the present study was undertaken to address the critical gap of non-availability of quantifiable FEES physiological data by exploring and establishing methods for the quantification of swallowing and related events in FEES. This was expected to improve the objectivity, reliability, and clinical applicability of FEES-based dysphagia assessment.

Aims and Objectives

The study aimed at quantifying the timing of the typical pharyngeal swallow and related events as seen in endoscopic evaluation in healthy adult individuals. It was hypothesized that by implementing frame-by-frame analysis of the dynamic endoscopic data of velar, pharyngeal and glottic functions during phonation and swallow, the temporal measures of specific physiological and functional events could be quantified. The onset, duration, and offset of specific swallow events and other physiological functions could then be estimated. Such data could serve as a basis for future standardization, clinical validation, and automatization of relevant pharyngeal physiology, thereby providing a quantifiable outcome from otherwise subjective interpretation of endoscopy. Specifically, this aim was targeted with the following objectives:

1. To develop a standard matrix for measuring pharyngeal swallow and related events from endoscopic data.
2. To implement the matrix for estimation of the timing of swallow and related events across bolus types and volumes
3. To compare the temporal measures across bolus volumes and consistencies

CHAPTER 2

REVIEW OF LITERATURE

Swallowing is a complex sensorimotor process that demands intricate coordination across the voluntary and reflexive neuromuscular systems to ensure safe, efficient, and adequate bolus transfer from the mouth to the stomach (Matsuo & Palmer, 2008). Any disruption in this physiology leads to serious clinical consequences of lower airway intrusion, inadequate nutritional intake, dehydration, poor health, and quality of life (Baijens et al., 2016; Clavé & Shaker, 2015). Early identification, assessment, and effective management of dysphagia are crucial for the most efficient health outcomes (Clavé & Shaker, 2015; Dziewas et al., 2021; Hinchey et al., 2005).

Swallowing assessment methods rely heavily on clinical subjective observations (Table 2), perceptual judgments, and clinician expertise, even while using instrumental assessments of swallowing physiology (Langmore, 2001; Leonard & Kendall, 2019). While the scales unquestionably provide valuable insights for clinical decision-making (Clavé & Shaker, 2015; Rosenbek et al., 1996), the inherent subjectivity, variability, and influence of external factors in judgement and interpretation make these methods less uniform and reliable across practice (Dziewas et al., 2021; Giraldo-Cadavid et al., 2017; McCullough et al., 2001).

Systematic quantification of instrumental assessments converts visually perceived information into measurable parameters. This can contribute significantly to improving reliability and consistency and reducing variability across clinicians in their professional judgments and interpretations. Moreover, quantification may also help detect and document subtle changes in the function, providing stronger evidence for the magnitude and direction of change. Transferring this to dysphagia diagnostics and management, quantification of the subjectively perceived physiology and function can assist the Speech-Language Pathologists

(SLPs) for evidence-based, reliable, and data-driven clinical decisions related to diagnosis and rehabilitation.

The advancements in technology have improved the medical diagnostics and procedures with revolutionary applications of machine-assisted diagnostics (American Speech-Language-Hearing Association, n.d.), remote surgeries (Malandraki et al., 2013; Ward et al., 2020), and automatization of test interpretations (Esteva et al., 2019; Martin-Harris et al., 2008; Steele & Cichero, 2014). Such innovative applications cross human, physical barriers of distance and make health care services equal, standardized and accessible beyond boundaries. The efficiency of health care systems can be improved drastically with faster, efficient, effective, and quality services with the available manpower, to meet the demands of a growing population. Across multiple domains and professions, quantification has been playing a critical role in improving diagnostic accuracy. The same is evidenced in the field of deglutition science as well, with an increase in the application of quantitative swallowing analysis in instrumental assessments. The current review of literature aimed to identify the instrumental evaluation methods that assist in the quantification of swallowing performance.

Pharyngeal and Oesophageal Manometry

Oesophageal manometry yields precise measurements of oesophageal contraction pressures, intra-bolus pressure, upper oesophageal sphincter (UES) relaxation time, lower oesophageal sphincter (LES) relaxation pressure, and the timing and vigour of peristaltic activity (Cook, 2009; Kahrilas & Pandolfino, 2018; Sweis & Fox, 2020). The derived indices from these measures are widely used in the diagnosis of oesophageal motility disorders, including achalasia, oesophageal spasm, and ineffective oesophageal motility (Kahrilas & Logemann, 1993; Pandolfino & Gawron, 2015). As such, oesophageal manometry represents a well-established, objective tool for evaluating non-structural swallowing disorders that may otherwise rely on subjective clinical interpretation (Herbella, & Patti, 2014).

Pharyngeal manometry, especially high-resolution manometry (HRM), has advanced the objective evaluation of swallowing by giving keen information about the measures of pressure generation and coordination during the pharyngeal phase of swallowing. Compared to observational methods, the HRM reflects precise spatiotemporal pressure patterns, which offers valuable interpretation into the mechanics of deglutition. A study by Kahrilas et al. (2017) revealed that HRM could accurately describe pharyngeal pressure events and coordination of swallowing and related structures. Omari et al. (2011), using impedance manometry, established pressure-flow analysis, which facilitated differentiating the pharyngeal weakness and UES outflow obstruction. Later it led to the development of Swallow Risk Index (SRI) and Post-Swallow Impedance Ratio (PSIR), proposed by Cock and Omari (2012) as an objective index of swallowing safety and efficiency. Steele et al. (2019) found that reduced pharyngeal pressure generation and weak pharyngeal contractile activity are associated with increased pharyngeal residue and greater dysphagia severity, particularly in neurogenic populations (Martin-Harris et al., 2008; Matsuo & Palmer, 2008; Steele & Cichero, 2014).

Despite being an objective and quantifiable modality, the clinical validation of pharyngeal manometry remains limited in key functional domains of swallowing. The pharyngeal shortening during a swallow displaces the sensor location in the pharynx, making physiological evaluation unreliable (Kahrilas et al., 2012; Omari et al, 2014). Further, the interdependent nature of swallowing events poses challenges for the interpretation of isolated pressure measures in relation to functional swallowing outcomes (McCulloch et al., 2010; Steele & Huckabee, 2007). Unlike imaging-based assessments such as Videofluoroscopic Swallow Study and Fiberoptic Endoscopic Evaluation of Swallowing, manometry does not provide direct visualization of airway events. The method has less robust evidence to support its reliable application in detecting and quantifying clinically critical outcomes such as airway intrusion, pharyngeal residue, and overall swallowing safety in persons at risk for dysphagia.

Further large-scale studies are required to establish its clinical validity in these domains and to integrate manometric findings with functional measures of swallowing safety and efficiency.

Oral pressure performance measures

The pressure dynamics of oral physiology during a swallow are critical for posterior movement of the bolus towards the pharynx (Matsuo & Palmer, 2008; Robbins et al., 2005). Quantification of oral pressures has been attempted in swallowing diagnostic and management approaches (Omari et al., 2014; Steele & Huckabee, 2007). The tools, such as the Iowa Oral Performance Instrument (IOPI), convert the pressure generated between the lips and during tongue-palate contact into numerical values that can be regularly monitored for changes across time (Clark et al., 2009; Robbins et al., 1995). These measures are explored widely for their factors in normal healthy adults (Robbins et al., 1995; Youmans et al., 2009) and in various clinical populations (Logemann, 1999; Martin-Harris et al., 2008; McHorney et al., 2002). The difference in oral pressure performance indicated the diagnostic validity of an oral weakness, but not directly the presence or absence of dysphagia. Similar to manometry, the oral pressure dynamics were an indirect inference of swallowing physiological capacity. There was no direct visualization of swallowing or its consequences, limiting its application in the detection of penetration and aspiration or in the evaluation of timing and coordination of swallowing events (Kahrilas & Pandolfino, 2005; Omari et al., 2014; Steele & Huckabee, 2007). More sophisticated imaging techniques that provide direct visualization of swallowing may be clinically useful in this regard (Brant & Helms, 2018; Bushberg et al., 2012).

Advanced Imaging techniques

Advanced imaging techniques are widely used across various healthcare domains, including speech and swallowing sciences, dentistry, neurology, and cardiology diagnostics, as well as research. They assist the health care professional to visualize internal anatomical structures and physiological processes (Bushberg et al., 2012). Diverse forms of energy are utilized for advanced internal imaging, such as X-rays, sound waves, magnetic fields, and radioactive tracers that generate detailed representations of internal organs (Mettler & Guiberteau, 2019). Common imaging technologies include X-ray radiography, computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography, nuclear medicine imaging, and endoscopic imaging (Brant & Helms, 2018; Mettler & Guiberteau, 2019). The clinical application of these techniques is enhanced when the visual information and observations are transformed into objective, quantifiable parameters.

Recent advances in dynamic imaging, particularly computed tomography and cine magnetic resonance imaging, have enabled detailed visualization of swallowing physiology (Matsuo et al., 2015; Olthoff et al., 2014). The three-dimensional and multi-planar visualization of swallowing structures has facilitated both morphological and kinematic analyses during deglutition (Kahrilas & Peters 2012; Matsuo et al., 2015; Olthoff et al., 2014). Through frame-by-frame analysis of reconstructed imaging sequences, critical swallowing parameters, especially the pharyngeal reflexive components of airway protection, are visualized and objectively measured (Ohta et al., 2019). The quantification of these parameters has provided a dynamic and spatially precise evaluation of swallowing physiology that extends beyond descriptive assessment.

Experimental evidence highlights the value of quantitative evaluation in clinical dysphagia diagnosis. Ohta et al., (2019) revealed that four-dimensional computed tomography (4D-CT) provided accurate visualization and measurement of structural movements during swallowing, basically the laryngeal elevation and UES opening, which were difficult to visualize using other conventional techniques. Kim et al. (2017) and Matsuo and Palmer (2008) highlighted that quantitative assessment of pharyngeal constriction and epiglottic inversion is important for perception of bolus propulsion and airway protection mechanisms. The real-time imaging studies have recognized restricted UES opening as a primary predictor of bolus flow resistance and cricopharyngeal dysfunction. The quantitative measures have led to differential diagnoses of not only the various conditions but also helped in making physiology-based management decisions for the management of dysphagia.

The real-time cine-MRI technique has emerged as a valuable modality for swallowing assessment due to its ability to provide high-resolution, radiation-free, multiplane visualization of soft tissue structures. Detailed evaluation of swallowing events, including tongue propulsion, velopharyngeal closure, laryngeal elevation, epiglottic inversion, pharyngeal constriction, UES opening, bolus transit, and residue patterns, is possible with this technology (Olthoff et al., 2014; Zhang et al., 2012). Pearson et al. (2013) highlighted the coordinated biomechanics of hyolaryngeal movement and airway protection with cine-MRI and demonstrated the capacity of this technique to detect residue distribution and structural asymmetries in dysphagic populations (Molfenter & Steele, 2013). Adding on to these clinical benefits, Takahashi et al., (2025) attempted a deep learning–based approach for automated quantification of pharyngeal area and contraction ratio using cine-MRI. These automated measures demonstrated the feasibility, reliability, and clinical applicability of objective measurement in swallowing assessment. Other volumetric parameters, spatial displacement, temporal sequencing, and structural coordination during swallowing have also shown promising results (Kahrilaş & Peters 2012, Matsuo et al., 2015, Olthoff et al., 2014). These multidimensional measures provide information on swallowing biomechanics that are not accessible through traditional two-dimensional X-ray-based techniques (Inamoto et al., 2024). These technological advancements enhance the utility of imaging techniques with the integration of quantitative analysis along with sophisticated visualization of internal swallowing physiology. This adds to the clinical value, which lies with enhanced diagnostic precision, reproducibility, and the overall effectiveness of dysphagia management.

Despite the advancements and demonstrated advantages of quantification in advanced imaging modalities, several inherent limitations restrict their routine clinical application in dysphagia rehabilitation. Although the four-dimensional CT (4D-CT) enables precise quantification of parameters such as laryngeal elevation and upper oesophageal sphincter (UES) opening, its clinical utility is significantly constrained by exposure to ionizing radiation (Ohta, et al, 2019) This limitation is particularly critical when repeated assessments are required, such as in longitudinal monitoring in vulnerable populations, such as pediatric and medically fragile patients. Additionally, real-time visualization of bolus flow dynamics during swallow is limited in these CT studies, restricting the ability to fully represent functional swallowing events. In contrast, while MRI may offer real-time visualization, lower temporal resolution restricts the quantification of precise physiological coordination that is critical in swallowing evaluation (Qlthoff et al., 2014, Zhang et al., 2012). This limitation interferes with the precise analysis of quick and transient swallowing events such as epiglottic inversion and airway closure. The preferred positioning for MRI evaluation is typically in a supine or otherwise constrained posture, which does not reflect natural feeding conditions and may alter normal swallowing physiology. Other practical limitations, including high cost, limited accessibility, prolonged acquisition times, and susceptibility to motion artifacts, further impact the feasibility and reliability of MRI in routine swallowing evaluation (Molfenter & Steele, 2013; Pearson et al., 2013). Therefore, these techniques may be better applied as complementary tools that provide detailed physiological insights in selected cases, together with more clinically feasible methods such as VFSS and FEES.

Ultrasound imaging

Ultrasound imaging has been increasingly explored as a non-invasive modality for the structural and functional assessment of swallowing. Various attempts have been made to quantify biomechanical parameters of swallowing using this method, especially hyoid bone displacement (mm), tongue thickness (cm), duration of muscle activity (ms), and blood flow velocity (cm/s) (Szabo, 2004). Using frame-by-frame analysis of image intensity, echo patterns, and temporal changes, ultrasound has enabled the extraction of kinematic, spatial, and temporal measures of swallowing physiology (Hoskins et al., 2010). These results position ultrasound as a promising tool for objective quantification of swallowing events, particularly in the oral and pharyngeal phases.

Studies on pharyngeal kinematics in healthy swallows have provided the preliminary indication of its clinical application. Using Doppler ultrasound, Sonies et al. (1995) demonstrated that temporal and trajectory-based characteristics of hyoid movement could differentiate typical and disordered swallowing patterns. Ma and Wrench (2022) reported that ultrasound could reliably quantify hyoid displacement and velocity, with greater anterior–superior displacement corresponding to critical swallowing events such as airway protection and upper oesophageal sphincter (UES) opening. Kim et al. (2024) investigated hyoid movement across different bolus viscosities and volumes in healthy individuals and demonstrated distinct phases of hyoid movement with phase-specific differences in movement distance, duration, and velocity. Beyond hyoid kinematics, ultrasound has also been applied to quantify tongue movements during speech and swallow. In the swallowing function, tongue movement measures indicate bolus propulsion and oral phase efficiency. Krekeler et al. (2025) demonstrated the feasibility and reliability of quantification of lingual movement and tongue contour using three-dimensional and four-dimensional ultrasound techniques during swallowing. This study highlighted the importance of analytical capability in addition to imaging resolution.

Despite these advancements, ultrasound continues to have limited clinical application. A recent scoping review by da Silva Martins et al. (2025) concluded that there was considerable variability in measurement techniques, and there are no standardized protocols across studies. More recently, Wang et al. (2025) noted that while ultrasound is non-invasive and patient-friendly, it demonstrated moderate validity and reliability in detecting swallowing impairment. Adding to the procedural variability, ultrasound is limited in direct visualization of the airway protection events or bolus flow through the pharynx. The visual field for ultrasound studies is limited, restricting the information that can be reliably obtained throughout the swallowing tract. In clinical diagnostics, ultrasound has yet to prove its accuracy compared to other established instrumental assessments through future research. da Silva Martins et al. (2025) emphasized the need to further verify the application of ultrasound in larger samples of healthy and clinical populations. As such, ultrasound remains a valuable adjunct tool, with further standardization and validation required to enhance its role in comprehensive dysphagia assessment.

Videofluoroscopic Swallow Study/ Modified Barium Swallow Study

Quantitative analyses of videofluoroscopic swallowing studies (VFSS) are available in the literature, and they significantly contributed to the objective analysis of swallowing physiology and pathophysiology. Several temporal measures have been developed to evaluate the coordination, timing, and efficiency of swallowing events. Early work by Logemann (1998) emphasized measures such as oral transit time (OTT), pharyngeal transit time (PTT), and total swallow duration that demonstrated prolonged durations to indicate delayed bolus propulsion and reduced swallowing efficiency. Further investigations expanded the focus toward event-specific temporal coordination. Perlman et al. (1993) examined swallow initiation timing and duration of pharyngeal events and reported adaptive modifications. Temporal coordination changed as a factor of bolus volume, while abnormal timing patterns reflected swallowing discoordination.

Further refinement of temporal analysis examined pharyngeal swallow initiation and airway protective mechanisms. Daniels et al. (1997) demonstrated that prolonged pharyngeal response time and delayed swallow initiation were closely associated with increased aspiration risk. Kendall et al. (2000) quantified the timing of pharyngeal swallow onset, laryngeal elevation, and upper oesophageal sphincter (UES) opening. In their study, delayed coordination of these events was associated with increased dysphagia severity. More recently, Kim and McCullough (2008) introduced measures such as stage transition duration (STD) and pharyngeal delay time and reported that increased delays in these measures compromised airway protection and swallow initiation efficiency.

Research has also explored the influence of bolus characteristics on temporal swallowing parameters using VFS5 Steele and Van Lieshout (2004) reported that oral phase duration increased and lingual movement altered with thicker bolus consistencies. These reflect adaptive modifications in oral motor control and the feasibility of quantification from VFSS. More recent studies by Steele et al, (2019) emphasized the clinical significance of temporal parameters such as stage transition duration, airway closure duration, and UES opening duration in reduced swallowing safety and efficiency.

Quantitative VFSS research has highlighted the need for standardization in temporal measurements. Molfenter and Steele (2011) reported wide variability in pharyngeal transit time and hyoid movement duration, emphasizing the importance of establishing standardized protocols and operational definitions for similar swallowing analyses. These investigations indicated that temporal measures derived from VFSS provide valuable objective insights into swallowing physiology, swallowing safety, bolus efficiency, and airway protection. However, the variability across studies reinforces the necessity for reproducible and standardized quantitative frameworks in instrumental dysphagia assessment.

Flexible Endoscopic Evaluation of Swallowing

In recent years, there has been a rise in interest in the possibility of deriving objective and quantifiable means from Flexible Endoscopic Evaluation of Swallowing (FEES). The longstanding concerns regarding the subjectivity of FEES interpretation were expected to be addressed through these methods. One of the earliest studies in this direction was provided by Butler et al. (2009), who investigated swallowing physiology in healthy young and older adults. The study quantified multiple temporal and functional swallowing variables, including Penetration-Aspiration Scale (PAS) scores, bolus dwell time, pharyngeal closure duration, and pharyngeal residue. Comparison of these measures across age, gender, bolus volume, and bolus type revealed measurable differences in the healthy population. Older adults exhibited prolonged bolus dwell time and had greater residue accumulation, especially for milk boluses. Occasional airway intrusion events were observed even in healthy individuals, particularly among older adults. These findings reinforced the concept that quantified FEES measures and indicated the capability of capturing clinically meaningful variations in swallowing physiology associated with age and bolus characteristics.

Implementing similar methods, Butler et al. (2011) specifically examined bolus dwell time using frame-by-frame analysis of FEES recordings across bolus volume, consistency, delivery method, and the anatomical location of the bolus head. The results revealed significant variations in this measure depending on bolus properties and bolus position before swallow initiation. Longer dwell times were observed for larger volumes and a deeper bolus head. The authors proposed that such variability reflects systematic and physiologically driven sensory-motor control mechanisms involved in swallow initiation.

A systematic approach in a similar direction was reported from Mozzanica et al. (2018) in the quantification of white-out duration as a temporal parameter of swallowing. Their study examined the relationship between the whiteout duration and that of age, sex, bolus volume, and bolus consistency. FEES recordings from healthy adults were analyzed using frame-by-frame analysis to measure the duration of the white-out phase as an indirect marker of pharyngeal swallowing events. The study found that white-out duration was a factor of bolus characteristics, with longer durations observed for larger bolus volumes and thicker consistencies. Older adults also exhibited prolonged white-out durations compared to younger individuals with minimal gender variations. These variations reflected underlying physiological adaptations rather than random fluctuations. Therefore, white-out duration may serve as a reproducible temporal measure for swallowing physiology from FEES, and it may be sensitive to both bolus properties and individual physiological differences.

Building upon these earlier investigations, Sutton et al. (2024) established normative temporal measures in healthy adults using retrospective FEES recordings. Through detailed frame-by-frame analysis, the investigators quantified swallowing events such as latency to white-out, white-out duration, and total swallow duration. The study also incorporated structured outcome measures such as the Penetration-Aspiration Scale (PAS) and Yale Residue Scale (YKS), along with quantified measures of the number of swallows per bolus. The findings demonstrated that the temporal and functional swallowing measures obtained from FEES could be represented within definable normative ranges in healthy adults. This procedure supported the feasibility and clinical applicability of quantitative FEES analysis. Similar to the observations reported by Mozzanica et al. (2018) and Butler et al. (2009, 2011), the variability identified in FEES measures was systematically associated with demographic and physiological variables such as age, bolus volume, bolus consistency, and swallow initiation characteristics Comparing these variables, Sutton et al (2024) demonstrated age-related adaptations in swallowing physiology exhibited through prolonged temporal durations and slightly increased variability. Increased bolus volumes were associated with a greater number of swallows per bolus in typical individuals. Correlating the quantified measures with those of PAS scores and residue scores, the study provided a preliminary indication of the clinical relevance of quantified FEES outcomes.

The reviewed studies provided converging evidence that FEES events are measurable, reproducible, and physiologically meaningful. Temporal measures such as latency, white-out duration, total swallow duration, and bolus dwell time have demonstrated sensitivity to clinically relevant variables, including age, bolus characteristics, airway protection, swallow initiation, and swallowing efficiency (Mozzanica et al., 2018; Butler et al., 2009, 2011; Sutton et al., 2024). However, the available literature also highlights important methodological and conceptual limitations in this direction. Many of the studies rely on indirect physiological markers, have non-standardized and variable operational definitions, and investigate isolated temporal parameters rather than a comprehensive and integrated analytical framework. Despite the promising evidence, FEES quantification continues to be non-standardized, constrained in reproducibility, and lacks clinically interpretable quantitative matrices for swallowing-related and laryngeal events. Addressing this gap may improve clinical decision-making accuracy and consistency, thereby enhancing diagnostic precision.

CHAPTER 3

METHOD

The present study was designed with the aim of examining the feasibility of developing a standardized method for the quantification of temporal events related to swallowing. This required identification of the events and their measures. Further, the measures had to be standardized in their definition and derivation. The investigators further implemented the developed procedure for deriving the measures in a prospective group of healthy adults to ensure the practical feasibility of implementation. This chapter explains in detail the systematic methodology followed for meeting the objectives of this study. All the procedures followed for the study were in line with the bio-behavioural and ethical committee of the All India Institute of Speech and Hearing, Mysore (SH/IRB/M.5/SLP.32/2025-26). Consent was signed by all participants before enrolling them in the study. They were allowed to withdraw their consent at any point in the study. The study was conducted in multiple phases:

Phase 1: Development of the standard matrix for pharyngeal swallow and related events

Step 1: Review of literature

A detailed review of the literature was conducted to compile the objective measures related to swallowing already attempted by previous research studies in this direction. Various research databases were reviewed for identification of research studies that (a) used the FEES procedure for swallow evaluation, (b) reported an objective measure of swallow or related events. From the identified research studies, the specific measure and its definition/ derivation method, as described by the authors, were tabulated.

Step 2: Delphi panel discussion on other possible measures

A group of four independent speech-language pathologists who routinely used FEES in their clinical practice independently listed the events observable in the procedure. These events were converted into temporal measures by including the onset, offset, duration and latency variables by the investigator.

Step 3: Development of definition/ derivation method for the listed measures

The list of measures from steps 1 and 2 was combined. Each temporal measure and its definition/derivation method, as per previous research, were tabulated. Certain measures had more than one derivation method prevailing in the literature (Example: offset of whiteout). All the reported definitions/derivations were tabulated. For the measures that were previously unexplored/unreported/with definitions were not available, the investigator proposed a derivation method. The tabulated temporal measures along with their definition(s) were provided to a group of seven SLPs for validation. All SLPs were familiar with and routinely incorporated the FEES procedure in their routine clinical work.

The SLPs were instructed to opt for the “most appropriate” derivation method for each temporal measure from the list. The investigator remained “non-interfering” but was available for any clarifications with each SLP during the process. In the event the reviewer required clarification on an already existing or newly proposed definition, the investigator performed the derivation as per all the definitions, and the SLP was required to choose the most appropriate method. If the SLP had any suggestions on modification or found it appropriate to propose a different definition, the same was allowed. Each judge did the process independently and in one sitting. In case a new definition was proposed by a reviewer, the specific measure went through a second round of validation among other SLPs. The responses were compiled to arrive at the most appropriate derivation method for each measure. A target of 80% agreement across judges for the selection of a derivation method.

Phase 2: Feasibility of implementation of the validated derivation method for quantifying FEES data in healthy individuals.

An attempt was made to explore the feasibility of implementing the derivation method for each temporal measure in a prospective sample of 20 healthy individuals who underwent the FEES procedure.

Participants

A total of twenty-five healthy individuals (n=25, 11 males and 14 females) aged 18-25 years participated in the study. These participants were recruited from a convenient sample of undergraduate students. The participants were included if they a) provided written consent to participate, b) had no history of oral, pharyngeal, laryngeal, or oesophageal structural alterations, c) had no recent fracture or suture of the perinasal area, d) had no history of seizure, e) had no active respiratory illnesses, f) had no hypersensitivity in the nasal or oral structures, g) had no known anaphylaxis attacks, h) had no history of dysphagia, and i) were not under medications for any acute or chronic illnesses. A participant or their data was excluded if (a) the consent was withdrawn or (b) they had a penetration-aspiration score of >2 (Rosenbeck et al., 1996) or (c) a pharyngeal residue score of >2 (Neubauer et al., 2015) in any bolus consistency, or (d) had an evident sensory/motoric effort in the swallow of any bolus.

Instrument

The flexible endoscopic system (M/S Atmos Medizinelectronic, Germany) with an 800 X 800 pixel high-definition imaging lens with chip-on-tip technology was used for obtaining FEES data for the current study. The pistol endoscope had a diameter of 3.9mm and a working length of 300mm. The data was captured at 30 frames per second (fps) with synchronized audio throughout the procedure. This formed the baseline for identification of the bolus, onset of the procedure, and instruction-based temporal measure derivation, such as the ‘latency’ measure. The scope was sterilized as per the manufacturer's instructions before and after the procedure. The sterilization was also done under UV for at least five minutes after completing the procedure on each participant. All recorded audio-visual FEES data was stored in .mp4 format. This file was transferred and imported into the analysis software for measuring the temporal points as per the validated definitions established in phase 1.

The Kinovea software (Charmant, 2007), a free open-access frame-by-frame motion-tracking software, was used for the identification of time frames of specific swallow and related events. This software was originally developed for studies on sports medicine and physical rehabilitation for motion analysis (Fernández-González et al., 2020). The .mp4 audio-video file was imported into the Kinovea software, and the exact time points in the playback bar for target frames were identified.

Instructions

Before starting the procedure, the details of the study and procedure were explained to the participant in a language that they comprehend. After obtaining consent, the participants were taken to the endoscopy lab, where further instructions regarding the procedure were provided. Each instruction was verified for comprehension before proceeding.

Before endoscopy: “I am going to slowly start passing this scope through one of your nasal entries. Once we are ready, I will give you a few items like milk, curd, mashed banana, and a biscuit to eat. You need to eat them as you usually do. Shall we proceed?”

During preparation for the endoscopic procedure:

Instruction 1: “Now, I am going to apply a bit of anesthesia in your nose so that you do not sneeze while I pass the scope. Are you ready?”

Instruction 2: "We are ready for the scope now. I am going to start the pass. Try not to move too much while I do this. Please raise your hands in case of any discomfort."

During the endoscopy:

Instruction 1: Say /i/

Instruction 2: "I am going to give you ………… (milk/curd/mashed banana/biscuit). Hold it in your mouth. Swallow when I ask you to do so."

Procedure

The participants were seated comfortably in a chair. The procedure was explained in detail in a language that the participant easily comprehended. After confirming that the instructions are clearly understood, the participant, the scope, and the boluses were prepared in the following steps:

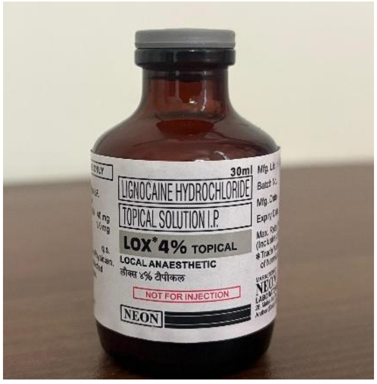
Preparation of the participant:

a) The compliant nostril was identified by asking the client to manually close one nostril at a time and perform a deep inhalation. The same was repeated for the other nostril. The passage that was comparatively clear for breathing was opted for in the scopy.
b) A cotton ball (Fig.1a) dipped in a Lidocaine 4% solution (Fig.1b) was inserted carefully into the chosen nasal passage after clear instructions on the purpose. The same was left in place for at least 3 minutes before the cotton ball, and any mucus was cleared from the nasal passage. The comfort of the participant was ensured at all times.
c) Instructions before the endoscopy were provided regarding the procedure and limitations of head movements.

Figure 1.

Consumables used for participant preparation

(a) Cotton Ball



(b) Lidocaine 4% solution

Preparation of the instrument:

a) A three-step cleaning of the scope was performed before performing the procedure on any participant. Initially, the scope was cleaned with an alcohol swab (Fig.2a), followed by a disinfectant solution (Fig.2b) and lastly under the UV sterilization unit (Fig.2c) for a minimum of 5minutes.
b) The sterilized scope was connected to the ATMOS interface. The recording software was customized for data recording and storage by selecting the destination folder and synchronization of audio-visual recording.
c) A pre-recording check on the camera clarity and light source was performed. Any troubleshooting was done before the scopy procedure.

Figure 2

Materials used for sanitization

(a) Alcohol Swab

(b) Disinfectant Solution

(c) UV Sterilization Unit

d) The participant was required to swallow three bolus consistencies (Fig.3a) and three bolus volumes (Fig.3b) for velar view and glottic view. The bolus consistencies given to the participant were the following:

(i) Thin liquid (IDDSI 1-2)- Milk of volumes 5ml, 10ml, 15 ml

(ii) Honey thick (IDDSI 3-4): Thick curd of volumes 5ml, 10ml, 15 ml

(iii) Puree/semi-solid (IDDSI 5-6): mashed banana of volumes 5ml, 10ml, 15ml

e) All the above boluses were added with green colour food-grade dye (Fig.c) to provide visual contrast in FEES image evaluation. All bolus preparations were done before the scopy, in front of the participant. Care was taken to keep all preparations untouched by hand to ensure food hygiene. The boluses were delivered to the participant in a measurement spoon (5 ml, 10 ml, and 15 ml).

Figure 3

Bolus volumes, consistencies and consumables used for FEES data

(a) Bolus Consistencies (Milk Curd and Mashed Banana)

(b) Three Bolus Volumes (l5ml 10ml 5ml)

(c) Green Food Dye

Endoscopy Procedure:

a) The participant was prepared for the procedure as detailed above.

b) The bolus was prepared for the procedure as detailed above.

c) The instrument was prepared as detailed above.

d) The participant was given instructions before the endoscopy regarding limiting head movements and breathing comfortably through the mouth.

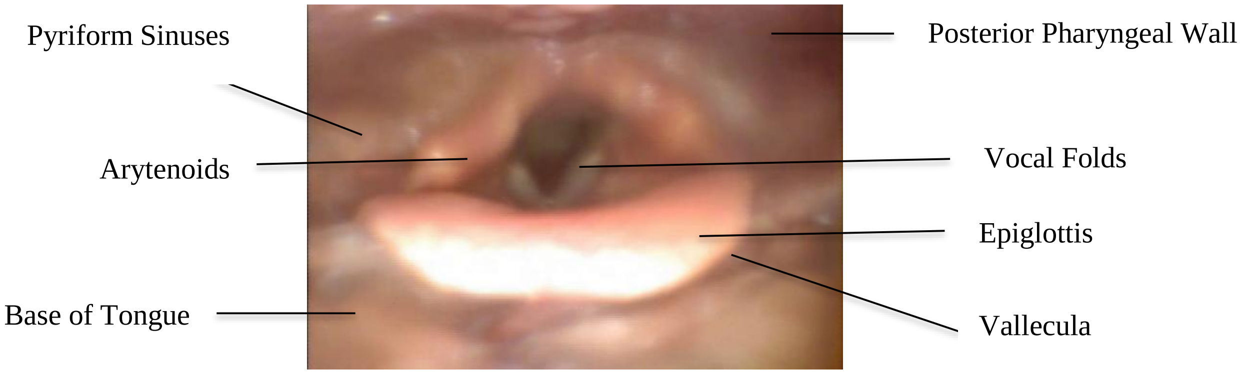
e) A trained FEES clinician performed the endoscopy by passing the scope through the anesthetized nasal passage. As the view approached the nasal side of the velum, the following tasks were performed by the participant with instructions.

  - Phonation of /i/ three times with a break of at least 2 seconds. This ensured that the onset, maximum velar elevation and offset of velar movement were visible.
  - Swallowing tasks: The participant was given bolus consistency, and each volume (a total of nine swallows) was delivered to their mouth using a spoon. They were instructed to hold the bolus in their mouth and to swallow it on the command of “swallow” from the endoscopist. This was done to measure the latency of swallowing.

f) The scope was inserted deeper into the oropharynx to visualize the hypopharynx. The frame of view was considered adequate if the valleculae, laryngeal vestibule, and pyriform sinuses were clearly visible (Figure 4). At this level of scope, the tasks of phonation and swallowing were repeated as described above.

Figure 4

Scope position targeted in the hypopharynx for swallow and phonation tasks



g) After ensuring delivery of all bolus samples, the scope was withdrawn from the upper airway, and the participant's comfort was ensured.

h) The scope was cleaned under running water with disinfectant soap solution, wiped dry with cotton, and placed inside the UV sterilization unit for at least five minutes before the next participant and procedure.

Analysis

The archived endoscopic data was exported as an .mp4 format into another storage device for offline analysis. The file was then imported into Kinovea software for frame-by-frame analysis. The frames indicated as reference points for each temporal measure were manually identified by the investigator. The frames identified for analysis are listed in Table 3 and detailed under the results section. A random set of 10% endoscopic data was re-analyzed by the same investigator after an interval of at least 2 weeks. The data was compared statistically to estimate intra-rater reliability of the measures.

Table 3

Details of the task and frames identified

Task	Function	Frames identified
Phonation	Velar movement	1. Onset of velar elevation 2. First frame of velar contact 3. Last frame of velar contact 4. Offset of velar movement
Phonation	Arytenoid movement	1. Onset of medial movement 2. Last frame of medial movement 3. Onset of lateral movement 4. Last frame of lateral movement
Swallow	Velar movement	1. Onset of velar elevation 2. First frame of velar contact 3. Last frame of velar contact 4. Offset of velar movement
	Pharyngeal Transit Time	1. The frame where the bolus enters the vallecula 2. Last frame where the minimum residue present is the complete swallow

Epiglottic Inversion	1. Onset of Inward Epiglottic movement (Towards Vocal Folds) 2. Partial Epiglottis Inversion (First frame of Whiteout) 3. Outward movement of Epiglottis (Towards Base of Tongue)
Whiteout Duration	1. First frame of whiteout 2. The frame is visible till the structures are visible clearly (minimum of 2 structures)
Spontaneous Response to residue	1. Frame visible till the structures are visible clearly. 2. First frame of whiteout of the second swallow

The following statistical analysis was done to satisfy the objectives of the current study:

- ➢ Cochrane Q test for interrater reliability
- ➢ Shapiro-Wilk's test for data normality check
- ➢ Repeated measure comparisons followed by post-hoc analysis for
    - ○ Comparing the temporal measure across bolus consistencies in 5ml, 10ml and 15ml bolus volumes
    - ○ Comparing the temporal measure across bolus volumes in thin liquid, honey-thick, and puree/semi-solid consistencies

CHAPTER 4

RESULTS AND DISCUSSION

The present study was aimed at developing and standardizing a temporal framework for quantifying swallowing and related events using Flexible Endoscopic Evaluation of Swallowing (FEES). The methodology was implemented in two systematic phases. The first phase developed and validated a standard matrix of temporal measures for phonation and swallowing tasks that are typically incorporated into the FEES evaluation protocol. This phase involved an extensive review of the literature to identify previously reported objective temporal parameters and their operational definitions. A panel of expert judges derived the relevant temporal events using a Delphi-based approach. The identified measures included onset, offset, duration, and latency-based parameters. Existing definitions from the literature, along with newly proposed derivations, were subjected to content validation by seven Speech-Language Pathologists. The definitions that were agreed upon by 80% of judges were finalized for further implementation.

The second phase examined the feasibility of implementing the validated temporal measures in a prospective sample of healthy adults. Twenty-five healthy adults between 18 and 25 years of age who were selected based on inclusion and exclusion criteria underwent FEES evaluation under standardized conditions. Controlled phonation and swallowing tasks were administered during the endoscopic protocol. The recorded endoscopic data were subsequently subjected to frame-by-frame analysis using Kinovea software to derive the temporal outcome measures strictly as per the derived definitions. Reliability of measurement was established through inter- and intra-rater analyses on a subset of the data, and non-parametric statistical methods were employed to compare the temporal measures across different bolus consistencies and volumes. The results of each objective are presented and discussed below.

Standardized definitions of temporal measures of swallow and related events from FEES examinations

Table 4 provides the details of the comprehensive set of temporal measures proposed from FEES evaluations by the Delphi-panel of experts. The frames of reference identified and the method of derivation that was content validated by the expert judges are also indicated. Detailed review of literature on the temporal outcome matrix and its derivational methods revealed considerable methodological variation across studies. Swallowing and related events in FEES evaluation was defined in broad perceptual terms with no specification on the frame of reference (Cordier et al., 2023; Swan et al., 2019). For example, the onset of the phonation task related to vocal cord movement was described as “the first frame showing medial movement of the true vocal cords” (Cooke et al., 1997), or as, “the onset of true vocal fold adduction, (Shiba & Chhetri, 2016), or as “the first frame in which complete contact and closure of the true vocal cords were observed” (Chhetri et al., 2016). Similarly, closure and offset measures were also variably defined across studies, challenging reproducibility and objective implementation of the same definitions for analysis in the current study.

Table 4

Validated definitions and details of the temporal measures of swallowing and related events included in the study

	Frames of reference	Unit of measurement	Validated derivational method and definition
Phonation			

Velar Movement	Onset	milliseconds (ms)	The first frame showing posterior movement of velum after the clinician says "say /i/".
	Maximum elevation	milliseconds (ms)	The final frame showing posterior movement of the velum after the onset.
	Offset	milliseconds (ms)	The final frame showing velum in baseline position after maximum velar movement.
	Velar Elevation	milliseconds (ms)	Derived from final frame showing posterior movement of the velum to first frame showing posterior movement of velum. (Maximum velar movement – Onset)
	Velar Relaxation	milliseconds (ms)	Derived from final frame showing posterior movement of the velum to final frame showing velum in baseline position after maximum velar movement. (Offset - Maximum velar movement)

Arytenoid Movement	Onset	milliseconds (ms)	The first frame on which initial approximation of arytenoids was observed.
	Contact	milliseconds (ms)	The first frame on which complete contact of arytenoids along their inner margin was observed.
	Offset	milliseconds (ms)	The last frame of lateral movement of aretenoid from the most medial position.
	Arytenoid Medial Movement	milliseconds (ms)	The duration from the first frame showing the initial approximation of the arytenoids to the first frame demonstrating complete medial contact of the arytenoids (Contact-Onset).
	Arytenoid Lateral Movement	milliseconds (ms)	The duration from the last frame showing complete medial contact of the arytenoids to the final frame demonstrating lateral movement of the

			arytenoids away from their most medial position (Offset-Contact).
Vocal Cord Movement	Onset	milliseconds (ms)	The first frame that shows medial movement of true vocal cords.
	Contact	milliseconds (ms)	The first frame that shows complete contact of both the true vocal cords.
	Offset	milliseconds (ms)	The last frame of the vocal cords in abduction from the most medial position.
	Time taken for adduction	milliseconds (ms)	The first frame that shows complete contact of both the true vocal cords to first frame that shows medial movement of true vocal cords (Onset-Contact).
	Time taken for abduction	milliseconds (ms)	The duration from the last frame of complete vocal fold closure to the frame showing the vocal folds at their most lateral position (Offset-Contact).
Swallowing			

Velar Movement	Onset	milliseconds (ms)	The first frame showing posterior movement of velum after the clinician says "swallow now".
	Maximum Velar Movement	milliseconds (ms)	The final frame showing posterior movement of velum after the onset.
	Offset	milliseconds (ms)	The final frame showing velum in baseline position after maximum velar movement.
	Time Taken for Elevation	milliseconds (ms)	Derived from final frame showing posterior movement of the velum to first frame showing posterior movement of velum. (Maximum velar movement – Onset)
	Time Taken for Relaxation	milliseconds (ms)	Derived from final frame showing posterior movement of the velum to final frame showing velum in baseline position after maximum velar

			movement. (Offset - Maximum velar movement)
Epiglottic Inversion	Onset	milliseconds (ms)	Frame showing the beginning of epiglottic movement downward over the airway.
	Partial	milliseconds (ms)	The first frame of visualizing the epiglottic rim in contact with posterior pharyngeal wall.
	Offset	milliseconds (ms)	The last frame of anterior movement of epiglottis towards the base of the tongue, after a white out.
	Time Taken for Return of Epiglottis	milliseconds (ms)	The duration from frame showing the beginning of epiglottic movement downward over the airway to last frame of anterior movement of epiglottis towards the base of the tongue, after a white out (Offset - Onset).

Pharyngeal Transit Time	Onset	milliseconds (ms)	The first movement of the head of bolus entering vallecula.
	Offset	milliseconds (ms)	The first frame demonstrates minimal residue after the white-out phase.
	Duration	milliseconds (ms)	The first frame demonstrates minimal residue after the white-out phase to first movement of the head of bolus entering vallecula. (Offset-Onset)
	Number of Swallows		The number of times WO occurred with each bolus.
White Out	Latency of White-out	milliseconds (ms)	The duration between the endoscopist saying "swallow now" to first frame of white-out
	Beginning	milliseconds (ms)	The first image completely obscured by the pharyngeal muscle contraction and subsequent closure of the pharynx

	End	milliseconds (ms)	The first frame in which all laryngeal structures were visible again.
	Duration	milliseconds (ms)	Using the primary swallow, the first frame of complete WO or the closest approximation to complete WO (by consensus) ending when the first frame of the hypopharynx is visualized converted to milliseconds
	Glottis Status Before Swallowing		Whether the glottis was open or closed on the frame just before whiteout.
	Glottis Status After Swallowing		Whether the glottis was open or closed on the frame just after whiteout.
Latency of residue	Response to	milliseconds (ms)	The time duration after the end of a white out resulting in residue post swallow to onset of next white out/ laryngeal adductor reflex.

From the review of literature, one of the major methodological limitations within contemporary FEES-based swallowing research was the absence of standardized operational definitions for temporal swallowing events. Previous investigations have described temporal parameters such as white-out duration (Labeit et al., 2020; Mozzanica et al., 2019; Ohmae et al., 1995; Perlman & VanDaele, 1993), pharyngeal transit time (Daniels et al., 2007; Kendall & Leonard, 2001; Sdravou et al., 2012), epiglottic inversion (Ohmae et al., 1995), bolus dwell time (Butler et al., 2009; Butler et al., 2011), and vocal fold movement (Perlman & Van Daele, 1993; Ohmae et al., 1995). There was substantial variability in the derivational methods of the FEES-derived temporal measures (Labeit et al., 2020; Mozzanica et al., 2019; Ohmae et al., 1995; Perlman & VanDaele, 1993). While some authors have specified onset and offset points using specific anatomical or physiological landmarks (Molfenter & Steele, 2012), others have relied on broader perceptual descriptions with no clear indication of reference frames (Butler et al., 2009; Perlman & Van Daele, 1993). Such methodological inconsistencies compromised reproducibility, limited comparability across studies, and contributed to inter- and intra-rater variability in temporal measurements (Kelly et al., 2006; Neubauer et al., 2019). This diminished the potential advantages of quantifying FEES by inducing heterogeneity in measurement, emphasizing subjective interpretation, and lack of methodological standardization (Baijens et al., 2016; Prikladnicki et al., 2022).

The present study addressed this gap by developing a comprehensive matrix of FEES-based temporal swallowing measures through a structured Delphi consensus process. In contrast to previous investigations that focused on isolated physiological parameters (Butler et al., 2009, 2011; Mozzanica et al., 2018; Sutton et al., 2024), the current study sought to establish a physiologically driven, comprehensive, integrated framework for the purpose of quantification of swallowing and related events observable during FEES examination. The finalized matrix included measures related to velar movement, arytenoid movement, vocal fold movement, epiglottic inversion, pharyngeal transit time, white-out events, spontaneous responses to residue, and glottic status before and after swallowing (Table 4). All retained measures achieved agreement from at least 80% of the expert panel, indicating consensus regarding their physiological relevance, clinical importance, and potential contribution to the assessment of swallowing safety and efficiency.

A notable strength of the present study was the use of clearly identifiable onset and offset frames anchored to observable anatomical and physiological landmarks for the purpose of quantification of FEES data. The operational definitions developed in the current study were scrutinized at multiple levels of the delphi panel for maximum clarity, objectivity, and clinical applicability while minimizing ambiguity during frame-by-frame analysis. Emphasis was placed on selecting landmarks corresponding to discrete physiological events, including movement initiation, structural contact, complete closure, maximal excursion, and release phases. Such an approach is critical for accurate temporal analysis as minor inconsistencies in landmark identification can impede measurement reliability. Establishing these precise operational definitions was a critical step toward improving reproducibility and reducing observer-dependent variability in FEES-based quantification.

Traditionally, FEES has primarily relied on perceptual rating systems to evaluate swallowing safety and efficiency, including scales for penetration-aspiration, secretion severity, and pharyngeal residue (Butler et al., 2009; Furkim et al., 2019; Langmore, 2008; Murray et al., 1996; Neubauer et al., 2019; Rosenbek et al., 1996). In contrast, objective temporal analysis has been more extensively explored using other instrumental evaluations such as videofluoroscopic swallow studies and manometry (Cook et al., 1989; Kahrilas et al., 1992; Kendall et al., 2000; Logemann, 1998; Martin-Harris & Jones, 2008; Martin-Harris et al., 2005; McConnell et al., 1990). Although perceptual scales provide clinically meaningful information regarding swallowing safety (Logemann, 1998; Rosenbek et al., 1996; Kendall et al., 2000; Martin-Harris et al., 2005) and swallowing efficiency (Daniels et al., 2004; McCullough et al., 2001; Steele & Grace-Martin, 2007), they are primarily expert clinical judgments. These perceptual scores may not fully capture the dynamic temporal organization of swallowing physiology. Temporal quantification enabled the measurement of event onset, duration, latency, sequencing, and coordination. Such measurements may facilitate the identification of subtle physiological variations that are not readily evident through perceptual evaluation alone and may ultimately contribute to distinguishing normal physiological variability from pathological swallowing behavior.

The broader significance of establishing standardized temporal definitions extends beyond the reliability of measurement in the current study. A unified framework for temporal analysis, such as that developed in the current study, enables inferentiality and meaningful comparison across studies. These definitions may be useful in facilitating estimation of any normative reference data, and strengthens the methodological rigor of future FEES-based research. The integration of objective physiological metrics with established functional rating scales may potentially enhance diagnostic precision, improved clinical decision-making, treatment planning, monitoring of therapeutic outcomes, and objective documentation of swallowing performance.

The current literature on FEES-based temporal quantification remains limited and fragmented with most studies examining individual physiological events in isolation. For the purpose of the current study, novel operational constructs had to be proposed along with the fragmented literature for obtaining expert consensus and physiological reasoning. However, the practical implementation of these measures tend to be influenced by factors inherent to FEES examination, including bolus trials, endoscope positioning, anatomical variability, and individual variability. These factors highlight the need for continued refinement and validation of the proposed framework.

Comparison of temporal measures of swallow-related events across bolus characteristics

The second objective of the current study was to validate the temporal matrix by evaluating the temporal characteristics of FEES events across different standardized bolus using frame-by-frame analysis of FEES studies from healthy adults. Twenty-five participants were subjected to the FEES procedure in this study. Two data sets were excluded from the analysis due to significant deviations in performance due to intolerance, anxiety and atypical swallowing physiology during examination resulting in a final dataset of 23 individuals. The FEES recordings were obtained using standardized bolus consistencies (IDDSI Levels 1, 3 and 5) and standardized bolus volumes (5ml, 10ml, and 15ml).

The validated matrix developed in Phase I was implemented to derive objective temporal measures. Using Kinovea software, frame-by-frame analysis was carried out and temporal measures were estimated in milliseconds. The analysis aimed at identifying the time frame of specific target frames as identified in phase 1. The duration and latency measures were derived from the target time frames and were used for comparisons to meet the objectives of this study.

A random 10% of the data (n=3) were reanalyzed by the same investigator to establish intra-rater reliability with intra-class correlation. The results revealed that the values of ICC ranged from 0.5 to 1.00 suggesting moderate to excellent agreement across the two ratings. Analyzing the raw data, not all frames of reference for temporal measures could be derived for all individuals, and for all boluses. There were substantial differences and heterogeneity in the number of available data for each temporal outcome considered for the study. The unequal distribution was primarily because of non-visualization of specific time frames in FEES data due to procedural and physiological variations. Visualization of specific landmarks and time frames were obscured by bolus material during endoscopic recording. Also, the transient and rapid nature of specific physiological events (for example, epiglottic inversion) limited the ability to capture all temporal frames consistently. To avoid any data dilution, the investigators strictly relied on validated definitions and specific time frames. This resulted in missing data points and unequal data distribution across measures. This may have limited the inferentiality of statistical comparisons, and also emphasize the need for further research with larger sample size and protocol controlled methods of experimentation. As the current study was taken up as a ‘proof-of-concept’ and feasibility study, the primary objective of phase 2 was to explore the feasibility of temporal quantification and its nature across related factors

Descriptive statistical measures (mean, median, standard deviations, interquartile deviations, minimum, maximum and range) were computed for all outcome measures Tests of normality with Shapiro-Wilk’s test revealed that the data were not normally distributed ($p>0.05$). Therefore, non-parametric statistical methods were employed for further analysis. The Friedman test was used to run within-group comparisons across different bolus consistencies and volumes. Post hoc pairwise comparisons were performed using the Wilcoxon signed-rank test for multiple comparisons. The results of the statistical comparison are described below for each specific FEES event.

Comparison of velar and glottic movement measures during phonation task

The study included velar movement (VM), arytenoid movement (AM) and true vocal cord movements (VC) during phonation of the vowel /i/ for quantification and comparison. Table 4 provided the guidelines for the identification of specific time frames of onset and offset of specific events. The time durations for velar elevation, velar relaxation, medial movement of the arytenoid, lateral movement of the arytenoid, medial movement of the true vocal cords, and lateral movement of the vocal cords were derived as per these validated definitions. The descriptive statistics of each of these measures are presented in Table 5.

Table 5

Descriptive Statistics of the Velar, Arytenoid and Vocal Fold Movement During Phonation Task

Temporal measure	n	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
Velar_ Elevation	21	246.35 (129.00)	281.01 (130.67)	82	681	598
Velar_Relaxation	21	200.78 (168.00)	242.14 (153.00)	83	674	591
Arytenoid_Medial	21	205.29 (105.00)	228.61 (124.78)	80	530	449
Arytenoid_Lateral	21	291.95 (282.00)	406.47 (245.36)	124	1018	894
Vocal Cord_Medial	21	205.29 (153.00)	244.06 (132.05)	80	570	490
Vocal Cord_Lateral	21	289.96 (379.00)	413.45 (245.99)	124	1018	894

Note: SD- Standard Deviation, IQD- Interquartile deviation

From Table 5, the longest durations were observed for lateral movement of the vocal cord (median = 289.96 ms, IQD = 379 ms) and arytenoid (median = 291.95 ms, IQD = 282 ms). The mean values followed a similar trend (Vocal cord_Lateral: M = 413.45 ms, SD = 245.99; Arytenoid_Lateral: M = 406.47 ms, SD = 245.36). As is evident from the table, there was considerable variability across all temporal measures indicated by the large standard deviations and ranges. The greatest variability was noted for lateral movements of the arytenoid and vocal cord rather than the medial movements. Velar movements during phonation also exhibited considerable variability. Minimum dispersion was obtained in the medial arytenoid medial movement compared to the remaining measures.

The large dispersion of these temporal measures in the healthy cohort suggests the typical adaptability and dynamic nature of the quantified events during the phonation task. The findings support the notion that swallowing measures should be interpreted as norm reference ranges rather than norm reference values. Wilcoxon's signed-rank test was run to explore the differences across these highly adaptable measures. Comparisons were made across velar elevation and relaxation; medial vs lateral arytenoid and vocal cord movement. The results revealed no significant difference across the duration of velar elevation and relaxation in the phonation task ($Z = -1.20$, $p = 0.23$). In contrast, there was a significant difference across the duration of the medial and lateral arytenoid ($Z = -2.937$, $p = 0.00$) and vocal cord ($Z = -2.56$, $p = 0.01$) movements. From Table 5, the duration of lateral arytenoid and vocal cord movements was longer than that of medial movements during phonation.

The above results on the temporal characteristics of velar, arytenoid, and vocal fold movements during a phonation task determined if the opposing movement durations differed from each other significantly. The absence of any significant difference between the duration of velar elevation and velar relaxation suggested the comparable time periods during the elevatory and lowering phases of velar movement during phonation. Physiologically, velar movement is thought to be governed by a combination of active muscular contraction and passive biomechanical forces (Inouye et al., 2016; Perry, 2011). Elevation of the velum and velopharyngeal closure is achieved through coordinated activation of the palatal muscles during speech production (Niimi et al., 1982; Perry et al., 2015). Following active elevation, relaxation of the velum may be facilitated by passive mechanisms such as elastic recoil of the soft palate and gravitational influences (Berry et al., 1999; Zhu et al., 2012) for return to its resting position. The balance between active elevation and passive descent may be indicated by the comparable durations observed for these opposing phases in the current study. The neuromuscular and biomechanical processes that guide velopharyngeal movement during phonation are temporally well-coordinated and symmetrical in healthy individuals during a phonation task.

In contrast, lateral movements of the arytenoid and vocal cords demonstrated significantly longer durations than medial movements, and the difference was statistically significant. Physiologically, medial movement during phonation represents an active neuromuscular-driven process that activates the intrinsic laryngeal adductor muscles for rapid and precise glottic closure (Hirano & Bless, 1993; Ludlow, 2005). Healthy phonation demands timely vocal fold approximation and stabilization of the glottis, corresponding to rapid medial movement of these structures. Previous investigations have demonstrated that arytenoid medial rotation initiates glottic closure (Chhetri et al., 2012; Hirano & Bless, 1993; Titze, 2000). However, we extend this statement to state that complete vocal fold approximation continues beyond arytenoid contact and involves further medial compression of the vocal folds. This is evident from the larger range of temporal duration for medial movement of vocal cords compared to that of arytenoid. Arytenoid movement may represent the primary structural approximation of the larynx (Alipour & Scherer, 2000; Chhetri et al., 2012; Hirano, 1974), but the active vocal fold closure requires an additional neuromuscular refinement mediated by the intrinsic laryngeal musculature (Ohmae et al., 1995; Van Daele et al., 2005; Chhetri et al., 2012; Hirano, 1981; Stemple, 2000).

Lateral movement of the arytenoid and vocal folds are the transition from an actively maintained adducted medial configuration to a more relaxed and open laryngeal posture (Ludlow, 2005; Shiba & Chhetri, 2016; Titze, 2000). Compared to medial closure, this lateral phase is likely influenced by the passive release of muscular contraction, tissue elasticity, and biomechanical recoil of the laryngeal framework. Generally, the reopening of glottis may occur more gradually, resulting in longer movement durations. The observed temporal asymmetry between medial and lateral movements therefore highlights an important physiological distinction between active neuromotor mechanisms responsible for glottic closure and the comparatively passive processes involved in laryngeal reopening.

From a methodological perspective, these findings provide preliminary evidence that FEES-based temporal measurements are capable of capturing physiologically meaningful differences between distinct movement phases of upper airway structures. While velar movements demonstrated temporal symmetry, arytenoid and vocal fold movements exhibited systematic differences that may be characteristics of phonatory function. Establishing these normative temporal relationships was important for future studies investigating whether neurological, structural, or functional disorders alter the timing, coordination, or efficiency of velopharyngeal and laryngeal movements.

Comparison of velar and glottic movement measures during swallow

Multiple durational measures were studied during the swallowing task, from the predefined definitions. Each measure was compared across bolus consistency and bolus volume using Friedman's test. Any significant difference at p <0.05 was debugged, with pairwise comparisons using the Wilcoxon signed-rank test. The result of the comparison across bolus characteristics for each temporal measure is detailed below.

a. Epiglottic Inversion

Table 6 provides the descriptive statistics for epiglottic inversion during swallows of varied bolus volumes and consistencies as derived from the pre-validated definition in phase 1 of the study. The frames of reference were observable in 95.45 % of thin liquid swallows in 5ml, 86.36 % of thin liquid swallows in 10ml, 77.27 % of thin liquid swallows in 15ml. 90.91 % of puree in 5ml, 86.36 % of puree in 10ml, 86.36 % of puree in 15ml, 90.91 % solid in 5ml, 81.82 % solid in 10ml and 86.36 % solid in 15ml. With increase in bolus volume and consistency, the frames of reference for epiglottic movement were less visible. The bolus covered the epiglottic rim and structures making the frame of initiation of movement less reliable. Also, the large volumes seemed to initiate white-out before the epiglottic movement, and the frame of reference for epiglottic inversion was mostly masked in the white-out phase for large volume swallows.

Table 6

Descriptive Statistics of the Epiglottic Inversion Across Bolus Volumes and Consistencies.

Temporal Measures	n	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
5ml Milk	21	968.95 (376)	1013.47 (271.91)	439	1587	1147
5ml Curd	20	968.40 (327)	1011.55 (252.37)	621	1533	912
5ml Banana	20	915.44 (438)	994.65 (416.74)	366	1927	1561
10ml Milk	19	961.11 (331)	960.13 (218.54)	584	1409	826
10ml Curd	18	1059.06 (544)	1072.46 (339.38)	590	1848	1258
10ml Banana	19	976.22 (428)	1001.55 (257.97)	599	1533	934
15ml Milk	17	1101.58 (253)	1120.49 (182.88)	799	1455	656

15ml Curd	19	1042.97 (449)	1093.97 (299.79)	714	1799	1086
15ml Banana	19	1077.81 (711)	1225.72 (710.16)	463	3640	3177

Note: SD- Standard Deviation, IQD- Interquartile deviation

From table 6, the mean and median values of epiglottic movement had a wide range of variability in all consistencies and volumes, suggesting heterogeneity and individual variability which is innate to swallowing. The highest and lowest median duration of epiglottic movement was observed for the 15 ml milk bolus (Median = 1101.58 ms, IQD = 253 ms), and 5 ml banana bolus (Median = 915.44 ms, IQD = 438 ms) respectively. Comparing within volumes, the median durations were relatively comparable across consistencies for 5ml boluses, ranging from 915.44 ms for banana to 968.95 ms for milk. Among these conditions, the 5 ml banana bolus demonstrated the greatest variability (Range = 1561 ms). In 15 ml boluses, median values ranged from 1042.97 ms to 110.581 ms, and the highest and lowest variability was in 15ml banana (range= 3177) and 15ml milk (range= 656) respectively. From the descriptive statistics, preliminary indication of interaction between bolus consistency and volume was evident. Generally, as the volume or consistency increased, variability in epiglottic inversion measure increased.

The observations of descriptive statistics were tested statistically with Friedman test across bolus consistencies. No significant difference across milk, curd and banana boluses in 5ml ($\chi^2(2) = 0.027$, $p = 0.99$), 10ml ($\chi^2(2) = 0.125$, $p = 0.94$), and 15ml ($\chi^2(2) = 0.441$, $p = 0.80$) volumes. Similarly, there was no significant difference across bolus volumes in the curd ($\chi^2(2) = 1.279$, $p = 0.53$), and banana ($\chi^2(2) = 5.148$, $p = 0.08$) consistencies, while the thinner bolus (milk) showed a statistically significant difference across bolus volumes ($\chi^2(2) = 8.373$, $p = 0.02$). Paired comparisons across bolus volumes using Wilcoxon's sign rank test in thin liquid consistency a statistically significant difference between the 10ml and 15ml volumes ($Z = -2.499$, $p = 0.01$) only.

From table 6, the median epiglottic movement duration for 5ml and 10ml thin liquid bolus was comparable, while the median was higher for 15ml bolus of the same consistency. The absence of significant difference across 5ml and 15ml thin-liquid bolus may be related to the large inter-quartile deviation across these volumes. Therefore, the duration of epiglottic inversion increased significantly with increase in bolus volume, especially in thin-liquids.

Swallowing is a highly adaptable sensorimotor behavior that continuously adjusts to sensory, environmental and overlapping demands. Previous research on epiglottic kinematics and airway-protection mechanisms has also demonstrated large inter-subject variability in swallowing. The large deviations in quantifiable measures are being increasingly recognized as a characteristic feature of normal swallowing physiology rather than a dysfunction marker (Pearson et al., 2016; Steele et al., 2019). The large range of duration of epiglottic inversion obtained in this study may represent physiological flexibility and dynamic nature of airway-protection strategies in healthy swallows, rather than inconsistency of performance.

A general trend of increasing epiglottic inversion duration with increasing bolus volume and consistency swallows in healthy individuals was evident in the results of this study. Although statistical differences were observed across thin-liquid volumes only, the overall pattern suggested that this measure adapted to the increasing biomechanical and airway-protection demands of challenging boluses. Previous studies have revealed that the risk of airway intrusion increased with volume (Butler et al., 2011; Butler et al., 2010). Healthy individuals therefore may adapt to this challenge with more robust and sustained airway-protective responses. The longer duration of epiglottic inversion observed during larger-volume swallows may therefore represent an adaptive mechanism that maintains laryngeal vestibule closure for an extended period during pharyngeal transit of the large bolus.

The physiological significance of this finding lies in the contribution of epiglottic inversion to airway protection. Inverted epiglottis temporarily disconnects the lower airway from pharyngeal cavity and redirects bolus away from the laryngeal inlet during pharyngeal swallow. However, the current understanding indicates that the epiglottic inversion is not an independent motor event (Pearson et al., 2016). It is widely recognized as a passive biomechanical consequence of hyolaryngeal excursion, tongue base retraction, and pharyngeal constriction (Ekberg, 1982; Logemann, 1998; Pearson et al., 2013; Steele et al., 2016). Temporal changes in epiglottic inversion may hence reflect adaptive modifications occurring elsewhere within the swallowing system. Support to this assumption can be derived from the changes in biomechanical measures of these physiologies reported by previous researchers (Dantas et al., 1990; Lazarus et al., 1993; Molfenter & Steele, 2013; Steele & Van Lieshout, 2004). Demand for greater anterior-superior hyoid movement (Dantas et al., 1990; Molfenter & Steele, 2013), stronger tongue base retraction (Butler et al., 2009; Steele & Van Lieshout, 2004), and enhanced pharyngeal driving forces (Dantas et al., 1990; Lazarus et al., 1993) may be higher with larger and thicker boluses. These physiological adjustments may indirectly influence the duration of epiglottic inversion observed during swallowing, as observed in the current study.

Epiglottic inversion could be effectively quantified in a subset of swallows only. Thinner consistencies and smaller bolus volumes provided the visualization of frames of reference more consistently, as the frames clearly occurred before and after a white-out event. In larger-volume swallows, rapid initiation of airway-protection mechanisms and probably an earlier white-out frequently obscured the reference frames required for deriving the measures of epiglottic movement. This highlights an inherent limitation of FEES-based temporal analysis. Overall findings indicated that epiglottic inversion duration was sensitive to bolus-dependent physiological adaptations. Thinner consistency and small volume boluses exhibited shorter duration of epiglottic inversion and larger boluses had prolonged inversion. This may be related to increased airway-protection demands with increasing consistency and volume. These findings reinforce the concept of quantifying the epiglottic inversion as a clinically important marker underlying safe swallowing. It may have to be interpreted alongside other measures of hyolaryngeal and pharyngeal function for clinical purposes.

b. Pharyngeal Transit Time

Table 7 represents the descriptive statistics of the Pharyngeal Transit Time derived across bolus consistencies and volume. Similar to epiglottic inversion measure, there was large dispersion of this measure, as derived from FEES imaging data. The variability in

Table 7

Descriptive Statistics of the Pharyngeal Transit Time Derived Across Bolus Volumes and Consistencies

PTT	n	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
5ml Milk	22	818.36 (245)	805.25 (170.99)	399	1072	673
5ml Curd	20	772.98 (341)	810.75 (209.00)	532	1263	732
5ml Banana	21	758.91 (704)	1057.01 (602.65)	531	2604	2073
10ml Milk	19	818.03 (260)	781.66 (206.27)	159	1016	857

10ml Curd	20	813.51 (329)	872.90 (253.15)	531	1408	877
10ml Banana	19	896.13 (313)	957.39 (377.46)	532	2233	1701
15ml Milk	17	832.71 (219)	1163.83 (964.74)	679	4142	3463
15ml Curd	19	773.08 (261)	806.88 (196.41)	531	1201	670
15ml Banana	21	832.71 (512)	1099.86 (952.05)	455	4953	4497

Note: SD- Standard Deviation, IQD-Interquartile deviation

performance increased with increasing volume (For example, 5ml milk:673; 10 ml milk: 857; 15ml milk: 3463) and consistency (For example, 5ml milk: Range = 673; 5ml curd: Range= 732; 5ml banana: Range= 2073), though the median pharyngeal transit appeared less influenced by bolus characteristics. These findings may suggest that both bolus volume and consistency influence pharyngeal transit time inducing larger variability in healthy swallowing performance.

Comparing the median using Friedman's test across bolus consistencies, there were no significant differences in 5ml ($\chi^2(2) = 2.083$, $p = 0.353$); 10ml ($\chi^2(2) = 1.164$, $p = 0.559$) and 15ml boluses ($\chi^2(2) = 0.677$, $p = 0.597$) . Similarly, there were no significant differences across bolus volumes in milk ($\chi^2(2) = 1.033$, $p = 0.597$), curd ($\chi^2(2) = 0.542$, $p = 0.762$), and banana ($\chi^2(2) = 0.261$, p = 0.878)boluses, supporting the descriptive observations from Table 7.

Pharyngeal transit time (PTT) is traditionally considered as the duration required for bolus passage through the pharynx and is an integrated measure of sensory input, pharyngeal propulsion drive, airway protection mechanism, and upper esophageal sphincter function (Dodds et al., 1989; Logemann, 1998; Perlman et al., 1994). In the present study, the PTT was calculated as the duration between the first frame of entry of bolus into the pharynx till the first frame after white-out event. Descriptive analyses revealed significant variability in PTT across healthy participants, with the magnitude of variability increasing with bolus volume and consistency. Although healthy individuals achieve successful pharyngeal bolus transport across a variety of swallowing conditions, the physiological strategies employed to accomplish this task may differ considerably between individuals (Humbert & Robbins, 2007; Molfenter & Steele, 2011; Steele & Cichero, 2014).

The pharyngeal transit time has been shown to vary with position (Cook et al., 1989; Rasley et al., 1993), bolus (Dantas et al., 1990; Lazarus et al., 1993), age (Robbins et al., 1992; Tracy et al., 1989), and other systemic factors (Logemann et al., 2000; Perlman et al., 1994). Few other reports have contradicted this by reporting stable transit times despite variations in bolus volume and consistency (Logemann, 1998; Martin-Harris et al., 2005; Steele et al., 2019). In the current study, the median PTT remained relatively stable across bolus consistencies and volumes. Statistical analysis further confirmed the absence of significant differences across consistencies at 5 ml, 10 ml, and 15 ml volumes, as well as across volumes within milk, curd, and banana boluses. These findings indicated that the swallowing physiology of healthy individuals were capable of accommodating changes in bolus characteristics while maintaining overall temporal efficiency of pharyngeal transit, as per the derivational methods used in this study. Stable PTT may suggest the highly adaptive nature of the pharyngeal swallow in healthy adults despite changes in sensory-motor demands. Modifications in one physiological component may be compensated by adjustments in others, resulting in preservation of overall transit timing (Logemann, 1998; Molfenter & Steele, 2012; Steele et al., 2019).

An important observation in the present study was the dissociation between central tendency (median) and variability (range). While median values remained relatively unchanged, the increasing ranges observed with larger volumes and more complex consistencies suggest greater diversity in individual swallowing adaptations. Semisolid boluses (banana, in the current study) demonstrated the greatest variability probably as they require bolus preparation, lingual control and forceful lingual propulsion, real time accurate sensory processing, and pharyngeal drive (Dantas et al., 1990; Humbert & Robbins, 2007; Palmer et al., 1992; Steele & Van Lieshout, 2004). The multiple processes may provide room for multiple equally effective swallowing strategies to emerge among healthy individuals. These adaptive responses may contribute to the wider distribution of values without necessarily altering the median performance of the group. Such findings further emphasize the need for normative data that capture both central tendencies and the natural variability inherent in healthy swallowing performance.

c. Latency of Whiteout

The descriptive data on the latency of white-out derived as per the pre-validated definitions for varied bolus types are presented in Table 8. Median latency values ranged from 41 ms to 83 ms with relatively comparable values across most bolus types among healthy adults. Despite the stability in median values, a significant range of measurement was observed in the outcome measure, indicating the degree of variability across bolus. In the 5 ml and 10ml boluses, thicker consistency (banana) demonstrated greater variability (5ml: Range = 2413 ms, 10ml: Range= 1140 ms) while in higher volumes milk demonstrated the greatest variability (15ml milk: Range = 3357 ms). Large discrepancies between mean and median values were observed in several bolus conditions suggesting skewed distributions and intersubject variability in swallow.

Unlike other temporal measures, there were instances of 0 msec latency of white out, that suggested immediate initiation of pharyngeal swallow on cue. These instances were relatively frequent for thicker boluses (curd and banana). Greater inter-participant variability was also observed for thicker bolus and larger volumes, suggesting increased diversity in swallowing performance across participants under these conditions.

Table 8

Descriptive Statistics of the Latency of Whiteout Measure Across Bolus Volume and Consistencies

Temporal Measures	N	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
5ml Milk	19	82.36 (44)	111.85 (82.51)	38	328	290
5ml Curd	14	79.80 (41)	97.48 (111.15)	41	466	425
5ml Banana	13	41.71 (104)	300.32 (668.42)	0	2413	2413
10ml Milk	16	81.50 (212)	141.74 (131.59)	40	466	426
10ml Curd	15	40.91 (123)	137.41 (195.04)	0	621	621
10ml Banana	12	82.93 (297)	2298.77 (326.09)	40	1180	1140
15ml Milk	11	80.31 (84)	386.27 (999.69)	40	3397	3357
15ml Curd	13	81.47 (161)	117.10 (111.05)	0	339	339
15ml Banana	10	60.55 (248)	157.46 (160.46)	41	506	465

Note: SD-Standard Deviation, IQD- Inter-quartile deviation.

Friedman's test revealed no significant differences in latency of white-out across bolus consistencies at 5 ml ($\chi^2(2) = 0.960$, $p = 0.619$), 10 ml ($\chi^2(2) = 0.800$, $p = 0.670$), and 15 ml ($\chi^2(2) = 3.714$, $p = 0.156$). Similarly, no significant differences were observed across bolus volumes for milk ($\chi^2(2) = 0.065$, $p = 0.968$), curd ($\chi^2(2) = 0.222$, $p = 0.895$), or banana ($\chi^2(2) = 2.800$, $p = 0.247$).

Latency of white-out was derived as the interval between verbal cue to swallow, and the onset of white-out. This was expected to reflect the temporal relationship between bolus transfer and the onset of pharyngeal constriction associated with swallowing. In the present study, median latency values remained relatively stable across bolus types and the same was confirmed statistically as not significantly different. This may indicate that healthy adults were capable of initiating swallow reflex with no interference from the sensory-motor demands of the bolus.

Swallow initiation is mediated by an integrated sensorimotor network that continuously monitors and adapts to changing bolus properties without affecting the swallowing safety and efficiency. Previous investigations have also reported accommodation of bolus characteristics without significant alterations in key swallowing measures (Kendall et al., 2000; Logemann, 1998; Martin-Harris et al., 2005; Molfenter & Steele, 2012; Palmer et al., 1992; Robbins et al., 2008; Steele et al., 2009). The findings of this study complement the previous reports and offer further support to the stability of latency of white-out measures in healthy swallowing.

Similar to the other measures, there was substantial variability associated with this measure as well. While the pattern of changes across bolus characteristics was relatively consistent in the other measures, the variations in latency of white out increased with consistency in 5ml and 10ml boluses, whereas the same reduced with increase in volume in thicker boluses. Statistically, these differences did not reach a level of significance, probably because of the large variability.

The occurrence of zero-latency events suggest that pharyngeal swallow was initiated almost at the same time as the cue. This may be possible if the bolus was already in or almost into the pharynx (posterior holding). The process model of swallow for solid boluses supports this physiological behaviour in healthy individuals, where cohesive bolus (such as curd and mashed banana in the current study) is held in the posterior oral cavity (sometimes in the valleculae) before swallow reflex is triggered (Hiiemae & Palmer, 1999; Matsuo & Palmer, 2008). This indicates highly efficient bolus control in the oro-pharyngeal stage of swallow, and subtle errors in this phenomenon can increase the risk of airway intrusion (Matsuo & Palmer, 2008; Steele & Miller, 2010).

Together, these findings suggested that latency of white-out was characterized by stable median measures, but considerable inter-individual variability in healthy adults. Bolus characteristics did not appear to substantially influence this temporal measure, but the effects may be masked statistically by the large dispersion. However, the general trend of the measure of latency included increase in latency with consistency in 5ml and 10ml boluses, but decrease with consistency in 15ml boluses.

d. Duration of Whiteout

Table 9 provides the descriptive statistics measures for the duration of white-out across varied bolus conditions. Similar to the other measures,

Table 9

Descriptive Statistics of the Duration of Whiteout Across Bolus Volumes and Consistencies

Temporal Measures	N	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
5ml Milk	22	705.95 (197)	715.99 (175.55)	399	1099	699
5ml Curd	22	730.77 (258)	752.55 (204.41)	529	1264	735
5ml Banana	21	695.32 (274)	675.34 (206.35)	169	1026	857
10ml Milk	19	697.98 (211)	721.39 (146.93)	522	1084	562

10ml Curd	18	775.61 (251)	783.09 (228.79)	442	1264	822
10ml Banana	19	829.08 (186)	841.76 (169.99)	532	1264	732
15ml Milk	17	736.38 (118)	755.03 (87.09)	593	934	342
15ml Curd	17	722.60 (273)	790.73 (164.34)	595	1109	514
15ml Banana	20	743.07 (371)	790.51 (297.94)	450	1700	1250

Note: SD- Standard Deviation, IQD-Interquartile Deviation

Table 9 represents descriptive statistics of the duration of whiteout across different bolus volumes and consistencies. From this table, the white-out duration had relatively comparable median values across most swallowing conditions with no clear pattern of variation across volume or consistency. However, the range of value for this measure was wide, indicating the degree of variability of duration of white-out in healthy swallows. Generally, the variability in duration of white-out increased with complex boluses i.e. larger volume and consistency. As is evident from the table, 15ml banana had the largest variability of duration of white-out (range=1250 ms). This may be related to the high demand for safe pharyngeal clearance of semi-solid bolus during swallow.

Friedman's test revealed no significant differences in white-out duration across bolus consistencies at 5 ml ($\chi^2(2) = 1.171$, $p = 0.557$), 10 ml ($\chi^2(2) = 4.000$, $p = 0.135$), and 15 ml ($\chi^2(2) = 1.720$, $p = 0.423$) or across bolus volumes in thin ($\chi^2(2) = 3.500$, $p = 0.174$) and thicker liquid ($\chi^2(2) = 1.968$, $p = 0.374$) . A significant effect of bolus volume was observed in semi-solid bolus swallows ($\chi^2(2) = 7.015$, $p = 0.030$). Subsequent pairwise comparisons revealed a significant difference between 10ml and 15ml volumes ($Z = -2.722$, $p = 0.006$) with the duration being longer for 10ml.

White-out duration represents the period of complete endoscopic obscuration during pharyngeal swallowing. Although the precise physiological contributors to white-out event remain debatable, it is generally considered to depict the integrated activity of pharyngeal constriction, tongue base retraction, hyolaryngeal excursion, and airway protective mechanisms occurring during the pharyngeal phase of swallowing (Langmore, 2001; Leder & Murray, 2008). Presence of white out is understood as presence of pharyngeal swallow reflex (Kelly et al., 2006; Langmore, 2001). Duration of white-out was hence expected to indicate the duration of pharyngeal swallowing activity as observed during FEES evaluation.

The median duration of white-out during swallow was relatively stable across bolus conditions in healthy individuals. Such stability may be attributable to physiological adjustments during the complex process of swallow to preserve the overall swallowing efficiency and airway protection. Though the median measure was relatively stable, the pattern of change in the variability of this measure is noteworthy. The variability within this measure increased with large volume, thick bolus swallows, 15ml banana bolus in the current study. The demand for precise oral processing, bolus manipulation, and coordinated oro-pharyngeal propulsion drives for complete and safe clearance in semisolid bolus (Matsuo & Palmer, 2008; Steele et al., 2015). The complexity of the process may permit multiple effective swallowing strategies among healthy individuals, resulting in greater inter-participant variability.

White-out duration differed significantly between 10 ml and 15 ml banana boluses, with 10ml bolus showing prolonged duration of white-out compared to the 15ml bolus. At this point of the study, it can only be assumed that the shorter duration of white-out in 15ml banana may be linked to the possibility of piece-deglutition for large and thick bolus among healthy individuals. The current study did not include specific instruction to clear the bolus in one swallow, neither was multiple swallow data eliminated during data analysis. The first swallow was included in the analysis for all measures. It is possible that the large bolus semi solid swallow was broken down to multiple swallows, which may have divided the bolus volume into smaller portions (Dantas et al., 1990; Hiss et al., 2004; Logemann, 1998). The duration of whiteout may adapt to modified bolus volumes (Kelly et al., 2007; Leder & Murray, 2008). It is also worthy to discuss that bolus consistency alone may not alter the duration of white-out in healthy adults. Interactions between bolus volume and consistency may become more relevant when swallowing demands increase, and this needs to be explored further in future.

The findings of this outcome measure suggest that white-out duration is a relatively stable temporal characteristic of healthy swallowing. This measure is sensitive to changes in bolus volume and/or consistency. The significant volume-related differences observed within banana swallows and the marked variability across participants may mask the subtle physiological adaptations in this measure. These findings support the inclusion of white-out duration within the broad framework of quantitative FEES analysis.

e) Number of Swallows

Table 10 provides the descriptive statistics of the number of swallows per bolus across different bolus volumes and consistencies. As per the pre-validated definitions, this was derived based on the number of white-out events per bolus. From this table, healthy adults performed a median of one or two swallows to clear the bolus efficiently irrespective of bolus conditions. However, from the range of values in this measure, it can be observed that the number of swallows generally tend to increase with increase in consistency and volume with the maximum number of swallows occurring in 15ml banana bolus (Maximum= 5, Range= 4). Thicker consistencies and larger bolus volumes were associated with increased swallowing frequency and greater variability of scores across participants.

Table 10

Descriptive Statistics of the Number of Swallows per Bolus Across Bolus Volumes and Consistencies.

	n	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
5ml Milk	22	1.00 (1)	1.41 (.50)	1	2	1
5ml Curd	21	2.00 (1)	1.67 (.57)	1	3	2
5ml Banana	21	2.00 (1)	1.76 (.62)	1	3	1
10ml Milk	19	1 (1)	1.32 (.47)	1	2	1
10ml Curd	20	2.00 (1)	1.70 (.65)	1	3	2
10ml Banana	19	2.00 (1)	1.84 (.68)	1	3	2
15ml Milk	18	1.50 (1)	1.61 (.69)	1	3	2
15ml Curd	19	2.00 (1)	2.21 (.78)	1	4	3
15ml Banana	21	2.00 (2)	2.57 (1.20)	1	5	4

Note: SD- Standard deviation, IQD- Interquartile deviation

Friedman's test across consistency revealed significant differences for the 10 ml ($\chi^2(2) = 10.400$, $p = 0.006$) and 15 ml ($\chi^2(2) = 12.000$, $p = 0.002$) bolus. Smaller bolus volumes (5ml) showed no significant differences across consistency ($\chi^2(2) = 5.091$, $p = 0.078$). Post hoc Wilcoxon signed-rank tests revealed significant differences across thin liquid (milk) and thick liquid (curd) and across thin liquid (milk) and semi-solid (mashed banana) in 10 ml (milk vs curd: $Z = -2.333$, $p = 0.020$; milk vs banana: $Z = -2.486$, $p = 0.013$) and 15 ml (milk vs curd: $Z = -3.162$, $p = 0.002$; milk vs banana: $Z = -2.745$, $p = 0.006$). From the table, thin liquid swallows required significantly fewer swallows than thicker boluses in both 10ml and 15ml volume condition.

Comparing across bolus volumes, Friedman's test revealed significant differences across volume for curd ($\chi^2(2) = 7.267$, $p = 0.026$) and banana ($\chi^2(2) = 6.400$, $p = 0.041$), whereas thin liquid did not show significant volume-related effects ($\chi^2(2) = 1.357$, $p = 0.507$). Pairwise comparisons revealed significantly greater swallowing frequencies for the larger semisolid boluses with statistically significant difference between 5 ml and 15 ml curd ($Z = -2.126$, $p = 0.033$), and banana ($Z = -2.584$, $p = 0.010$). Similar effects were present across 10 ml and 15 ml boluses in curd ($Z = -2.530$, $p = 0.011$) as well as banana ($Z = -2.070$, $p = 0.038$).

The number of swallows required for bolus clearance reflects the interaction between bolus characteristics and the adaptive capacity of the swallowing mechanism. In the present study, healthy adults generally completed swallowing within one or two swallows, suggesting efficient oral and pharyngeal bolus clearance across all conditions. However, systematic increases in swallowing frequency were observed with increasing bolus volume and consistency, particularly for thicker boluses.

Rheological properties of swallowed bolus influence swallowing behaviour (Dantas et al., 1990; Steele et al., 2015). Semisolid boluses possess greater viscosity, cohesiveness, and resistance to flow (Cichero et al., 2013; Steele et al., 2015), which increases the sensory and biomechanical demands of bolus transport (Matsuo & Palmer, 2008; Steele et al., 2015). Hence, larger semisolid boluses may require additional swallowing attempts to achieve complete oral and pharyngeal clearance (Clavé & Shaker, 2015; Dantas et al., 1990). Larger boluses require greater oral containment, pharyngeal propulsion, and airway protection (Dantas et al., 1990; Matsuo & Palmer, 2008). To compensate, healthy adults may divide the bolus into smaller portions for sequential transport. This phenomenon, commonly referred to as piecemeal deglutition, is frequently observed in healthy adults when swallowing larger-volume or semisolid boluses and is considered a normal adaptive strategy rather than a sign of impairment (Clavé & Shaker, 2015; Humbert et al., 2012; Omari et al., 2020, 2022; Steele et al., 2020). This explains the increased swallowing frequency observed for larger volumes and thicker consistencies in the current study.

This result also relates to and justifies the previous finding on duration of white-out. The current results revealed a significantly greater number of swallows for the 15 ml banana condition. This same bolus was revealed to have a shorter duration of white-out compared to the 10 ml bolus, in spite of the expected increase in swallow demand with a larger bolus volume. This discrepancy may be explained by the occurrence of piecemeal deglutition during larger-volume semisolid swallows that may involve a shorter period of pharyngeal constriction and endoscopic white-out for individual swallows. This way, the demand for greater effort may be compensated without an overall reduction in the safety or efficiency of the swallow. Therefore, the reduced white-out duration observed in the 15 ml banana condition (detailed in the previous section) may indicate distribution of the larger bolus across multiple swallow events rather than a reduction in swallowing demand at a larger bolus volume. These findings highlight the importance of considering quantifiable measures in conjunction with behavioral swallowing adaptations when interpreting FEES findings.

Interestingly, there was no significant increase in swallowing frequency with increase in thin liquid bolus volumes. Healthy adults may be able to accommodate changes in liquid volume without altering swallowing frequency, probably due to the rheological properties. Thin liquids have rapid oro-pharyngeal transit and demand less oral processing than semisolid bolus. Efficient clearance of thin liquid boluses, even at larger volumes, may require fewer swallowing attempts (Logemann, 1998; Palmer et al., 1992; Steele et al., 2009).

From this section, findings indicate that both bolus consistency and volume influence swallowing frequency. Thicker and larger boluses elicit a greater number of swallows, probably as part of normal physiological adaptation. The number of swallows is a sensitive marker of swallowing demands and may provide useful information regarding swallowing behavior during FEES-based assessment. Also, the findings suggest that white-out duration and swallowing frequency may represent complementary aspects, with one focusing on the temporal characteristics (duration of white out) and the other on overall strategy adopted (number of swallows per bolus).

f) Latency of Response to Residue

Table 11 presents the descriptive statistics for latency of response to residue across bolus volumes and consistencies. The number of measurable observations varied across swallow conditions in healthy adults due to the absence of residue for measured bolus swallows. Like in other measures considered in the study, there was considerable variability evident in the latency of response to residue in all bolus conditions. This is evident from the large interquartile deviations, standard deviations, and wide ranges (Table 11). The median response latency was generally longer for thin liquid (milk) boluses, and the median latency decreased with an increase in consistency. In the 5 ml condition, milk (Median = 3604.18 ms, IQD = 3113 ms) exhibited relatively longer response latencies compared to curd (Median = 3203.72 ms, IQD = 4496 ms) and banana (Median = 2144.77 ms, IQD =1945). Greater variability was observed for 5 ml curd, 15 ml milk, and 15 ml curd, while banana boluses generally demonstrated lower latency values and comparatively reduced dispersion.

Table 11

Descriptive Statistics of Latency of Response to Residue Across Bolus Volumes and Consistencies

Temporal Measures	N	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
5ml Milk	9	3604.18 (3113)	3962.42 (2322.70)	1039	8524	7486
5ml Curd	13	3203.72 (4496)	4452.62 (3768.51)	490	13323	12832
5ml Banana	14	2144.77 (1945)	2652.63 (1568.16)	735	6783	6047
10ml Milk	6	3678.56 (3658)	3970.02 (2126.52)	879	6798	5919
10ml Curd	10	2890.42 (2163)	3270.82 (1300.36)	1887	5393	3505
10ml Banana	13	3005.42 (3259)	3151.48 (1706.19)	655	5782	5128
15ml Milk	8	3270.23 (4841)	3745.27 (3031.28)	409	9175	8767
15ml Curd	14	2691.31 (4816)	4172.88 (3389.27)	1283	12682	11399
15ml Banana	16	1718.80 (1206)	2387.69 (2287.06)	320	8376	8055

Note: SD- Standard Deviation, IQD- Interquartile deviation

Friedman's test revealed no significant differences in latency of spontaneous response to residue across bolus consistencies in 5 ml ($\chi^2(2) = 1.750$, $p = 0.417$), 10 ml ($\chi^2(2) = 3.600$, $p = 0.165$), and 15 ml ($\chi^2(2) = 2.800$, $p = 0.247$) conditions. Similarly, no significant differences were observed across bolus volumes for milk ($\chi^2(2) = 1.000$, $p = 0.607$), curd ($\chi^2(2) = 1.705$, $p = 0.417$), or banana ($\chi^2(2) = 2.600$, $p = 0.273$) consistencies.

Latency of spontaneous response to pharyngeal residue was defined as the duration between the end of the pharyngeal swallow resulting in post-swallow residue and the initiation of a subsequent spontaneous clearing swallow. Unlike the other primary swallowing measures that directly characterized bolus transport, this temporal parameter indirectly quantified the pharyngeal sensory awareness and the behavioral response to residue in the pharynx. Previous studies have shown that spontaneous clearing swallows occur in response to pharyngeal residue and contribute to improved bolus clearance and swallowing efficiency (Steele et al., 2011). Reduced laryngeal sensation has been associated with increased pharyngeal residue and impaired spontaneous residue clearance (Miles et al., 2019). Similarly, repeated spontaneous swallows have been reported as a compensatory mechanism for managing residual material in the pharynx (Baijens et al., 2015). These findings emphasize the important role of pharyngeal sensory awareness in detecting and responding to post-swallow residue.

Though descriptive statistics revealed large variability across bolus conditions, statistical analysis found no significant differences across bolus consistencies or volumes. Healthy adults may maintain relatively stable residue-clearing responses despite variations in bolus characteristics, at least in controlled swallow conditions.

There were two related observations that could be made from the data in table 11. First, a typical swallow of controlled boluses may not have pharyngeal residue that calls for a spontaneous response. In this scenario, the absence of significant difference across volumes and consistencies may have to be interpreted as a floor effect. This explanation is supported by the observation of gradual increase in the number of available data points with increasing bolus volume and consistency (Table 11). This meant that the number of swallows that had a clearance response post-swallow increased with volume and consistency. Secondly, the finding may indicate relatively stable response latency among the swallows that required a clearance response. This could be a testament for the efficient pharyngeal sensory monitoring and clearance mechanisms that operate consistently across different swallowing conditions in healthy adults. Once residue is perceived, healthy individuals may be capable of generating an appropriate clearing response irrespective of bolus volume or consistency.

Considerable inter-participant variability could be observed from the data suggesting heterogeneity in response to residue. This may relate to a range of sensory detection thresholds (Shapira-Galitz et al., 2019), residue tolerance (Stokely et al., 2015), and spontaneous swallowing behavior (Baijens et al., 2015) among healthy individuals. Other factors such as the amount and anatomical location of residue, respiratory-swallow coordination, and individual swallowing strategies may also influence the measure. Further research to control and identify the possible interaction between these factors could be of great clinical interest.

Interestingly, semisolid banana boluses tended to have shorter median response latencies, relatively less variability, and larger number of datapoints. Although these differences were not statistically significant, these findings may point at the greater cohesiveness and sensory salience of semisolid residue (Steele et al., 2015; Molfenter & Steele, 2013) facilitating earlier recognition of residue and quick spontaneous clearance behaviour in healthy individuals. In contrast, thin-liquid residue may be less prominent in sensory detection leading to greater variability in response timing. However, these interpretations were based on a small, unequal sample size and needs to be taken with caution until further studies prove the clinical application of these measures. Latency of spontaneous response to residue could only be quantified when both post-swallow residue and a subsequent spontaneous clearing swallow were observed. The measure may be more reliable in persons with dysphagia on whom the probability of visualizing the reference frames is higher.

g) *Velar Movement During Swallow*

Table 12 presents the descriptive statistics for velar elevation and velar relaxation durations across different bolus consistencies and volumes. Both phases of velar movement revealed a high range of variability across swallowing conditions. Generally, velar relaxation durations were consistently longer than velar elevation durations across most of the boluses.

Table 12

Descriptive statistics of velar elevation and velar relaxation during swallow of varied bolus volumes and consistencies

Bolus type	Velar Movement	N	Median (IQD)	Mean (SD)	Minimum	Maximum	Range
5ml Milk	Velar Elevation	22	82.60 (92)	128.19 (95.92)	40	412	372
	Velar Relaxation	22	336.15 (255)	348.66 (181.90)	41	801	760
5ml Curd	Velar Elevation	22	123.18 (175)	216.62 (319.10)	40	1486	1446
	Velar Relaxation	22	399.04 (233)	381.58 (147.89)	166	641	475
5ml Banana	Velar Elevation	21	123.66 (155)	197.84 (190.51)	40	829	789
	Velar Relaxation	21	361.40 (209)	402.32 (214.77)	200	1149	949
10ml Milk	Velar Elevation	21	84.66 (140)	127.15 (91.41)	41	366	326
	Velar Relaxation	21	286.31 (238)	313.39 (170.75)	81	682	601
10ml Curd	Velar Elevation	21	164.72 (137)	208.52 (189.41)	79	829	750
	Velar Relaxation	21	408.53 (176)	402.36 (139.26)	160	733	573
10ml Banana	Velar Elevation	22	123.17 (119)	147.30 (104.17)	40	401	362
	Velar	22	341.88	381.86	165	980	816

	Relaxation		(289)	(204.50)			
15ml Milk	Velar Elevation	22	124.15 (135)	191.28 (154.99)	40	634	594
	Velar Relaxation	22	360.75 (244)	404.92 (259.64)	122	1396	1274
15ml Curd	Velar Elevation	22	178.15 (177)	209.89 (128.37)	41	535	494
	Velar Relaxation	22	371.70 (258)	373.75 (155.91)	120	721	600
15ml Banana	Velar Elevation	21	120.14 (124)	149.06 (113.06)	41	479	439
	Velar Relaxation	21	122.07 (124)	150.96 (112.88)	41	479	439

Note: SD- Standard Deviation, IQD- Interquartile deviation

Interpreting velar elevation across bolus types from the data table, thin liquid bolus (milk) had shorter durations compared to thicker boluses. Interestingly, the thick liquid bolus (curd) had a consistently longer duration of velar elevation in 5ml, 10ml and 15ml bolus volumes. Variability was large across all bolus types, but maximum variability was observed for thicker consistencies (5 ml curd: Range = 1446 ms; 5 ml banana: Range = 789 ms; 10 ml curd: Range = 750 ms). Similarly, in velar relaxation measures, duration was longer for thicker boluses compared to milk boluses. Unlike in velar elevation, velar relaxation had greater variability 15 ml milk condition (Range = 1274 ms).

Friedman's test across bolus types and velar movements revealed statistically significant differences at $p < 0.00$. There was significant difference across consistency in 5ml ($\chi^2(5) = 46.221$, $p < 0.001$), 10 ml ($\chi^2(5) = 53.757$, $p < 0.001$), and 15 ml boluses ($\chi^2(5) = 34.819$, $p < 0.001$). There was statistically significant difference across bolus volumes within milk ($\chi^2(5) = 41.997$, $p < 0.001$), curd ($\chi^2(5) = 36.229$, $p < 0.001$), and banana ($\chi^2(5) = 51.501$,

$p < 0.001$). To further understand the differences, pairwise comparisons using Wilcoxon signed-rank tests was run, The results revealed statistically significant differences between velar elevation and velar relaxation durations in all bolus conditions except 15ml banana (5 ml milk: $Z = -3.652$, $p < 0.001$; 5 ml curd: $Z = -2.841$, $p = 0.005$; 5 ml banana: $Z = -3.146$, $p = 0.002$; 10 ml milk: $Z = -3.563$, $p < 0.001$; 10 ml curd: $Z = -3.146$, $p = 0.002$; 10 ml banana: $Z = -3.667$, $p < 0.001$; 15 ml milk: $Z = -3.036$, $p = 0.002$; 15 ml curd: $Z = -3.306$, $p = 0.002$). Across these conditions, velar relaxation consistently remained longer than velar elevation (Table 12). This indicates that velopharyngeal closure and reopening are temporally distinct phases of swallowing.

As per the pre-validated definitions, velar elevation was derived from maximum velar movement - Onset. Similarly, velar relaxation was derived from offset- maximum velar movement. The pattern of prolonged duration for velar relaxation was consistent across bolus consistencies and volumes and was supported by significant differences between the two movements in nearly all swallowing conditions.

Velar elevation is an active neuromuscular event requiring coordinated contraction of the velar elevators. Complete velar elevation not only seals the nasopharynx from pharyngeal bolus flow, but also contributes to the positive pressure generation in the pharyngeal swallow phase. These pressure dynamics is found to be a contributor to effective pharyngeal clearance (Matsuo & Palmer, 2008; Steele & Van Lieshout, 2004). The speed of velopharyngeal closure, therefore, must be relatable to the pharyngeal swallow phase initiation, which is known to be extremely short in typical swallows (Logemann, 1998; Miller, 1982). In contrast, velar relaxation is the reopening of the velopharyngeal port following bolus passage through the pharynx. Unlike elevation, relaxation is not an actively driven movement but is a combination of muscular relaxation, tissue elasticity, gravitational influences, and respiratory function.

These factors may prolong velopharyngeal reopening (velar relaxation), and explains the findings of the current study.

The consistency effect in velar elevation duration with longer duration for curd may be related to the increased sensorimotor demands. Thicker bolus has slower flow rate and hence longer pharyngeal transit (Dantas et al., 1990; Hind et al., 2001). The need for stronger pressure is therefore higher in thicker bolus, and hence velar elevation may be longer in thicker boluses. This may be especially true for thicker liquid considering the cohesiveness, yet fast flow rate that requires quick velar closure. Maintaining velopharyngeal closure for a longer period may therefore contribute to continued pharyngeal pressure generation for directing bolus flow efficiently through the pharynx. These adaptations are consistent with previous reports that testify adaptations in swallowing physiology in response to bolus characteristics (Dantas et al., 1990; Matsuo & Palmer, 2008; Steele & Miller, 2010). Although the bolus characteristics may influence the duration of individual velar movements, the fundamental temporal organization of this physiology remains stable in healthy swallowing. Therefore, quantification of velar movements for swallow may serve as a marker for categorizing the function for the purpose of clinical diagnosis. Future studies need to explore the clinical validity of this function further.

h) Glottic Status Before and After Swallow

The measure included descriptively noting down the status of the glottis/vocal fold (open or close) just immediately before and after the white out event during swallow. Based on this description, a tallying of the pattern was made for each swallow from each participant. Four patterns were tallied: open-open; open-close, close-open, close-close. The frequency of occurrence of each of these patterns is provided in table 13.

Table 13

Frequency of occurrence of glottic closure patterns across bolus volumes and consistencies

Glottis Status	n	Open-Open	Open-Close	Close-Open	Close-Close
5ml Milk	16	8	-	5	3
5ml Curd	12	4	2	4	2
5ml Banana	14	5	3	4	2
10ml Milk	10	4	-	5	1
10ml Curd	12	6	-	4	2
10ml Banana	11	5	1	5	-
15ml Milk	10	2	-	6	2
15ml Curd	11	2	1	6	2
15ml Banana	11	3	1	6	1
		39	8	45	15

Analysis of glottic status before and after the white-out phase across bolus consistency (milk, curd, banana) and volumes (5 ml, 10 ml, 15 ml) revealed distinct patterns of airway protection and respiratory coordination. Among the observed configurations, Close–Open (C–O) and Open–Open (O–O) patterns occurred most frequently across bolus conditions. The open-close pattern was least frequent in healthy adult swallows.

Smaller bolus volumes (5 ml) demonstrated greater variability in glottic patterns, especially the thicker boluses, that presented with all four types of swallows in 5ml curd and 5ml mashed banana bolus. Larger boluses (10–15 ml) elicited more consistent closure patterns before swallow (Close–Open and Close–Close), indicating stronger airway protection with increasing volume. Interestingly, thin liquids (milk) were associated with predominantly open glottic configurations after white-out. This may either suggest resumption of breathing at the end of swallowing or enhanced airway protection for more challenging bolus types.

During a swallow, the airway is protected by sealing off the upper airway from the laryngeal inlet through physiological functions. The adduction of vocal folds is one of the critical physiological functions. Approximation of the arytenoids to the epiglottic petiole, epiglottic inversion, and hyolaryngeal excursion to seal the laryngeal inlet under the base of the tongue are all other examples. Literature suggests that these mechanisms of safe swallow proceed in an inferior-superior pattern, true vocal fold closure being one among the first mechanisms (Matsuo & Palmer, 2008; Perlman et al., 1999). Before swallowing, the vocal folds may remain open, and after swallowing, they may open to resume respiration, resulting in a close-open pattern. From the table 13, this seemed to be the normal swallowing physiology for most swallows, wherein the glottis closes before the whiteout to prevent penetration or aspiration and reopens immediately afterward to resume respiration (Logemann et al., 1992; Ohmae et al., 1995; Van Daele et al., 2005).

The Open–Open (O–O) pattern was also frequently observed in healthy swallows. This pattern may seem dangerous in the first instance, as the glottis remains open before and after the swallow, increasing the risk of penetration and aspiration. However, this only indicated that the timing of glottis closure varied across bolus conditions among healthy individuals. On detailed scrutiny of the frequency of patterns, the frequency of swallows with glottis remaining open before whiteout (open-close and open-open) patterns increased with bolus complexity (volume and consistency). The relatively lower occurrence of Close–Close (C–C) patterns suggests prolonged glottic closure, and sustained airway protection beyond the white-out duration is not a healthy pattern (Logemann et al., 1992; Martin et al., 1993; Power et al., 2007).

Differences in glottic closure patterns across bolus volumes and consistencies may be attributed to the varied sensorimotor demands of swallowing thicker or larger boluses (Dantas et al., 1990; Hind et al., 2001; Molfenter & Steele, 2013). Thicker boluses (curd, banana) have longer pharyngeal transit (Dantas et al., 1990; Steele & Van Lieshout, 2004) and hence may require prolonged laryngeal closure and greater airway protective adjustments (Logemann et al., 1992; Perlman et al., 1994). Similarly, large columns may also alter the timing of respiratory–swallow coordination, contributing to variability in glottic configurations (Martin et al., 1994; Preiksaitis et al., 1992). The presence of Close–Close patterns in thicker consistencies and larger volumes supports the earlier closure of the glottis, before the pharyngeal swallow initiation, as a compensation to avoid premature spillage of a large bolus into the laryngeal vestibule. These swallows may also require prolonged airway protection, resulting in a closed glottis even after the pharyngeal swallow reflex has ended.

The white-out phase represents the time of maximal pharyngeal constriction and airway closure (Butler et al., 2009; Kelly et al., 2007; Langmore, 2001). Assessing glottic status before and after this phase provided valuable insight into the timing and reliability of airway protection. The observed variability underscores the importance of temporal analysis in FEES to capture subtle differences in airway closure dynamics.

The present study indicated that quantification of FEES-based events of swallow was feasible with standard derivation definitions established in the current study. However, the adaptive and dynamic nature of healthy swallows may obscure the visualization and identification of specific frames of reference. Therefore, not all measures may be derivable from all swallows. In the current study, this led to unequal data distribution, interfering with the statistical power of its findings. The current study was primarily developed as a 'proof-of-concept' that explored the feasibility of the method in healthy swallows. The findings strongly suggest that the method is feasible; however, the clinical validity needs to be further experimented with for the application of these methods for diagnostic purposes. Further research with larger samples and comparison of these measures with other instrumental methods is necessary before the quantified measures may be applied for clinical purposes.

CHAPTER 5

SUMMARY AND CONCLUSION

The current study explored the feasibility of quantification of the swallowing and related events in the temporal domain as visualized in FEES of healthy individuals. A standardized methodology and feasibility in this direction was expected to provide objective methods to interpret FEES findings, which is currently interpreted through perceptual judgements, expert opinions and rating scales. Such an objective approach would be more reliable, valid, and uniform across clinical practice. The current study was the first of its kind to include a comprehensive set of measures of swallowing as well as other related events in a typical FEES Protocol.

The study was carried out in two phases. The first phase included the development of a standard derivational matrix that could potentially quantify swallowing and related endoscopic events. For this, a detailed review of literature was carried out to identify the previously reported objective measures and their derivation methods. The authors also proposed additional temporal measures and definitions that could contribute to quantification of FEES data. All the derivations went through multiple levels of delphi-based expert consensus procedure for clinical relevance of the measure, appropriateness of the derivation method, and definitions framed for each measure. Expert consensus of at least 80% was targeted and obtained for all measures included in the current study. The temporal measures obtained for the study included onset, offset of specific events. Based on these the duration and latency measures were systematically derived for each event.

The second phase of the study explored the feasibility of implementation of the standard derivational matrix in FEES recordings from a cohort of healthy individuals. A total of 25 individuals between 18 and 25 years participated in the study. After exclusion of 2 participants due to atypical swallow behaviours, 23 FEES evaluations were subjected to analysis for derivation of temporal measures as per pre-validated definitions. The measures were derived from phonation tasks and swallowing tasks using frame-by-frame analysis conducted using Kinovea software. The onset and offset frames of specific targeted events were documented. Duration and latency measures were then derived for further analysis. The significant observations from the current study were as follows:

1.Temporal quantification of FEES is feasible but constrained by visualization limitations: Several swallowing events could be temporally quantified using standardized frame-by-frame FEES analysis. The validated definitions enabled this process to objectively measure velar movement, glottic function, epiglottic inversion, pharyngeal transit, white-out events, residue response, and swallowing frequency in swallowing and phonation tasks. However, not all temporal measures could be derived consistently across all participants and bolus conditions. Visualization of reference frames was frequently obscured by white-out phenomena, bolus masking the anatomical landmarks, rapid physiological movements, and natural adaptations in healthy swallowing behavior. This resulted in unequal data distribution across measures and bolus conditions. Nevertheless, the study proposes that FEES evaluations possess considerable potential as a quantitative tool beyond its traditional descriptive clinical use.

2. Healthy swallowing is characterized by temporal variability:

The most consistent findings across all measures included in the study was the presence of large variability as revealed in the interquartile deviations, standard deviation and range measures. This was true for measures of epiglottic inversion, pharyngeal transit time, white-out duration, velar movements, latency of response to residue, and laryngeal movements during phonation. The study proposes that healthy swallowing should not be interpreted using rigid normative values. Rather, swallowing physiology operates within wide normative ranges that may be a reflection of physiological adaptability. Therefore, abnormal swallowing may be better identified through absence of adaptive patterns rather than comparison against normative cut-off values.

3. Temporal symmetry and asymmetry exist in upper airway physiology:

Velar elevation and velar relaxation during phonation of /i/ demonstrated no significant temporal differences. This suggested symmetrical timing of velopharyngeal opening and closing probably indicating efficient neuromuscular control and active biomechanical mechanisms in velar function related to phonation. Whereas, lateral arytenoid and vocal fold movement was significantly longer than medial movement during phonation probably indicating the rapid, active neuromuscular process. Glottic reopening after phonation was comparatively slower. This temporal asymmetry appears to be a characteristic feature of normal laryngeal physiology.

4. Epiglottic inversion adapts to bolus volume

One of the clearest physiological adaptations identified in the study was the prolongation of epiglottic inversion with increasing thin-liquid volume. While 5ml and 10ml liquid swallows had similar duration of epiglottic inversion, there was a significant difference observed between 10 ml and 15 ml milk swallows. Longer inversion durations in larger-volume swallows may be a physiological adaptation to greater airway protection requirements through prolonged laryngeal vestibule closure. Thus, epiglottic inversion appears to be a sensitive marker of bolus-dependent adaptation during swallowing.

5. Pharyngeal transit time remains stable despite changing swallowing demands

Although variability increased with larger and thicker boluses, median pharyngeal transit times remained relatively constant across bolus conditions with no statistically significant differences. Healthy adults may compensate for changing bolus characteristics at multiple levels of the complex swallowing process, and these modifications did not seem to affect the overall pharyngeal transport time. The stability of pharyngeal transit time may represent a hallmark of typical swallowing physiology.

6. Swallow initiation timing remains stable across bolus conditions

Latency of white-out demonstrated stable median values with no significant differences across volume or consistency. The occurrence of zero-latency events, particularly for thicker boluses was unique from other temporal measures, and may be related to effective posterior bolus holding, sensory monitoring and capacity to quickly trigger the pharyngeal swallow on command. These findings support the robustness of swallow initiation mechanisms in healthy adults.

7. White-out duration is generally stable but influenced by bolus-volume interactions

White-out duration remained relatively stable across most swallowing conditions except large volumes of thick bolus. On further analysis 10 ml banana bolus demonstrated longer white-out duration than the 15 ml banana bolus. Combining this finding with the result under 'number of swallows per bolus' measure, we argue that the finding is related to the increased number of swallow frequency (piece meal swallow), whereby larger semisolid boluses are divided into multiple smaller swallows in large bolus volumes. This necessitates the cautious interpretation of temporal measures with swallowing behaviors.

8. Number of swallows is highly sensitive to bolus volume and consistency

The number of swallows demonstrated some of the clearest and most consistent bolus-related effects. Healthy adults generally cleared boluses of 5ml, 10ml and 15ml boluses in one or two swallows. However, larger volumes and thicker boluses increased swallowing frequency. These findings indicate that swallowing frequency serves as a sensitive behavioral marker of swallowing demand. Piecemeal deglutition may be a normal adaptive strategy during larger and more challenging bolus conditions.

9. Response to residue reflects stable sensory monitoring mechanisms:

There were no significant differences in the latency of spontaneous response to residue in healthy individuals despite the large variability in this measure. This may either indicate the highly efficient and robust pharyngeal sensory monitoring mechanism in healthy adults. The semisolid boluses tended to evoke faster responses probably reflecting greater sensory salience.

10. Velopharyngeal movement demonstrates distinct swallowing-specific timing patterns

One of the strongest findings of the study was the consistent difference between velar elevation and velar relaxation during swallowing. Across almost all bolus conditions, velar relaxation was significantly longer than velar elevation. These findings suggest that velar movements during swallow are different from that of phonation. In swallow, the velar elevation is a rapid, actively driven process while reopening is slower. The timing was also different across bolus consistencies with thicker boluses giving longer velar activity. These findings support the quantification of velar timing as a promising quantitative marker of swallowing function.

11. Glottic closure patterns reveal adaptive airway-protection strategies

Analysis of glottic status before and after swallowing revealed multiple airway-protection patterns, among which the close-open and open-open pattern was most frequent. Larger and thicker boluses had increased occurrence of closure-based patterns, suggesting enhanced airway-protection requirements. These findings once again reinforce the dynamic and adaptive nature of laryngeal behavior during swallowing.

Temporal measures of healthy swallowing were characterized by two seemingly opposing features: Remarkable stability in functions such as swallow initiation, pharyngeal transit, and residue response, while revealing astounding adaptability in airway protection, velopharyngeal function, epiglottic behavior, and swallowing strategies as demands. Healthy swallowing seems to be inherently variable and normative ranges rather than normative values may be clinically relevant.

The findings of this study provide strong preliminary evidence that temporal quantification of FEES events is feasible if the derivation methods are standardized. Multiple physiologically meaningful temporal parameters could be derived from FEES recordings and demonstrated systematic relationships with swallowing demands. However, the magnitude of these findings and clinical validation has to be established confirmatively before the same could be incorporated into routine diagnostic and rehabilitative practice.

Preservation of functional performance does not imply uniformity of physiological execution. Variability itself may represent a normal feature of swallowing physiology rather than a marker of dysfunction. Consequently, interpretation of the swallowing measures should consider not a normative value but also the extent of physiological dispersion.

Clinical implications

This study has provided dysphagia professionals with standardized definitions for specific temporal measures, as can be implemented for quantification of FEES data, these temporal measures, when implemented for clinical interpretation, might be more reliable, consistent, and reproducible if future results prove the validity and clinical utility. Further, the reduction in professional interpretation variability offers consistency in patient understanding and progress. Documentation of these objective data might help clinicians in identification of minute changes in the conventional observational assessments. In the long run, the standardized framework may help in machine learning and automated swallowing interpretation.

Limitations

The study included a limited age range of healthy adults which affects the generalizability across lifespan. Since this was a proof of concept study, feasibility of the procedure was primarily the objective, rather than establishing the normative. The challenges posed by FEES data resulted in a large number of missing data points and unequal distribution of the data. This limited the magnitude and power of statistical interpretations.

Future Directions:

The present study represents an important step in the evolution of FEES from a predominantly perceptual assessment method toward a more objective and quantifiable tool for swallowing evaluation. By developing a structured matrix of operationally defined temporal measures, this study provides a reproducible framework for quantitative FEES analysis that may support future reliability studies, normative database development, multicenter research initiatives, and the eventual development of automated or machine-learning-assisted swallowing analysis systems.

1. Normative values must be established using a large number of data with more diverse populations.
2. Interrater and intra-rater reliability of these measures across lifespan needs to be established for these temporal measures.

3. Machine learning and artificial intelligence for automatic FEES evaluations should be done to achieve the efficient objectivity and clinical usability.
4. Establishing the reliability, sensitivity, responsiveness, and clinical utility of these temporal measures across diverse dysphagic populations and clinical conditions.
5. Validation against established instrumental techniques, including videofluoroscopy and manometry, may further strengthen their physiological interpretation.

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