An Exploratory Study on Quantification of Swallow Related Endoscopic Events in Neurogenic Dysphagia

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CERTIFICATE

This is to certify that this dissertation entitled **"An Exploratory Study on Quantification of Swallow Related Endoscopic Events in Neurogenic Dysphagia"** 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 P01II24S123037. 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.

Mysuru
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This is to certify that this dissertation entitled **"An Exploratory Study on Quantification of Swallow Related Endoscopic Events in Neurogenic Dysphagia"**. This has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier for the award of any Diploma or Degree to any other University.

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DECLARATION

This is to certify that this dissertation entitled **"An Exploratory Study on Quantification of Swallow-Related Endoscopic Events in Neurogenic Dysphagia"** is the result of my own study under the guidance of Dr Gayathri Krishnan, Assistant Professor in Speech/Language Pathology, Centre for Swallowing Disorder, All India Institute of Speech and Hearing, Mysuru-570006, and has not been submitted earlier for the award of any Diploma or Degree to any other University.

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DEDICATED WITH LOVE AND GRATITUDE TO MY DEAR

VAPPACHI, UMMACHI, ITHA, VAVA, AND MY GUIDE

DR. GAYATHRI MA'AM

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ABSTRACT

Introduction: While technological advancements have provided professionals with high-quality FEES imaging data, clinical interpretation continues to rely predominantly on subjective, perceptual judgments of swallowing efficiency. This leads to variability, limiting clinical validity, and challenges in procedural standardization. Developing validated objective metrics for FEES events can enhance diagnostic precision. While prior studies have examined isolated parameters, there is limited work integrating standardization, validation, and comparison of temporal measures of endoscopic events with normative reference data.

Methodology: This observational study included neurogenic dysphagia cohorts who underwent FEES evaluation as part of their clinical evaluation. The FEES evaluation followed the typical protocol, including phonatory, respiratory, and swallowing tasks across controlled bolus volumes and consistencies from safe to challenging boluses with evaluation of swallowing safety and efficiency. Individual video clips were screened for optimal visualization and absence of artifacts by two independent SLPs. The "clear" data were selected for motion analysis based on a pre-validated definition of temporal parameters using Kinovea software. The measures included duration of white-out (WO), duration of epiglottic movement (EM), pharyngeal transit time (PTT), and glottic status (GS) before and after swallow for each FEES evaluation data.

Results and discussion: The present study derived a series of objective temporal swallowing measures from FEES recordings using pre-validated operational definitions. The large heterogeneity in the data and unequal data distribution across participants limited group statistical analysis across variables. Hence, visual data comparison across individual neurogenic data points and median outcome measures obtained from healthy adults in another parallel study across thin liquid, pureed, and solid bolus consistencies was conducted. This descriptive analysis

demonstrated significant inter-individual variability within the neurogenic cohort, with several temporal measures deviating from normative reference values. Measures related to swallow initiation, pharyngeal transit, airway protection, epiglottic inversion, glottic closure patterns, and swallow frequency revealed consistency-specific deviations in magnitude. Participants with neurogenic dysphagia demonstrated delayed swallow initiation, prolonged pharyngeal transit characteristics, altered airway protective responses, and increased swallow frequency with more challenging bolus consistencies.

Correlation analyses explored the relationship between objective temporal measures and subjective measures of swallowing safety (Penetration-Aspiration Scale, PAS) and efficiency (Yale Pharyngeal Residue Severity Rating scale). The results revealed no significant association between these measures across bolus consistencies, which indicated that the residue might be influenced by physiological factors, rather than the temporal parameters which was assessed in the current study. Significant correlation were reported between specific temporal measures and PAS scores. Increased number of swallows were observed with lower PAS scores in thin liquids and higher PAS scores in pureed consistency. Hence, number of swallows can be considered as a clinical indicator of swallowing impairment. Delayed swallow initiation positively correlated with PAS scores in solid consistency. Delayed swallow reflex can contribute to increased airway intrusion. These results substantiate the relevance of temporal measures obtained from FEES and their contribution in detecting swallowing safety in neurogenic cohort.

Conclusion:

The current study showed feasibility in using temporal measures from FEES through motion analysis. The data revealed individual variability in performance of specific tasks. Due to unequal distribution of data points, the temporal measures varied across participants. Median based benchmarking was done to analyze incomplete dysphagia datasets. The results of the present study emphasized the clinical use of FEES temporal measures in swallowing performance in neurogenic cohort. In future, such quantifiable temporal parameters pay way for future automation and development of AI driven tools for dysphagia assessment.

CHAPTER I

INTRODUCTION

Swallowing is a basic yet complex reflexive function that integrates multiple body systems, including the respiratory, digestive, neuromuscular, and endocrine systems, for its optimal functioning. Various structures and processes orchestrate this process to transfer the food from the mouth to the stomach. The swallowing function is coordinated by an intricate, precise control from multiple levels of the central nervous system, including the cortex, subcortical structures, cerebellum, and the brainstem reflex centers. Traditionally, swallowing is classified into three phases: oral, pharyngeal, and esophageal (D'Alatri et al., 2025).

Dysphagia is a term used to describe the impairment in bolus transfer from the mouth to the stomach due to impairments in the oral, pharyngeal, and/or esophageal phases. The condition is associated with difficulties in swallowing safety, and/or efficacy. Consequences of dysphagia often include malnutrition and dehydration. Unmanaged dysphagia can be life-threatening with aspiration pneumonia and death (Rofes et al., 2011). Aging, as well as various medical conditions such as stroke, neurological disorders, brain injury, muscular disorders, head and neck cancers, and overall decline of physical health, can make individuals experience dysphagia (O'Horo et al., 2015).

The heterogeneity in dysphagia among professionals has led to different definitions and classifications of dysphagia. From the swallowing phase-specific perspective, dysphagia can be classified into oral preparatory, oral propulsive, pharyngeal, and esophageal dysphagia. Oral dysphagia is classified as a subtype of oropharyngeal dysphagia, which results from impaired tongue control, poor dentition, and reduced oral competence (Dewan, 2024). In the neurogenic population, lingual discoordination contributes to oral phase dysphagia by disrupting the bolus control and propulsion (Daniels et al., 1999). Pharyngeal dysphagia occurs due to impairment in bolus propulsion efficiently and safely through the pharynx. Various etiological factors of dysphagia can interfere with pharyngeal transit of a bolus, such as stroke, tumor, structural defects, respiratory disorders, and inadequate UES opening, compromising the efficiency and safety of swallowing (Dewan, 2024). Esophageal dysphagia is characterized by swallowing difficulty as a primary symptom, and the causative conditions can be anatomical defects or neuromuscular dysfunction in the esophagus (Kruger, 2014). Dysphagia can occur due to psychological or emotional factors without any identifiable physiological impairments; this is termed as psychogenic dysphagia (Alzuabi et al., 2023).

Among the various classifications of dysphagia, neurogenic dysphagia is associated with neurological conditions that affect the central and/or peripheral nervous system (Bakheit, 2001). Neurogenic dysphagia can be defined as dysphagia due to dysfunction of the swallowing mechanism in those individuals who have suffered from neurologic disease or insult (Chandran & Doucet, 2024). Unspecified neurogenic oropharyngeal dysphagia can stem from occult cerebrovascular disease, including confluent periventricular infarcts or small brainstem strokes. Other potential causes include motor neuron disease resulting in bulbar or pseudobulbar palsy and progressive dysphagia with minimal limb involvement; inflammatory myopathies such as polymyositis; myasthenia gravis; medication-induced dysphagia; and psychiatric disorders that may mimic swallowing apraxia (Buchholz, 1994).

Dysphagia is increasingly recognized as a significant global health concern due to its high prevalence and associated complications. The global prevalence of oropharyngeal dysphagia was reported to be 43.8% (Rajati et al., 2022). It is estimated that around 400,000 to 800,000 individuals develop neurogenic dysphagia per year globally (Robbins, 1999). The prevalence of post-stroke dysphagia was found to be 46.6% (Song et al., 2024), while dysphagia occurs in approximately 52–82% of individuals with Parkinson's disease and 44% of individuals with multiple sclerosis (Clavé et al., 2004). In other neurological conditions, prevalence ranges from 13–57% in conditions like dementia and from 30–100% in motor neuron disease (Panebianco et al., 2020). Martino et al. (2005) reported that dysphagia prevalence remains particularly high in brainstem strokes and was found to be strongly associated with an increased risk of pneumonia associated with unmanaged aspiration. A recent meta-analysis reported a prevalence of 36.3% in the post-stroke population of Asia. There was a lesion-specific variability in the prevalence, with the highest prevalence of dysphagia in the brainstem infarcts (92.5%) and 6.6% in cerebral hemorrhage (Meng et al., 2020). These findings highlight the substantial burden of neurogenic dysphagia and underscore the need for accurate and reliable diagnostic approaches.

A comprehensive evaluation of swallowing function is fundamental to the accurate identification and effective management of dysphagia (Attrill et al., 2018; Logemann, 1998; Matsuo & Palmer, 2008). Speech-Language Pathologists (SLPs) employ a combination of clinical, subjective, and instrumental assessment approaches to obtain a holistic understanding of swallowing physiology and impairment. The clinical or bedside swallowing assessment constitutes the first step in the evaluation process. It involves a systematic and detailed collection of case history, followed by an examination of oral sensory-motor functions as well as the cognitive status, respiratory support, and laryngeal function associated with swallowing function. Typically, these components are evaluated before the administration of oral bolus trials (Riquelme, 2015). Presence, nature, severity, and contributing factors of dysphagia are observed in this context, with the background reports and complaints to formulate a probable clinical diagnosis. To support standardization and clinical decision-making, several structured protocols have been developed, including the Mann Assessment of Swallowing Ability (MASA, Mann, 2002), the Gugging Swallowing Screen (GUSS, Trapl et al., 2007), and other clinical swallowing examination procedures (Daniels et al., 1997; Massey & Jedlicka, 2002; Trapl et al., 2007).

Despite their popularity and high clinical utility, subjective bedside evaluations are primarily effective as screening tools that help identify individuals who may require further assessment (Kaneoka et al., 2013; Neubauer et al., 2015; Rosenbek et al., 1996). Subjective assessments, though based on clinical observations and expertise, demonstrate variability, making the outcomes limited in predictive validity (Lim et al., 2023). The outcomes of clinical swallow examinations are mainly dependent on the clinician's expertise and experience (McCullough et al., 2000). Various studies have attempted to document the psychometric measures of clinical bedside swallow evaluation tools, and the reported sensitivity values range from 21% to 93%, while specificity ranges from 46% to 93%, particularly when administered by experienced professionals (Bours et al., 2009; Daniels et al., 1997). The variability in psychometric properties of these tools documented in the literature reflects the differences in assessment components and variations in validity across patient populations (Martino et al., 2000). A comprehensive systematic review compiled evidence from four diagnostic accuracy studies to investigate the clinical relevance and diagnostic precision of clinical swallow examination in relation to the routine instrumental evaluations in the suspected dysphagia population. The findings demonstrated variable sensitivity, specificity, and predictive values of the clinical swallowing examination procedure, implying inconsistency in their diagnostic accuracy. Although these methods can identify dysphagia, there is a lack of evidence to support their ability to predict aspiration in individuals who are at risk of dysphagia (Haas & Bailey, 2024). Clinical swallow examinations are primarily restricted to observations of the overt signs of dysphagia. Timely detection of subtle and mild events of airway intrusion is crucial in health care, especially in individuals who are immunocompromised due to associated conditions.

Lynch et al. (2017) reported that for moderate to severe dysphagia, the sensitivity rates (77% and 86%) remained higher, whereas the specificity rates were comparatively lower (52% and 65%). This indicates the constrained ability of bedside assessments to rule out dysphagia-related risks. Therefore, even though clinical swallow examination remains a crucial component of dysphagia assessment, it is insufficient as a standalone diagnostic tool.

The clinical practice guidelines around the globe emphasise the use of instrumental assessments along with the subjective evaluation by swallow experts. A comprehensive guideline published advocated for the structured, step-wise diagnostic criteria to be administered for an appropriate diagnosis of neurogenic dysphagia.

The assessment should initially focus on gathering the medical history, followed by standardized bedside screening procedures and instrumental diagnosis. For better tracking of bolus flow, penetration aspiration risks, bolus residue, and other pathophysiological mechanisms, both Flexible Endoscopic Evaluation of Swallowing (FEES) and the Videofluoroscopic Swallowing Study (VFSS) were regarded as the most appropriate tools (Dziewas et al., 2021). Instrumental evaluation is therefore implemented in dysphagia diagnostics and management on a regular basis. Instrumental evaluations are often implemented to confirm, corroborate, and complement clinical subjective observations. Often, instrumental evaluations are required to detect silent aspiration, to quantify the swallowing inefficiency and safety risk, and to particularly identify the physiological impairments that contribute to the consequences of dysphagia in an individual. This is critical information that enables accurate diagnosis prior to the formulation of management strategies.

Various instrumental methods are relied upon for assessing and confirming the diagnostic components of dysphagia. Inconsistencies observed in the clinical swallow examinations prompted the use of instrumental evaluations among clinicians three times more often than noninstrumental alternatives (Mathers–Schmidt & Kurlinski, 2003). Instrumental evaluations are vital in the detection of the risk of aspiration (Boesch, 2024) and are assistive in confirming as well as monitoring therapy effectiveness (Wirth et al., 2016). The frequently used instrumental methods for swallowing evaluation include videofluoroscopy, electromyography, ultrasound, three-dimensional dynamic computed tomography imaging, endoscopy, airflow measurement, electromagnetic articulography, lingual and pharyngeal manometry, swallowing acoustics/accelerometry, electromagnetic articulography, and electropalatography (Steele, 2015). Broadly, these methods can be categorized into imaging and non-imaging modalities (Langmore, 2001; Logemann, 1998). Non-imaging techniques are useful for biofeedback, screening, and documentation of approximate baseline functioning. They do not allow direct visualization of the swallowing mechanism or its sequelae. They are limited in their capacity to provide detailed information regarding the specific physiological impairments that contribute to the clinical presentation and also do not allow measures of coordination and sequencing of swallowing events (Omari et al., 2014; Pandolfino et al., 2005; Steele & Huckabee, 2007). The gold-standard imaging techniques for instrumental swallowing evaluation are the Videofluoroscopic Swallow Study (VFSS) and the Flexible Endoscopic Evaluation of Swallowing (FEES). These two methods are popular among practitioners as imaging-based techniques that offer critical insights into the physiological aspects of swallowing. The information provided by these assessment methods cannot be obtained through clinical subjective examinations alone.

Videofluoroscopic swallowing study is a dynamic radiological procedure that allows real-time visualization of swallowing structures across the phases of swallow, including the oral, pharyngeal, and esophageal phases. This method enables the clinician to observe, analyse, and interpret the pathophysiology that contributes to dysphagic symptoms. VFSS can be performed in both lateral and anterior views, providing comprehensive information on the bolus flow from the mouth through the pharynx to the stomach. It is considered the gold standard assessment in dysphagia practice, considering the comprehensive view and evaluation that could be done using this technique. Despite the high diagnostic value, there are certain practical limitations that interfere with the routine and repeated evaluation of the diagnosis. Some of the practical limitations include the requirement for specialized radiographic equipment, the need for patient transport, and exposure to ionizing radiation. These limitations restrict its accessibility and feasibility in clinical settings.

Flexible Endoscopic Evaluation of Swallowing (FEES, Langmore et al., 1988) has emerged as an alternative approach for the assessment of swallowing physiology. The procedure involved the transnasal insertion of a flexible endoscope to visualise the pharyngeal regions before and after bolus flow. This method facilitates detailed examination of the structural integrity and functional aspects associated with pharyngeal swallow through direct and real-time visualization of the swallowing process. The complete procedure of FEES follows a structured and comprehensive assessment protocol that includes structural and functional assessment of nasal, nasopharyngeal, oropharyngeal, laryngeal, and hypopharyngeal structures. The contribution of the key anatomical structures in these areas, including the velum, base of tongue, posterior pharyngeal wall, vocal folds, and epiglottis for speech, respiratory, and swallowing functions, is evaluated with FEES for a comprehensive swallowing assessment. The protocol advocates for the individual to perform tasks such as phonation and voluntary breath holding during the endoscopy to evaluate the functional integrity of the pharyngolaryngeal and respiratory system, following which swallowing trials are conducted with utmost consideration for patient safety. The oral trials are discontinued when significant airway intrusions are visualized in a specific bolus consistency. The SLP may also implement corrective compensations in positioning, feeding strategy, pacing, or airway protection maneuvers. FEES is also used as a feedback tool in dysphagia rehabilitation (Curtis, 2024). This multidimensional approach enables the clinicians to derive detailed information needed for accurate diagnosis and individualised intervention planning (Dziewas et al., 2021; Langmore, 2001; Logemann, 1998a; Murray, 1999)

Direct visualisation of clinically significant events such as penetration, aspiration, and post-swallow residue facilitates accurate diagnosis and management (Dziewas et al., 2021; Langmore, 2001). Langmore et al. (1991) conducted a comparative analysis of VFSS and FEES in individuals with dysphagia and reported a high degree of agreement between the two procedures, suggesting the clinical validity of the procedure. Chiu (2020) discussed the application of FEES in the evaluation of pharyngeal structures, while VFSS provided insights into the overall physiology of swallowing. A recent systematic review reported higher sensitivity of FEES compared to VFSS for detecting aspiration, penetration, and residue, along with marginally improved detection of premature spillage compared to VFSS. However, both procedures were found to have similar diagnostic accuracy (Ferrari De Castro et al., 2025). The FEES procedure provided better visualization of the anatomical structures and the residue (Pisegna & Langmore, 2016). Compared to other methods, FEES detected pharyngeal residue with high sensitivity, while VFSS detected premature spillage and aspiration (Fattori et al., 2016). Their study concluded that FEES had the upper hand in detecting oropharyngeal dysphagia compared to VFSS.

In contrast to the VFSS, FEES allows for the assessment of bilateral pharyngeal and laryngeal function within a single examination. The absence of radiation exposure permits repeated assessments over short intervals, which facilitate continuous, repeated monitoring of patient progress (Dziewas et al., 2021; Giraldo-Cadavid et al., 2017; Langmore, 2001, 2017). The portability of FEES equipment is another advantage that makes this method a preferred one in medically fragile, critically ill, or "difficult to move" individuals. There is a leaning preference for FEES among SLPs in both clinical and research contexts due to practical advantages, including reduced need for patient transport, minimal infrastructural requirements, and the absence of time constraints associated with radiographic procedures (Schindler et al., 2022).

Evidence has shown that FEES is generally well accepted and tolerated by dysphagic individuals with minimal discomfort reported during the procedure (A. M. Kelly et al., 2007; Langmore, 2017). The American Speech and Hearing Association has recommended FEES as a safe and validated assessment method for both the pediatric and adult population, if it is done by a trained and qualified professional (Langmore, 2017).

FEES have been used commonly in academic, clinical and research areas in recent years. There is need for standardization of the FEES protocols and the outcome measures, despite the advantages of the method. Better image resolution, frame rate, and good illumination of the endoscope have improved the diagnostic precision and effectiveness of FEES

NEED FOR THE STUDY

Early identification and diagnosis of dysphagia is essential for the prevention of serious consequences, including aspiration pneumonia, dehydration, malnutrition, and prolonged hospitalization (Wieseke et al., 2008). A comprehensive approach to swallowing assessment with both clinical and instrumental evaluations is important in ensuring diagnostic precision (Haas & Bailey, 2024). Though multiple protocols and procedures exist for clinical swallowing examinations, they are highly subjective and continue to rely on perceptual interpretations for categorizing swallowing functions (Belafsky et al., 2008; Crary et al., 2005; DePippo et al., 1994; Edmiaston et al., 2010; Martino et al., 2009; Trapl et al., 2007; Wallace et al., 2000). Such subjective methods induce significant limitations in accuracy, validity, and practice uniformity across professionals (Cordier et al., 2023; Mathers–Schmidt & Kurlinski, 2003). Indirectly, the variability could affect the trust of the client and their caregiver in the professional and the profession at large.

Imaging-based instrumental evaluations are standardized in their protocols and procedures, providing face validity (Fransson et al., 2025; Martin-Harris et al., 2008). The instrumental evaluations are recorded and reproducible, and provide a more factual interpretation of the physiology. They have the potential to minimize the perceptual judgments, thereby promoting uniform, evidence-based clinical decision-making. Medical imaging technology uses temporal, spatial, and kinematic measures to quantify the changes in the target structure and function with correction. For example, imaging-based assessments such as ultrasonography provide quantifiable outcome measures such as muscle thickness (Maeda et al., 2023). Similarly, esophageal manometry investigates the motion, contraction, and pressure of the esophagus to understand esophageal motility disorders (Baldwin & Puckett, 2022). Such quantifiable measures improve the diagnostic precision and also allow for the least progress to be documented. Such feedback can make the client engaged, involved, and motivated throughout the rehabilitation process (Park et al., 2017). However, these are indirect representations of swallowing and are limited in their clinical application in detecting swallowing safety and efficiency concerns.

FEES, in contrast, provides a direct visualization of pharyngeal as well as laryngeal functions during swallowing and related events. The reliability of FEES interpretation is variable according to clinical expertise (Krishnan et al., 2024). The direct, real-time visualization in FEES examinations is interpreted through various rating and perceptual categorical scales (Curtis et al., 2022; Kaneoka et al., 2013; Neubauer et al., 2015). These rating scales are standardized in their overall procedure and have shown acceptable reliability and sensitivity in categorizing the direct observations of pharyngeal function into normal and abnormal (Curtis et al., 2022; Kaneoka et al., 2013; Murray et al., 1996; Neubauer et al., 2015; O'Neil et al., 1999; Rosenbek et al., 1996; Starmer et al., 2021). For example, there are rating scales that aim at quantifying the penetration and aspiration (Curtis et al., 2022; Rosenbeck et al., 1996), pharyngeal residue (Kaneoka et al., 2014; Murray et al., 1996; Neubauer et al., 2015), and overall severity (O'Neil et al., 1999; Starmer et al., 2021) of swallowing function from FEES studies. However, the supporting evidence in incorporating these perceptual scales and their psychometric measures has not been consistently replicated across independent research groups (Curtis et al., 2022; Kaneoka et al., 2014; Neubauer et al., 2015; Rosenbek et al., 1996; Starmer et al., 2021). These methods may assist in making a diagnosis, but may not be able to detect, evaluate, or document micro-adjustments and the small progress made during the rehabilitation process. The existing subjective rating scales, therefore, lack the ability to capture fine, real-time physiological changes during a swallow from FEES examination. The absence of a single valid and reliable tool for FEES assessment urges clinicians and researchers to adapt, refine, customize, and develop their own methods of FEES reporting, further interfering with the uniform evidence-based professional practice.

There is a need to explore more objective, reproducible, clinically valid, and reliable outcome measures from FEES examinations for swallowing function assessment. Objective quantification of the physiological events has the potential to enhance the accuracy of diagnosis by reducing the perceptual interpretations and inter- and intra-judge variability, allowing precision in categorization of swallowing as well as the specific functions that are impaired. Further, objective quantification may be able to reveal and quantify the change across time in an individual undergoing rehabilitation, thereby assisting in the prediction of therapy outcomes. Few initiatives have been reported in the direction of quantification of FEES events in the last decade (Butler et al., 2009, 2011; Mozzanica et al., 2019; Yoon et al., 2019). These studies have primarily attempted to quantify the white-out duration across associated variables. Other measures that were explored include oral transit time, bolus dwell time, arytenoid movement, glottic closure, pharyngeal aerated area with bolus held in the oral cavity, the pharyngeal area of residual bolus during swallowing, the pharyngeal constriction ratio, the pharyngeal closure duration, supraglottic closure, maximum pharyngoesophageal segment opening, pharyngoesophageal segment opening duration, soft palate elevation, aryepiglottic fold elevation, airway closure duration, bolus dwell time, total swallowing duration, and total pharyngeal transit time (Butler et al., 2009, 2011; Daniels et al., 2007; Kendall et al., 2000; Kuuskoski et al., 2024; Van Daele et al., 2005).

Swallowing is a time-sensitive, precise, and intricately coordinated neuromuscular process. This makes temporal measurement a significant dimension in swallowing physiology. The onset, offset, duration, latency, and sequencing of the specific processes in pharyngeal swallow are known to be significant predictors of swallowing safety, as seen in the VFSS (Logemann, 1998;

Molfenter & Steele, 2014; Perlman et al., 1993). These measures are not derivable through the existing subjective methods in the interpretation of FEES. The temporal measures are clinically significant in the population of neurological dysphagia, in whom this subtle coordination of swallowing physiology in the time domain is known to be disturbed (Kim et al., 2023; Molfenter & Steele, 2014),

Neurological conditions such as stroke, traumatic brain injury, degenerative disorders, and other acquired brain injuries disrupt the timing, sequencing, and coordination of swallowing and related events (Al-Khaled et al., 2016; Lee et al., 2016; Logemann, 1998; Singh & Hamdy, 2006). The delayed initiation of the swallow reflex, increased transit times, and timing incoordination across bolus transport and airway protection make the population at high risk of aspiration. In FEES, these errors are not manifested as gross abnormalities and are often neglected in analysis with the perceptual scales. The consequences of these errors, the airway intrusion and residue, are more often observed and reported. There is a need to shift from the consequence to the root error that manifests in swallowing difficulty in an individual with dysphagia. Quantification of temporal measures of swallow in FEES studies of individuals with neurological dysphagia could therefore be an initial step towards improving diagnostic accuracy and targeted management planning.

Prevailing studies in this direction are focused on quantifying the ‘white-out’ phase that corresponds to pharyngeal constriction related to swallowing (Ohmae et al., 1995). These studies suggest that the duration of white-out varied across bolus types (Betito et al., 2026; Mozzanica et al., 2019) and was significantly different across age (Butler et al., 2011; Mozzanica et al., 2019). The duration of the whiteout was also associated with airway intrusion events and pharyngeal residue (Benjapornlert et al., 2020; Betito et al., 2024). These findings provide preliminary evidence and support the feasibility of quantification of FEES events in the temporal domain that could differentiate normal and deviated swallowing functions more objectively.

Existing literature on objective quantification of FEES events, especially the whiteout phenomenon, emerges from diverse and heterogeneous clinical populations. There is a substantial gap in extending the procedure to a broader range of swallowing events and specifically to populations in whom the temporal measures are known to be a significant predictor, such as those with neurogenic dysphagia. Expanding quantification beyond isolated phenomena of whiteout duration may enable clinicians to include comprehensive temporal profiling of swallowing events. This could enhance the diagnostic capabilities of FEES. The possibility of the integration of such quantitative measures with emerging digital and computational tools, such as artificial intelligence, holds a promise for the future through semi-automated or fully automated FEES analysis. These methods can improve reliability, efficiency, and precision by enabling the detection of subtle deviations and tracking of therapeutic progress with high precision. Hence, there is a need to develop standardized quantitative protocols for FEES to improve and facilitate consistency across clinical and research settings. The absence of such standardized metrics remains a critical limitation in the current dysphagia practice. Addressing this gap is essential for advancing FEES evaluation from a predominantly qualitative tool to a robust, objective, and data-driven diagnostic modality.

In this context, the current study was proposed upon the foundational work of Betito et al. (2024). The study further advanced the quantification of FEES-derived measures beyond the duration of whiteout to a comprehensive set of temporal measures. While previous research has reported the potential of whiteout-related parameters in clinical validation in a heterogeneous group of individuals with dysphagia, the current study focused on exploring the multiple temporal measures in a single group with neurological dysphagia. This group with dysphagia was thought to be particularly relevant for the study, owing to the temporal discoordination often found to be a defining characteristic and significant prognostic predictor in this population. By systematically quantifying FEES data in this population, the current study aimed to enhance diagnostic accuracy, improve the reliability of assessment, and contribute to the development of objective, standardized protocols for clinical practice.

Aim of the study

The current study aimed to derive quantitative measures of swallowing and related events from the Flexible Endoscopic Evaluation of Swallowing (FEES) data of individuals with neurogenic dysphagia. We hypothesized that the onset, offset, duration, and latency measures of specific physiological events related to the pharyngeal phase of swallow can provide clinically significant information related to the safety, efficiency, and severity of dysphagia, and that they can support the subjective observations of expert FEES clinicians. For this study, neurogenic dysphagia is defined as a condition in which an individual experiences difficulty in the oral, pharyngeal, or oropharyngeal phases of swallow after a central or peripheral neurological lesion, including but not limited to stroke, trauma, surgery, motor neurone disease, and other neurodegenerative disorders.

Objectives of the study

Specifically, the study was conducted with the following objectives:

1. To standardize the definition of objective temporal measures that could be derived from the FEES data of persons with neurogenic dysphagia.

2. To compare the objective measures using the standardized definitions in persons with neurogenic dysphagia across bolus consistencies (IDDSI 1-2; IDDSI 4-5; IDDSI 6-7; IDDSI-8).
3. To explore the relationship between the objective and subjective measures of safety and efficiency.

CHAPTER II

REVIEW OF LITERATURE

The existing diagnostic approaches for dysphagia include both qualitative clinical swallowing examinations and instrumental evaluations that continue to be judged and interpreted perceptually within the background of clinical expertise. Previous studies have frequently concluded that the subjectivity, variability, and lack of standardized metrics in the current procedures continue to affect clinical diagnostic precision, management planning, and progress tracking in individuals with dysphagia (Prikladnicki et al., 2022; Speyer et al., 2022). In this context, the primary aim of the current study was to explore and extend quantitative approaches to the FEES studies with a particular focus on a comprehensive set of event-based temporal measures. This was expected to enhance the accuracy and reliability of dysphagia assessment using the endoscopic procedure. This chapter is aimed at presenting a brief review of the literature that is grounded in the need to advance the methods for the objective assessment of swallowing physiology. This chapter includes the reported attempts at quantification of swallowing physiology across various instrumental modalities of swallowing evaluation, examines the established and emerging quantitative parameters, and critically analyzes current approaches to FEES interpretation. The literature that places emphasis on the quantification of events observed during Flexible Endoscopic Evaluation of Swallowing (FEES) is the prime focus of this chapter.

Swallowing physiology is best analyzed with instrumental swallowing assessments. These methods are broadly categorized into imaging and non-imaging techniques. Imaging modalities include functional MRI, ultrasonography, swallowing computed tomography, scintigraphy, videofluoroscopy, Doppler spectrum analysis, and Flexible Endoscopic Evaluation of Swallowing (Argon et al., 2004; Humbert & Robbins, 2007; Inamoto et al., 2022; Sonies et al., 1996, 2003).

These methods provide direct visualization of the swallow process. Other non-imaging and indirect approaches to swallow function include tools such as the Iowa Oral Performance Instrument (IOPI), high-resolution pharyngeal and esophageal manometry, cervical auscultation, and surface electromyography (Cock & Omari, 2017; Gyawali & Kahrilas, 2023; Lagarde et al., 2016; Pitts et al., 2022; Poorjavad et al., 2017). Among all these methods, videofluoroscopy and FEES remain the most widely utilized imaging techniques for swallowing evaluation (Cichero & Murdoch, 2006).

Quantification of swallowing physiology using non-imaging modalities

Quantification of swallowing physiology has been gaining increasing attention among contemporary dysphagia researchers, clinicians, and professional practices. The imaging and non-imaging modalities of swallowing evaluation have been subjected to rigorous experimentation for their objectivity. Below, we summarize the previous research that has attempted to evidence quantification of swallowing physiology in individuals with dysphagia using indirect or non-imaging modalities of swallowing assessment.

Iowa Oral Performance Instrument (IOPI)

The Iowa Oral Performance Instrument (IOPI) is popular among dysphagia clinicians and is widely used in rehabilitation as a reliable tool for measuring lip and tongue strength and endurance. It provides quantifiable indices that may indicate the oral phase function. For example, a meta-analysis revealed that individuals with Parkinson’s disease exhibited significantly reduced tongue strength and endurance when compared to age-matched healthy individuals. This deviation in tongue performance was thought to be relevant in understanding oral preparatory and propulsive deficits in this population (Pitts et al., 2022). Another systematic review and meta-analysis by

Franciotti et al. (2022) supported the reliability of IOPI measures and reported that maximum tongue pressure (MIP) was a consistent and robust quantitative parameter in differentiating healthy and weak oral stage functions.

However, the use of IOPI is restricted to lip and tongue function. IOPI instrument doesn't record complex and coordinated nature of swallowing. It is not recommended for the assessment of pharyngeal events, airway protection, bolus flow or penetration/aspiration risk. These limitations restrict the utility of IOPI in dysphagia population. Variability also has been reported in the endurance measures across the normal population, which further limits the clinical application of the instrument. (Franciotti et al., 2022). Therefore, IOPI provide objective data on swallowing performance, however it cannot be used as a standalone tool to quantify swallowing physiology.

Surface electromyography (sEMG)

Surface electromyography (sEMG) quantifies swallowing-related muscle activity and is used as a non-invasive and objective method in the swallowing rehabilitation process. The method is valid in detecting age-related increases in swallowing duration (Vaiman et al., 2004), supporting its quantitative applicability in swallowing assessment. Advanced multi-channel systems enable muscle synergy frameworks, allowing detailed analysis of muscle activation patterns. Distinct activation profiles corresponding to the oral, early pharyngeal, and late pharyngeal phases of swallowing have been identified that further underscore the coordinated neuromuscular control underlying the process of swallowing (Murakami et al., 2023). However, similar to other non-imaging modalities, sEMG provides indirect measures of swallowing without direct visualization of bolus flow or airway events, limiting its clinical utility in dysphagia diagnostics. While sEMG can provide valuable insights into the temporal activation patterns related to swallowing, these are limited to superficial muscles of swallowing physiology and may not directly suggest functional integrity or changes.

Repetitive Oral Suction Swallow (ROSS)

The Repetitive Oral Suction Swallow (ROSS) test was introduced as a bedside, non-invasive method aimed at capturing the underrepresented parameters such as swallowing capacity and temporal sequencing of oral and pharyngeal events (Nilsson et al., 1995). The ROSS test enables quantification of multiple swallowing-related variables, including oral-pharyngeal transit time, suction pressure, bolus volume, suction duration, and associated respiratory patterns. It provides a rapid, reliable, and radiation-free approach to evaluating swallowing function, making it suitable for clinical settings where instrumental imaging may not be feasible (Nilsson et al., 1996). Though a strong correlation between temporal measures obtained through the ROSS test and those derived from videofluoroscopic analysis has been demonstrated (Nilsson et al., 1995), the test remains limited to indirect measurement of swallowing events. It does not provide a visualization of structured dynamics or functional integrity during swallowing. Thus, its utility is limited in capturing the intricate complexity of swallowing physiology.

Manometric evaluations

Pharyngeal and esophageal manometry have recently gained research interest and are being extensively investigated as objective methods for quantifying pressure and temporal dynamics associated with swallowing. The upper esophageal sphincter (UES) function in relation to other parameters of swallowing is thoroughly explored in typical and atypical swallowing functions. Conventional pharyngeal manometry is often done along with videofluoroscopic swallow studies to enhance interpretative accuracy. It measures intraluminal pressures within the pharyngo-esophageal segment (Castell & Castell, 1993; K. J. Yoon et al., 2014).

Further technological advancements have led to the development of High-Resolution Pharyngeal Manometry (HRPM), which quantifies both pressure and temporal parameters across multiple regions of the swallowing pathway. Dharmarathna et al. (2020) examined two decades of research in pediatric swallowing assessment and concluded that videofluoroscopy and manometry were the most extensively utilized instrumental methods for evaluating suck–swallow coordination and aspiration in children. The authors emphasized that high-resolution manometry provided reliable and validated measures of pressure and timing within the pharyngeal and esophageal phases of swallowing. In addition to the UES function targeted in esophageal manometry, more critical functions, such as the intrabolus transfer and pharyngeal contraction, are studied as a function of time. This method has been shown to be clinically meaningful in differentiating swallowing impairment (Sibley et al., 2023). Combining pharyngeal with esophageal manometry, intraluminal pressure profiles, and coordination could contribute to pharyngeal and esophageal motility disorders. Asymmetric pressure patterns during the bolus passage may help in identifying oropharyngeal swallowing inefficiency (Hila et al., 2001). Support for the clinical applicability of this method in dysphagia can be found in the reports of C.-H. Park et al. (2017). Their manometric protocol differentiated the pressure and timing measures across the levels of the pharyngeal system, including the velopharynx, tongue base, and UES regions. Reduced maximal pressures at the velopharynx and tongue base; decreased UES relaxation duration; and lower resting UES pressures, with minimal UES pressure changes, were found to have clinical validity and utility in implementing this quantitative assessment tool.

Similar to other non-imaging methods in swallowing evaluation, in spite of the quantification of pharyngeal and esophageal manometry procedures, the same is not widely used in the clinical diagnosis of dysphagia. The reasons include the complexity of the procedure, its acceptance by the patient group, and the lack of direct visualization of the swallowing process. Manometry does not aid in quantifying the consequences of swallowing impairment, such as airway intrusion or residue. This procedure does not provide any information on the various physiological swallowing events associated with a swallow. Consequently, critical clinical events such as penetration, aspiration, and residue cannot be directly observed through manometric measures alone. Therefore, manometry is insufficient as a standalone tool for comprehensive dysphagia diagnosis

Ultrasound

Ultrasound is a non-invasive method that provides the visualization of the anatomical structures, including the tongue, hyoid bone, larynx, and other muscles during swallowing. It is an objective method used for the assessment of structures and functions related to swallowing (Hsiao et al., 2021; Maeda et al., 2023). Kwong et al. (2022) investigated hyolaryngeal excursions and tongue base retraction in relation to the timing of swallowing events across different bolus conditions. Their findings indicated consistent movement patterns across bolus characteristics, suggesting the clinical utility of ultrasound in capturing temporal aspects of swallowing. The procedure permits for quantification of muscle bulk, area, contour, and movement dynamics in swallow (E. Kelly et al., 2024; Mori et al., 2019; Wang et al., 2025). Significant differences in these parameters were reported in individuals with sarcopenia at risk for dysphagia (Maeda et al., 2023; Mori et al., 2019; Ogawa et al., 2018; W. Zhang et al., 2025). A narrative review by Maeda et al. (2023) highlighted the advantages of clinical feasibility, portability, absence of radiation, and cost-effectiveness when compared to other conventional imaging techniques employed in dysphagia assessment. Despite these capabilities, ultrasonography does not permit direct visualization of intraluminal events. Consequently, its application remains limited in providing a detailed functional assessment of swallowing.

Electromagnetic Midsagittal Articulography (EMMA)

The empirical evidence in the assessment of the oral stages of swallowing is scarce. Electromagnetic Midsagittal Articulography (EMMA) is one such method that explores oral articulatory movements during swallowing. EMMA provides a high-resolution description of oral movements for tongue positions during swallowing events. The kinematic parameters and the movement trajectories measured using EMMA correlated well with the X-ray microbeam studies (Steele & Lieshout, 2004). However, this method does not provide direct visualization of swallowing and is limited to the assessment of specific functions such as lip, tongue, and jaw movements (Steele & Lieshout, 2004a). Pharyngeal events related to swallowing are inaccessible to this procedure. Further, the non-portable equipment setup and the interference of sensor placements with the normal swallowing process limit the diagnostic applicability of this procedure in dysphagia diagnostics.

Scintigraphy

Scintigraphy is a minimally radioactive procedure that has been identified as a reliable and objective modality for the quantitative assessment of oropharyngeal dysphagia. Scintigraphy is particularly sensitive to bolus characteristics (Baulieu et al., 2007; Shaw et al., 2004) and allows for tracking functional changes over time (Huang et al., 2006; A. C. V. Silva et al., 2008). Galli et al. (2000) reported that individuals with neurological disorders exhibited significantly prolonged oral, pharyngeal, and esophageal transit times, along with increased bolus retention, supporting the utility of scintigraphy in detecting temporal and functional abnormalities associated with dysphagia. The temporal measures of swallowing, such as the oral, pharyngeal, and esophageal transit times, can be derived from the indirect image of swallow through regional count analysis. Clinicians benefit from the insight of swallowing efficiency and bolus clearance (Shaw et al., 2004). The lack of detailed anatomical visualization and the inaccessibility of information related to airway protection during a swallow have restrained the popularity of this procedure on a routine basis.

From the above review of the literature, quantitative assessment of swallowing physiology has been of immense research and clinical interest. The various instrumental modalities of assessment have contributed valuable objective data by quantifying discrete components of swallowing, such as tongue strength, muscle activation patterns, pressure dynamics, transit times, and bolus-related variables. For instance, maximum tongue pressure has been identified as a reliable quantitative marker (Franciotti et al., 2022), while muscle synergy analysis using sEMG has enabled phase-specific characterization of swallowing activity (Murakami et al., 2023). Similarly, manometric measures such as the Pharyngeal Contractile Integral have been proposed as meaningful indicators of swallowing impairment (Sibley et al., 2023), and scintigraphy has demonstrated strong predictive value for regional dysfunction and temporal measures such as transit times and residue (Shaw et al., 2004).

However, critical limitations continue to restrict the routine implementation of these procedures in comprehensive swallowing. Most of the instrumental modalities rely on indirect assessment of swallowing physiology and do not reflect on the functional integrity and consequences of these measures on bolus flow or airway protection. More advanced methodologies, such as that of manometry, are being rigorously explored for their clinical utility, but are currently beyond their application as a diagnostic measure of dysphagia (Dharmarathna et al., 2020), as they do not permit visualization of swallowing events. The same limitation restricts the use of ultrasonography (Maeda et al., 2023) and scintigraphy (Galli et al., 2000). All these methods are also restricted by their inability to capture real-time pharyngeal events that are central to dysphagia diagnosis. Events such as penetration, aspiration, and residue formation occur rapidly and require simultaneous spatial and temporal resolution, which are not delivered by the above-discussed objective modalities of swallowing evaluation.

Differences in instrumentation, definition of objective parameters, and the method of derivation of these parameters across research studies result in inconsistencies in findings and make generalization difficult. Lack of integration between structural visualization and quantification is yet another challenge in the existing methods of quantification of swallowing function. While certain modalities provide numerical and objective data (e.g., IOPI, manometry) offer structural or kinematic visualization with indirect quantification (e.g., ultrasonography). This fragmentation limits the ability to obtain an understanding of swallowing physiology that encompasses both structure and function. For example, while temporal measures such as transit time have been extensively studied, their interpretation and clinical thresholds remain variable (Furkim et al., 2019), indicating a lack of standardization in quantitative swallowing research.

Quantification of physiology of swallowing using imaging modalities

Videofluoroscopic swallow study (VFSS) has been extensively utilized as a primary modality for quantitative analysis of swallowing physiology. This method of evaluation has been able to capture dynamic bolus transit across all phases of swallowing. Several studies have attempted to derive objective temporal and kinematic parameters from VFSS to enhance its diagnostic precision.

Clinical relevance of VFSS quantification has been established across multiple studies (Kim et al., 2023; Miles et al., 2022; Weckmueller et al., 2011). Subsequent studies have further explored the relationship between VFSS-derived parameters and clinically significant outcomes such as aspiration (Okumura et al., 2021). Various kinematic measures of hyoid displacement, swallowing durations, and timing intervals were evaluated to determine their association with penetration–aspiration events (Bingjie et al., 2010; Smaoui et al., 2022; Wei et al., 2022). Among the thirteen parameters studied by Molfenter and Steele (2014), the duration of UES opening demonstrated a statistically significant difference across aspirating and non-aspirating individuals, with a significantly shorter duration of UES opening in individuals with aspiration during a swallow. The kinematic measures of hyoid movement did not reach statistical significance, probably suggesting that temporal measures of swallow may be a relevant factor in predicting dysphagia.

Temporal and kinematic quantification of swallowing physiology has been extensively explored in the VFSS procedure. Temporal parameters such as Oral transit time (OTT), pharyngeal transit time (PTT), pharyngeal delay time, bolus head timing, stage transition duration (STD), pharyngeal swallow initiation, pharyngeal retention (PR), bolus arrival at the valleculae, onset of laryngeal closure, pharyngeal delay time, laryngeal vestibule closure duration, and UES opening duration have been systematically investigated (Bingjie et al., 2010; Kim et al., 2023; Martin-Harris et al., 2007; Sdravou et al., 2012; Weckmueller et al., 2011). Weckmueller et al. (2011) demonstrated that the duration of specific oral and pharyngeal events increased with age and varied with feeding techniques. The authors concluded that these results indicate the adaptive biomechanical changes in swallowing and also provide evidence for the quantification of swallowing physiology. Similarly, studies examining dysphagic populations revealed that shorter UES opening duration is significantly associated with aspiration risk (Park et al., 2016). A videofluoroscopic analysis done in healthy cohorts by Nascimento et al. (2015) found that larger bolus volumes increased UES opening duration, while thicker consistencies prolonged pharyngeal transit time.

Advancements in computational analysis have further enhanced VFSS quantification. Wu et al. (2025) developed an automated system integrating contour extraction and feature tracking to quantify multiple kinematic and temporal parameters. Their findings reported reduced biomechanical efficiency in dysphagic populations, highlighting the potential of automated quantification to improve objectivity and reliability.

Martin-Harris et al. (2003) substantiated that airway protective and bolus transit events (hyoid excursion, laryngeal closure, and PES opening) occur in tightly coupled temporal proximity to ensure safe bolus passage. They emphasized that normal swallowing consists of coordinated groups of events rather than a simple linear sequence and that these VFSS-based timing patterns provide a useful framework for identifying abnormal swallowing and aspiration risk. Extending this understanding to neurogenic dysphagia, Krishnan et al. (2022) used VFSS to examine the onset and sequencing of oropharyngeal swallowing events in post-stroke individuals and found that key events such as bolus transport initiation, soft palate elevation, UES opening, hyoid movement, and laryngeal closure occurred more independently, reflecting reduced temporal coordination in neurogenic cohorts. Collectively, these studies underscore that normal swallowing function followed coordinated timing patterns, whereas dysphagia is marked by disrupted or poorly synchronized events. Hence, VFSS-based temporal measures may have relevance and clinical utility in detecting abnormal swallow patterns in individuals at risk for dysphagia.

Flexible endoscopic evaluation of swallowing (FEES) is another popular imaging method for dysphagia evaluation. Comparative evidence across VFSS and FEES suggested that FEES provides superior visualization of pharyngeal phase events while VFSS offers better assessment of oral and esophageal phases (Labeit et al., 2022). Higher sensitivity of FEES in detecting aspiration in post-stroke dysphagia encourages practicing professionals to incorporate this procedure as a first-line, radiation-free assessment tool (Helliwell et al., 2023). However, the interpretation of FEES observations remains largely dependent on perceptual frameworks. Several scales have been developed to standardize and provide a structure for the interpretation of observations from FEES. These scales aim at a perceptual quantification of clinically relevant outcomes such as residue, penetration–aspiration, and swallowing efficiency. For instance, the Mansoura Fiberoptic Endoscopic Evaluation of Swallowing Residue Rating Scale (MFRRS) offers structured grading of post-swallow residue with good reliability (Sabry et al., 2021). The Secretion Severity Rating Scale (Murray et al., 1996) semi-objectifies swallowing performance by quantifying pooled secretions and spontaneous swallowing frequency. These methods have demonstrated a strong association between secretion accumulation, reduced spontaneous swallowing, and aspiration risk (Murray et al., 1996).

The FEES-based rating scales can be used for the interpretation of directly viewes structures and swallowing performances. However, these scales are purely subjective and mostly rely on clinician judgement (Neubauer et al., 2016; Pisegna et al., 2018; Rosenbek et al., 1996). Variability in interpretation across clinicians, differences in scale selection, and lack of standardization affect the validity, reliability, and uniformity of FEES-based assessments. This variability in measurement restricts the use of these scales across studies and thereby affects the integration of the obtained findings into clinical practice. Since FEES is a data-rich modality capable of directly visualizing critical pharyngeal events, more quantitative approaches to its analysis have not been fully integrated into its interpretation

An earlier contribution to this line of investigation was given by Butler et al. (2009), who examined swallowing physiology in healthy young and older adults. Multiple temporal and functional swallowing parameters were quantified. The authors attempted to include PAS cores, bolus dwell time, pharyngeal closure duration, and the severity of pharyngeal residue, then these measures were compared across age, gender, bolus volume, and type. The findings showed differences within healthy populations. Geriatric population demonstrated longer bolus dwell time and greater residue, especially for thin consistency. Occasional airway intrusion events were noted even in healthy individuals, particularly among older adults. In the same line of research methodology, Butler et al. (2011) explored bolus dwell time using frame-by-frame analysis of FEES recordings across bolus consistency, volume, delivery method, and the anatomical location of the bolus head. The findings indicated notable differences in this measure depending on bolus properties and bolus position ahead of swallow initiation. Longer dwell time was observed for larger volumes and deeper bolus heads. The authors proposed that these variabilities indicated sensory motor control mechanism involved in the initiation of swallow.

.Mozzanica et al. (2019) compared the duration of whiteout during the swallow of various boluses in adults and reported that the phenomenon was longer in older adults compared to others. They concluded that the duration of white-out may serve as a reproducible temporal measure for swallowing physiology from FEES, and that it may be sensitive to both bolus properties and individual physiological differences. They also mentioned the interaction between age, gender, and bolus characteristics in this outcome measure. Tamin et al. (2023) explored the pharyngeal transit time, pharyngeal delay time, pharyngeal response time, pre-swallow leakage, residue, penetration, aspiration, and secretions in healthy individuals and reported norms across different food consistencies in healthy adults. Building on earlier evidence, Betito et al. (2024) added the intensity of whiteout, along with temporal measures, and correlated penetration-aspiration scores and pharyngeal residue ratings using retrospective data analysis from a heterogeneous population of persons with dysphagia. The study further affirmed the age and bolus effect on the quantified outcome measures and provided a preliminary indication that the objective measures could be used clinically. The longer and weaker whiteout correlated with the penetration–aspiration event, and shorter whiteout duration correlated with greater saliva pooling.

More recently, Sutton et al. (2024) attempted to correlate quantified frequency and temporal measures related to the whiteout phenomenon with those of subjective assessments of safety, efficiency, and sensory response in adults. 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 (YRS), 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. Their findings supported those of Mozzanica et al. (2019) and confirmed that age and bolus characteristics influenced the quantified FEES outcome measures without gender differences. These reports support the concept of quantification of events observed in clinical FEES procedures for identification of deviance in pharyngeal and laryngeal functions and their probable relevance in complementing the prevailing subjective measures of swallowing. Hence, quantification of the FEES procedure, particularly the temporal features, may offer a more robust and objective framework for identifying abnormalities, establishing normative data, and comparing swallowing patterns across populations (Mendell & Logemann, 2007). This highlights a critical need to develop objective, quantifiable measures within FEES that can enhance its validity, improve inter- and intra-rater reliability, and support standardized, evidence-based clinical decision-making.

Advanced imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) provide high spatial and temporal resolution (Inamoto et al., 2022, 2024). But the application of these modalities on a routine basis for clinical practice is constrained by issues of feasibility, accessibility, and cost. These limitations highlight a critical gap in current dysphagia assessment approaches and underscore the need for methodologies that integrate direct visualization with objective, reproducible quantification of swallowing events, particularly at the level of the pharynx, where clinically significant dysfunctions are most evident.

Significance of Temporal Coordination Measures in Swallowing Evaluation

Swallowing requires precise initiation, coordination, sequencing, and termination of physiological events, making it an inherently time-dependent neuromuscular process. The precision across time determines the swallowing safety and efficiency (Aykac et al., 2025; Matsuo & Palmer, 2009; Ye-Lin et al., 2022). Therefore, temporal measures of swallow provide critical insights into the dynamic coordination and integrity of the underlying neural control. Unlike subjective clinical interpretations, quantifiable temporal parameters offer a more precise characterization of swallowing physiology (Jeong et al., 2023; Lam et al., 2024). Several previous investigations have emphasized the importance of temporal coordination in identifying functional impairments in the diagnosis of dysphagia (Hughes & Wiles, 1996; Saconato et al., 2020; Waito et al., 2020).

Furkim et al. (2019) systematized temporal analysis by identifying four key domains: bolus transit time, pharyngeal response time, laryngeal closure time, and upper esophageal sphincter (UES) opening time. Prolonged temporal measures were consistently associated with clinically significant outcomes such as airway penetration and aspiration (Dai et al., 2024; Kim et al., 2023; D. Park et al., 2016; Shu et al., 2023; Zhang et al., 2016). Delayed hyoid elevation, prolonged epiglottic inversion, and altered UES opening quantified from VFSS studies characterized dysphagia in neurological populations (Saconato et al., 2020). Similarly, prolonged latency of laryngeal vestibular closure and delayed airway protection mechanisms in individuals diagnosed with amyotrophic lateral sclerosis were directly associated with compromised swallowing safety (Waito et al., 2020). R. Leonard et al. (2023) demonstrated that the Bolus Clearance Ratio, a quantitative index of pharyngeal efficiency, was significantly correlated with pharyngeal transit time and aspiration severity, further reiterating the functional relevance of timing in swallowing efficiency. Delay in response to pharyngeal residue and short UES opening duration was associated with airway penetration (Kim et al., 2023; Zhang et al., 2016). These reports highlight the diagnostic relevance of temporal measures in persons with dysphagia. However, the heterogeneity in their definitions and procedures of derivation limits generalization and interpretation across studies. This is exemplified in the definition of the white-out (WO) phase during FEES, which has been described by Ohmae et al.(1995) as a first image completely obscured by the pharyngeal muscle contraction and subsequent closure of the pharynx, while more recent work by Mozzanica et al. (2019) operationalizes WO as a phase of obscured view appreciable through FEES corresponding to the transit of the bolus through the pharynx. Similarly, pharyngeal transit time has been defined differently by Sdravou et al. (2011), conceptualizing it as the interval from the bolus head passing the base of the tongue until the bolus tail passes through the cricopharyngeal sphincter, while Kendall & Leonard (2001) describe the measure as the time between the onset and completion of bolus pharyngeal transit.

Temporal measures obtained from other non-imaging modalities also support their clinical relevance in dysphagia diagnosis. Altered bolus transit times and increased residue in post-stroke populations indicated impaired temporal coordination in scintigraphy studies (A. C. V. D. Silva et al., 2010). Non-instrumental bedside assessments have also shown that measures such as time per swallow and swallowing capacity are sensitive indicators of dysfunction in motor neuron disease (Hughes & Wiles, 1996). A scoping review by Bandeira et al. (2024) identified temporal parameters of transit time and latency as among the most frequently investigated quantitative indices across all instrumental swallowing assessments, highlighting their central role in swallowing research. The preliminary attempts at quantification of FEES made by Warnecke et al. (2021) also identified delayed swallowing reflex and premature bolus spillage to reflect disruptions in the timing and sequencing of swallowing events.

High-resolution computed tomography (CT) with superior spatial and temporal resolution allows for frame-by-frame quantification of swallowing events (Inamoto et al., 2022; 2024). More precise temporal changes in pharyngolaryngeal volume and coordination during swallowing were evident in the dynamic imaging using 320-row area detector CT (Iida et al., 2017). Magnetic resonance imaging (MRI) and functional MRI (fMRI) extended this capability by facilitating the study of temporal sequencing alongside neural control mechanisms (W. S. Kim et al., 1987; Malandraki et al., 2011).

Despite the strong evidence supporting temporal measures, variability in parameter definitions, measurement techniques, and analytical approaches contributes to inconsistencies across studies (Furkim et al., 2019). Additionally, modalities such as ultrasonography face challenges in consistently capturing temporal abnormalities due to operator dependency and technical constraints (Leite et al., 2014; Potente et al., 2023). Advanced imaging techniques, though precise, are limited in routine clinical use due to feasibility and cost. Therefore, there is a pressing need to explore additional quantifiable and objective measures derived from direct visualization-based swallowing assessments. Modalities such as FEES are accessible, cost-effective, and widely accepted in clinical practice and offer significant potential in this direction. Advancing quantitative frameworks within such methods may enhance their clinical relevance, diagnostic precision, and contribution to evidence-based practice.

CHAPTER III

METHOD

The present study was conducted with the objective of exploring the possibility of deriving quantifiable temporal measures associated with swallowing events in the neurogenic dysphagia population. This study proposed a need for the identification of (a) relevant swallowing events observed during the instrumental evaluation, (b) the relevant temporal measures that can be derived in neurogenic population, (c) developing and standardizing the operational definitions for derivation, and (d) systematically deriving the measures in neurogenic dysphagia. Measures that were defined, reproducible, and clinically meaningful within dysphagic evaluation were emphasized

To meet the objectives of the study, a retrospective design was adopted after a detailed review of the literature for the identification of the temporal measures and their definitions. A retrospective analysis of Flexible Endoscopic Evaluation of Swallowing (FEES) clinical evaluation records from individuals diagnosed with oral, pharyngeal, and/or oropharyngeal dysphagia in the Centre for Swallowing Disorders was done to identify the datasets that can be used for the study. The data from the period 2024-2025 were selected as uniformity in instrumentation and clinical protocols was established during this time period. The FEES recording were analyzed systematically to extract and quantify the temporal parameters of swallowing.

The research followed the ethical guidelines for bio-behavioral research as mentioned by the institutional ethical committee of the All India Institute of Speech and Hearing, Mysore. Ethical consent was obtained (Ref no: SH/IRB/M.5/SLP.35/2025-26) For the current study, specific consent was not required, as the consent for the use of the FEES data for research and training purposes were routinely obtained from all the patients undergoing instrumental evaluations. For the present study, all patient data were de-identified to ensure confidentiality and secure handling of clinical information. The study was carried out in multiple phases, each designed to systematically address the objectives and ensure methodological rigor.

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 the identification of research studies that (a) used the FEES procedure for swallow evaluation and (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 a definition/derivation method for the listed measures

The list of measures from step 1 and step 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 and for which definitions were not available, the investigator proposed a derivation method considering the frames visualized in the FEES evaluation. The definitions were supported with annotated images as examples for practical guidance. The tabulated temporal measure and its definition(s) were provided to a group of seven speech-language pathologists 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 a single 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 neurogenic dysphagia.

The current study employed an exploratory retrospective design with an analysis of the archived clinical FEES data set in the center for swallowing disorders. The clinical data records in the center were reviewed for shortlisting the clients diagnosed with oral, pharyngeal, or oropharyngeal dysphagia secondary to a neurological event. For the current study, neurological dysphagia was defined as ‘dysphagia following a neurological insult at central or peripheral neural levels.'

Selection of relevant endoscopic data

A total of 101 FEES recordings were retrieved from the FEES database spanning from January 2024 to March 2026. From them, a total of 42 archived data points were selected based on the following inclusion and exclusion criteria:

Inclusion criteria

1. Date of appointment between January 2024 and March 2026
2. Age > 18 years.
3. Medical history of neurological lesions confirmed with a neurological report.
4. No known history of surgical or structural alterations in the oral, pharyngeal, or esophageal structures.
5. Recommended for FEES evaluation after clinical swallow examination from experts

Exclusion criteria:

1. The FEES was performed for the reevaluation of a previous client
2. Presence of non-neurological comorbidities that contribute to swallowing difficulties (ex: gastroesophageal reflux disease, severe cognitive-linguistic decline, etc.)

The FEES recordings of each of the 42 shortlisted clients were retrieved for further methodological scrutiny. A total of 6 recordings had to be excluded as the FEES recording was done as part of therapy progress tracking/reevaluation. Another 15 data were excluded due to lack of at least one safe bolus/severe dysphagia (n=7), absence of swallowing reflex (n=1), and poor recording quality (n=7). The remaining 21 recordings were reviewed by two speech-language pathologists independently to tabulate the following:

1. ***Bolus consistencies used for evaluation:*** The FEES protocol followed in the centre for swallowing disorders, AIISH, aimed at minimizing aspiration events. The protocol started with a small quantity of the safest bolus and proceeded further up/down the IDDSI levels with utmost caution to patient safety. Generally, a thin liquid (IDDSI 1-2), puree/mashed food (IDDSI 3-4), and a solid (IDDSI 6-7) were attempted as part of the evaluation protocol. The evaluation was discontinued for a particular bolus consistency if airway intrusion was observed. Therefore, not all bolus consistency was given to all clients, and the bolus volumes were generally 5ml, considering patient safety. In very rare cases, another bolus volume could be safely attempted for evaluation. However, for the purpose of this study, the 5 ml bolus was considered for further research purposes, as this was the only bolus volume that was attempted in all clients with at least partially functional pharyngeal swallow. In instances where multiple visualizations of the same bolus were available, the most clear performance in terms of visual clarity (described below) was selected.
2. ***Clarity of swallow for each consistency:*** It was common for the FEES evaluations to show fogging and loss of pre- and post-swallow hypopharyngeal view due to movement artifacts or pharyngeal movements. These could significantly interfere with the identification of swallowing and related events and were hence screened before attempting any quantification. Specifically, the following frames had to be available for clear visualization under each of the bolus swallows:
    a) Entry of bolus into the pharynx

b) Onset of whiteout

c) Offset of whiteout

d) Frame after offset of whiteout

e) Response to the residue or any airway penetration observed.

The tabulation of the two SLPs was reviewed by a third investigator to identify the possible recordings for inclusion. The criteria followed for inclusion were (a) at least two bolus consistencies had been tried in the FEES recording, and (b) the frame before and after the swallow event was free from fogging or artifacts. A total of 21 recordings had to be excluded from the original dataset while systematically ensuring the quality of the final dataset. A total of 15 FEES recordings were included for the analysis of temporal measures. The demographic details of the client records included in the analysis are given in Table 1

Table 1

Demographic Details and Medical History of the Selected Participants

Sl no.	*Age (in years)*	*Gender*	*Type of Dysphagia*	*Neurological Diagnosis*
1.	18	Male	Oral Dysphagia	Traumatic Brain Injury. Poor function of the interhemispheric fissure. Rt posterior parietal hematoma.
2.	45	Female	Oropharyngeal dysphagia	Multiple subacute infarcts in the posterior parietal, B/L occipital lobes, B/L cerebellar hemispheres, and medulla.
3.	50	Male	Oropharyngeal dysphagia	Bell's palsy, small vessel ischemia disease.
4.	55	Male	Oropharyngeal dysphagia	Acute infarct in the upper medulla and the left cerebellar hemisphere.
5.	60	Male	Pharyngeal dysphagia	CVA with left hemiplegia
6.	62	Male	Oropharyngeal dysphagia	Multifocal and multi-phase patchy acute Left MCA and Watershed territory infarct. Sub-acute infarct with possible hemorrhagic transformation involving the left anterior capsulo-ganglionic region.
7.	63	Male	Oropharyngeal dysphagia	CVA of left cerebellar peduncles, left pons, left thalamus, corona radiata, and centrum semiovale
8.	65	Female	Oropharyngeal	Grade 1 small vessel ischemic changes and

			dysphagia	age-related cerebral and cerebellar atrophy
9.	66	Male	Pharyngeal dysphagia	Parkinson's disease and cerebellar infarct
10.	68	Male	Oropharyngeal dysphagia	Parkinson's disease
11.	73	Male	Oropharyngeal dysphagia	Bilateral fronto-parieto-temporal lobe chronic lacunar infarct.
12.	75	Male	Oropharyngeal dysphagia	Recurrent CVA
13.	79	Male	Pharyngeal dysphagia	CVA infarct in PCA
14.	81	Male	Oropharyngeal dysphagia	Lacunar infarct in right internal capsule and atypical parkinsonism
15.	82	Male	Oropharyngeal dysphagia	Acute left dorso lateral medullary infarct

Estimation of the pre-validated temporal measures

The FEES recordings available in .mP4 format were imported to the analysis software for the derivation of temporal measures. The motion analysis was performed with Kinovea (Charmant, 2004) software, an open-source high-definition motion analysis tool implemented for sports medicine and physical rehabilitation research. The software permitted frame-by-frame motion analysis of minute and quick physiological movements. The current study utilized this application for quantifying the endoscopic data.

The endoscopic data were analyzed with the Kinovea software as per the standardized operational definitions for each temporal measure. The time frames for each validated temporal measure were identified for each swallow from the FEES recording. The time frames included onset, offset, and latency of an event (details provided in the results section). A random 10% of the data was re-analyzed by the investigator after a minimum of 2 weeks from the initial assessment for estimating intra-judge reliability. Another 10% of the data was re-analyzed by another investigator familiar with the pre-validated definitions to establish inter-judge reliability. The data related to subjective assessment of safety, efficiency, and severity of swallowing impairment as performed and validated by two expert FEES clinicians for the purpose of clinical documentation in the centre were also tabulated.

Statistical analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS v26.0) software. The final data were subjected to the following statistical analysis

- ➢ Normality testing using Shapiro-Wilk's test of normality
- ➢ Interclass and intraclass correlation for inter-rater and intra-rater reliability on 10% of the data
- ➢ Central tendency measures (mean/median) and dispersion measures (standard deviation/interquartile deviation) for each temporal measure
- ➢ Repeated measure analysis across bolus consistencies, followed by post hoc analysis, if indicated.
- ➢ Spearman's correlation for exploring the relationship between the temporal measures and the penetration aspiration score and the residue score.

CHAPTER IV

RESULTS AND DISCUSSION

The current study aimed to explore the quantification of the swallowing-related temporal measures in a population with neurogenic dysphagia based on pre-validated derivation methods. The study employed a retrospective method of analyzing carefully included archived FEES data sets. The results of the study are being discussed under the following sections:

Standardized definition of objective temporal measures derived from FEES

Table 2 details the list of temporal measures that were included for validation from the seven SLPs. Out of 18 proposed measures, 17 were validated with 80% agreement across judges. The definition of 'post-swallow movement' had poor agreement on the frame of reference and clinical utility across the seven judges. Hence, this measure was eliminated from the temporal measures. Another four measures were validated for their definition of derivation but could not be included in the study due to inconsistencies and practical limitations from the retrospective data. For example, the latency of response to airway intrusion was validated as 'the duration between the offset of whiteout to the laryngeal adductor reflex,' as per the judges. While implementing this in the analysis, many FEES evaluations included instructions to swallow or voluntarily cough, as instructed by the clinician, which altered the validity of this measure. The duration of post-swallow movements was hence eliminated due to the difficulty in identifying the exact final frame after swallow. Bolus dwell time was excluded as the residue persisted for more than 10 seconds, after which the clinician initiated compensatory strategies to clear the pharyngeal residue. Hence, these outcome measures were excluded to maintain the reliability of the study. Therefore, from the original 18 measures, a total of 15 temporal measures were included in further phases of the study.

Table 2.

List of Quantifiable Outcome Measures and Their Validated Definitions

Outcome measure	Validated Definition/ derivation method	Unit	Included/ Excluded	Justifications for inclusion/ exclusion
Onset of whiteout	The first image is completely obscured by pharyngeal muscle contraction and subsequent closure of the pharynx.	msec	Included	Frame of reference for the calculation of the duration of white-out
Offset of whiteout	The first frame in which all laryngeal structures were visible again.	msec	Included	Frame of reference for the calculation of the duration of white-out
Latency of the swallow reflex	The time interval between the endoscopist's cue 'swallow now' and the onset of the first frame of white-out (WO).	msec	Included	Indicates the delay between pharyngeal entry of the bolus and pharyngeal response.
Duration of whiteout	The duration was measured from the onset of complete white-out (WO) to the first frame in which the hypopharynx became visible	msec	Included	Duration of WO determines the duration of pharyngeal constriction and the laryngeal airway closure.
Glottic status before white out	Whether the glottis was open or closed on the frame just before whiteout.		Included	Indicates the preparation for airway protection before swallow.
Glottic status after white out	Whether the glottis was open or closed on the frame just after whiteout.		Included	Indicates the risk of airway intrusion after swallow.
Onset of epiglottic inversion	The frame demonstrating the initiation of the downward movement of the epiglottis over the airway.	msec	Included	Frame of reference for 'time taken for the return of the epiglottis postswallow' measure

Partial inversion of epiglottic inversion	The first frame demonstrates contact between the epiglottic rim and the posterior pharyngeal wall (i.e., white-out).	msec	Excluded	The frame was not consistently visible across recordings, leading to high missing points.
Offset of epiglottic inversion	The final frame demonstrates the anterior movement of the epiglottis toward the base of the tongue after white-out.	msec	Included	Frame of reference for 'time taken for the return of the epiglottis postswallow' measure
Time taken for the return of the epiglottis post-swallow	The time interval from the initiation of epiglottic downward movement over the airway to the final frame of anterior epiglottic movement toward the base of the tongue after white-out (Offset-Onset).	msec	Included	Helps in determining the efficiency and timing related to swallowing and airway protection.
Latency of response to residue	The duration between the offset of whiteout and another swallow.	msec	Excluded	The latency of compensatory swallowing behaviors may reflect the critical time window for prolonged airway protection.
Latency of response to the airway intrusion	The duration between the offset of whiteout to the laryngeal adductor reflex.	msec	Excluded	This measure was eliminated, as the response targeted was reflexive, while the retrospective data was diluted with clinicians' attempts at compensatory strategies aimed at pharyngeal residue clearance.

Onset of pharyngeal transit time	The earliest frame showing either the presence of the bolus head in the pharynx or the onset of white-out, whichever occurred first.	msec	Included	Frame of reference for the calculation of pharyngeal transit time
Offset of pharyngeal transit time	The first frame demonstrates minimal residue after the white-out phase.	msec	Included	Frame of reference for the calculation of pharyngeal transit time
Pharyngeal transit time	The time interval from the earliest frame showing either bolus head presence in the pharynx or white-out onset (whichever occurs first) to the first frame demonstrating minimal residue after the white-out phase (Offset-Onset).	msec	Included	This duration measure gives the time spent by the bolus in the pharynx during the passage.
Number of swallows/bolus	The number of white-out (WO) events for each bolus.	number	Included	The swallowing attempts required to clear the bolus underscore the swallowing efficiency and coordination.
Duration of post-swallow movements	The duration of the time frame from the offset of whiteout to the last frame with the hypopharynx returns to its baseline status.	msec	Excluded	The measure was excluded due to practical limitations in determining the last frame of the swallow before the next swallow/trial.
Bolus dwell time	The duration from entry of the bolus head into the pharynx/onset of white-out (whichever is visible first) till complete clearance of residue	msec	Excluded	In clients with severe dysphagia, the dwell time was more than 10 seconds, and residue was cleared through forceful expectoration or

or >10sec (if the residue is not cleared completely).	suction. This limited uniform application of the definition.

**Note: The highlighted temporal measures were derived from a specific frame of reference, as per validated definitions. Further comparisons were made only for these highlighted measures. The non-highlighted outcome measures were either (a) used as reference frames for derivation or (b) excluded due to reliability or validity errors, as mentioned.*

From the pre-validated definitions, frames of reference for deriving the measure were identified for the calculation of derived temporal measures. A total of nine derived measures were included for further analysis.

Comparison of the objective measures across bolus consistencies in neurogenic dysphagia

Before statistically comparing the measures across bolus consistencies, the objective data derived as per the validated definitions were subjected to inter-judge and intra-judge reliability. Intra-rater reliability was used to determine the consistency of ratings over time by the researcher. A randomly selected 10% subset of the dataset was re-analyzed by the primary investigator following a minimum interval of two weeks from the initial evaluation. This time gap was maintained to minimize recall bias and ensure independent reassessment. The investigator re-evaluated all outcome measures listed in Table 2 using the same derivation criteria established during the validation phase.

The intra-rater reliability analysis was calculated using the Intra-class Correlation Coefficient (ICC). The results demonstrated perfect agreement for all temporal measures across milk, curd, and biscuit consistencies. The measures of latency of swallow reflex, duration of white-out, latency of response to residue, pharyngeal transit time, and epiglottic inversion all yielded ICC of 1.00, indicating excellent consistency and reproducibility of measurements within the same rater across repeated evaluations. The inter-rater reliability was assessed to determine the consistency of ratings across different evaluators; an independent 10% subset of the dataset was randomly selected and re-analyzed by another investigator who was blinded to the original ratings. All raters utilized the finalized outcome measures, standardized definitions, and annotated visual images. Agreement across raters was computed for each outcome measure under all specified criteria.

The inter-rater reliability analysis using the Interclass Correlation Coefficient (ICC) demonstrated excellent agreement between raters for most of the temporal measures across all bolus consistencies. Excellent reliability was obtained in the duration of white-out (milk: $r = 1.00$, $p < 0.001$; Curd: $r = 1.00$, $p < 0.001$; solid: $r = 1.00$, $p < 0.001$), pharyngeal transit time (milk: $r = 1.00$, $p < 0.001$; Curd: $r = 1.00$, $p < 0.001$; solid: $r = 1.00$, $p < 0.001$) and epiglottic inversion (milk: $r = 1.00$, $p < 0.001$; Curd: $r = 1.00$, $p < 0.001$; solid: $r = 1.00$, $p < 0.001$). In contrast, the latency of response to residue measure revealed relatively low inter-rater reliability across milk ($r = 0.343$, $p > 0.001$), curd ($r = 0.265$, $p > 0.001$), and solid consistency ($r = 0.296$, $p > 0.001$), boluses. Therefore, this measure was not considered reliable for quantification and was eliminated from further comparisons.

The measures “latency of response to airway intrusion” and “latency of response to residue**”** were excluded from further analysis because the retrospective nature of the dataset precluded reliable identification of the intended frames of physiological onset events. The validated definition of ‘latency of response to airway intrusion’ included the interval between whiteout offset and the onset of the laryngeal adductor reflex. Similarly, the ‘latency of response to residue’ included the interval between whiteout offset and the initiation of a subsequent swallow. These definitions assumed the occurrence of a spontaneous, observable protective response. However, many examinations included compensatory maneuvers, clinician-directed airway-clearing behaviors, or voluntary residue-management strategies that occurred before any reflexive response could be identified. These confounded the temporal relationships that these measures were designed to capture. Also, airway intrusion was observed in a limited number of participants, and when present, the response was often externally prompted rather than spontaneous, restricting the validity of temporal quantification.

Pharyngeal residue was observed even before the initiation of swallowing in several participants; this led to missing data and inconsistent identification of response across the two rates for the ‘latency of response to residue’ measure. This observation was reasonable as impaired pharyngeal sensation and poor awareness of residue are manifested as common features of neurogenic dysphagia (Dziewas et al., 2024). Similarly, for another measure ‘latency of response to airway intrusion’, aspiration and penetration occurred without any protective mechanisms. Thus, the reliable measurement of these temporal measures was challenging.

Silent aspiration, diminished laryngopharyngeal sensation, and impaired reflexive airway protection are well-documented characteristics of neurogenic swallowing disorders, and these limited the applicability of pre-validated definitions in the derivation of these quantifiable outcomes. Evidence from neurological populations has demonstrated reduced cough sensitivity, diminished urge-to-cough responses, and impaired airway defense mechanisms, indicating disruption of the sensory pathways responsible for detecting airway compromise (Bolser et al., 2013; Silverman et al., 2016). The absence of a response itself may represent a clinically meaningful finding, rather than quantified response latency. The presence or absence of a spontaneous response to airway intrusion or pharyngeal residue may provide more clinically relevant information regarding sensory integrity and airway protective function in individuals with neurogenic dysphagia.

After the elimination of latency of response to residue and airway intrusion, a total of seven outcome measures were included for further statistical analysis. Table 3 provides the descriptive data on the seven included outcome measures. As the target population was neurogenic dysphagia, not all bolus trials could be administered, considering their aspiration risk, and not all functions could be visualized. This led to multiple missing data points in the final dataset. Therefore, the sample size for each temporal measure varied. The descriptive statistics revealed substantial variability in all the outcome measures across bolus consistencies in neurogenic dysphagia. The group means and median were judged to be heterogeneous and not the true representative of the population, with large dispersion measures. Hence, further objective comparisons were not meaningful. Therefore, comparison of measures across bolus consistencies for each participant was done on an individual basis, using visual plotting to facilitate qualitative interpretation of the distributional patterns and the deviations from typical swallowing performance across bolus consistencies.

For the visual plotting, the median and interquartile range of each measure in typical healthy individuals obtained in another study (Preethi et al., unpublished dissertation) were used as reference points. The performance of each participant in the neurogenic group was plotted against the normal range for comparison of performance using a Swarm plot created using RStudio.

Table 3.

Mean (Standard Deviation) and Median (Interquartile Deviation) of the Temporal Measures Across Bolus Consistencies.

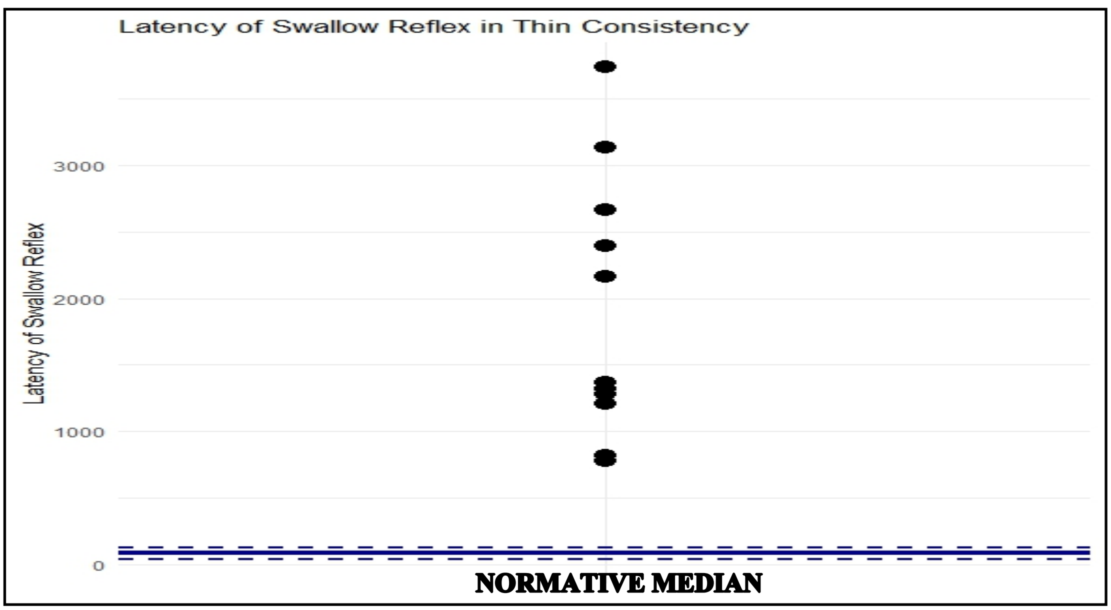
Temporal measure	Thin liquid			Puree/mashed bolus			Solid		
	Sample size	Mean (SD)	Median (IQD)	Sample size	Mean (SD)	Median (IQD)	Sample size	Mean (SD)	Median (IQD)
Latency of swallow reflex	11	1391.29 (1203.30)	1279.14 (2392)	12	3020.57 (2040.23)	3750.10 (4464.00)	11	2585.40 (3018.60)	1733.33 (4708.00)
Duration of whiteout	11	956.43 (482.25)	866.52 (522.00)	12	4869.90 (13489.00)	735.81 (1029.00)	11	841.55 (711.06)	741.99 (467.00)
Pharyngeal transit time	11	1260.83 (1012.29)	1105.70 (998.00)	11	2806.94 (2010.35)	2252.34 (3800.00)	11	2744.04 (2345.40)	1702.47 (4197.00)
Epiglottic inversion	9	267.10 (1805.26)	733.33 (3203.00)	9	287.05 (1770.08)	700 (1550.00)	7	1154.25 (2897.72)	245.73(2553.00)
Number of swallows/ bolus	9	3.33 (3.67)	2.00 (1.00)	9	4.22 (4.24)	4.00 (3.00)	10	3.70 (2.41)	3.00 (4.00)

Latency of swallow reflex

For the latency of the swallow reflex, swarm plots were generated to visually compare the individual latency of swallow reflex values in the neurogenic dysphagia cohort with the normative median obtained from healthy adults across bolus consistencies in milk (Figure 1), curd (Figure 2), and solid boluses (Figure 3). These figures illustrate the visual plot of the latency of the swallow reflex in neurogenic cohorts compared to the median latency of the swallow reflex obtained from a group of healthy adults in similar boluses. The horizontal lines denote the normative median range, whereas the individual data points indicate the individual values from the neurogenic cohort.

Figure 1

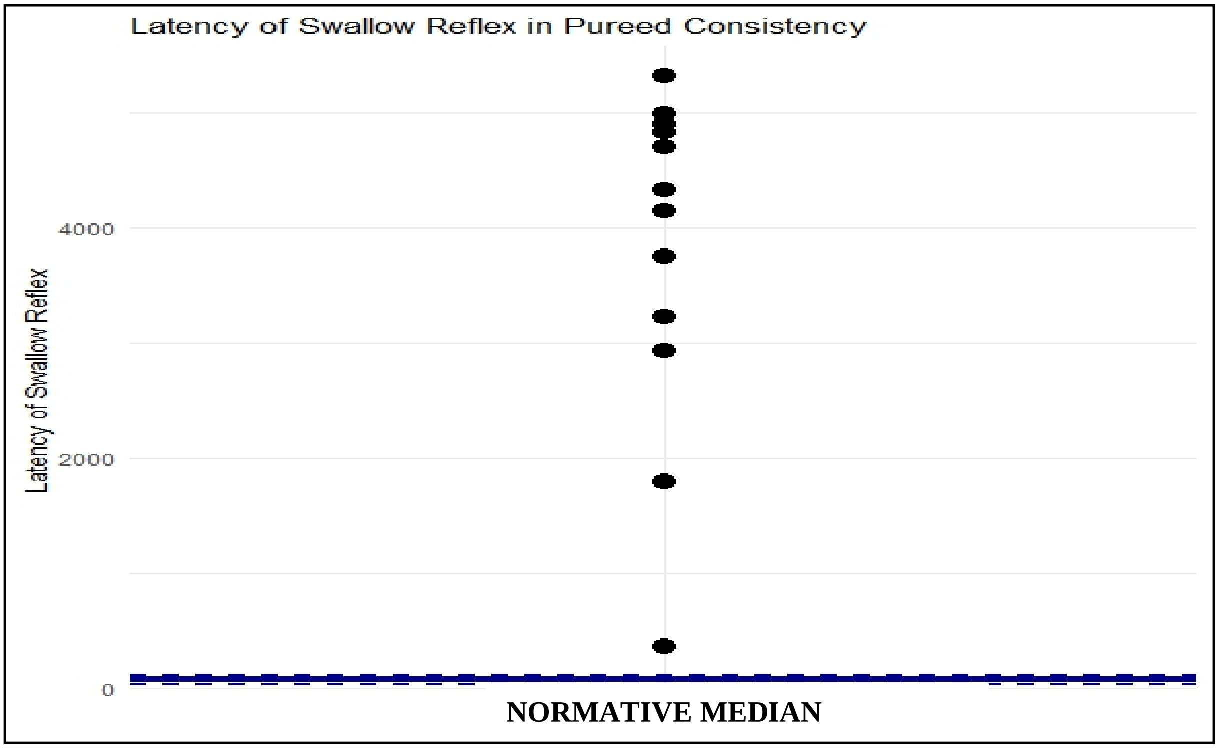
Latency of Swallow Reflex in Thin Consistency (Milk) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of latency of the swallow reflex during milk swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the latency of swallow reflex during milk swallows in the neurogenic cohort included in the current study.

Figure 2.

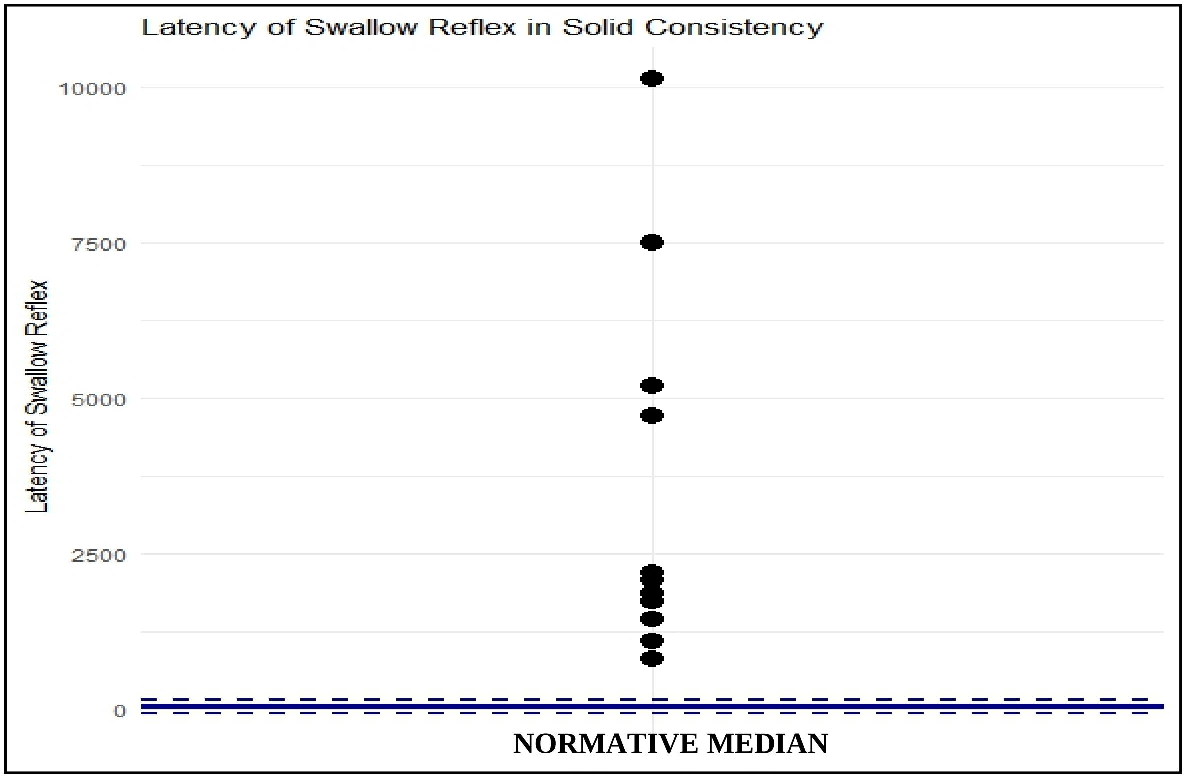
Latency of Swallow Reflex in Puree Consistency (Curd) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of latency of the swallow reflex during puree swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the latency of swallow reflex during puree swallows in the neurogenic cohort included in the current study.

Figure 3.

Latency of Swallow Reflex in Solid Consistency Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of latency of the swallow reflex during solid swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the latency of swallow reflex during solid swallows in the neurogenic cohort included in the current study.

Swallowing latency is a function of efficient sensory-motor integration and precise temporal coordination that aids timely initiation of the pharyngeal swallow response (Namasivayam-MacDonald et al., 2018). In the current study, the latency of swallow reflex was pre-defined as 'the time interval between the endoscopist's cue 'swallow now' and the onset of the first frame of white-out (WO)' (Table 2). From Figure 1-3, the latency of the swallow reflex in the neurogenic dysphagia group was longer compared to the median latency of the swallowing reflex obtained from healthy individuals in milk, curd, and solid consistencies. This indicated a longer interval between the cue to swallow and the onset of white-out in neurogenic dysphagia. Longer intervals or delayed initiation of the pharyngeal swallow response may be related to the increased variability in swallowing physiology associated with neurological impairment in thin liquids, purees, and solid boluses. The majority of participants demonstrated prolonged swallow latency with marked interindividual variability.

Increased latency of the swallow reflex may reflect delayed initiation of the pharyngeal swallow and/or slower bolus transit toward the pharynx. Such delays may be attributed to impaired sensory input, disrupted sensorimotor integration, and reduced efficiency of the central neural mechanisms responsible for swallow initiation. Huckabee & Pelletier (1999) defined delayed pharyngeal swallow as the failure to generate a coordinated and timely pharyngeal response following bolus entry into the pharynx. The findings of the present study are consistent with this definition, as individuals with neurogenic dysphagia demonstrated prolonged and highly variable swallow reflex latencies relative to the normative cohort, suggesting impaired coordination of sensory and motor swallowing processes.

The observation from the current study is supported by previous literature demonstrating abnormalities in swallow initiation among neurological populations. Dziewas et al. (2021) reported delayed triggering of the swallowing response in neurogenic dysphagia, while Labeit et al. (2023) identified pharyngeal sensory impairment as a significant contributor to delayed or absent swallow reflexes in post-stroke dysphagia. Impaired pharyngeal sensation has been recognized as a key mechanism underlying dysphagia following neurological injury, as it reduces the sensory input and delays the activation of the pharyngeal swallowing network, compromising airway protection (Johnson et al., 1993). Similar findings have also been reported in individuals with infratentorial stroke, where disruption of brainstem swallowing pathways was associated with impaired swallow triggering (Suárez-Escudero et al., 2022). These findings support the results of this study and suggest that prolonged latency of the swallow reflex may serve as an objective indicator of impaired sensory–motor integration and increased swallowing safety risk in neurogenic dysphagia.

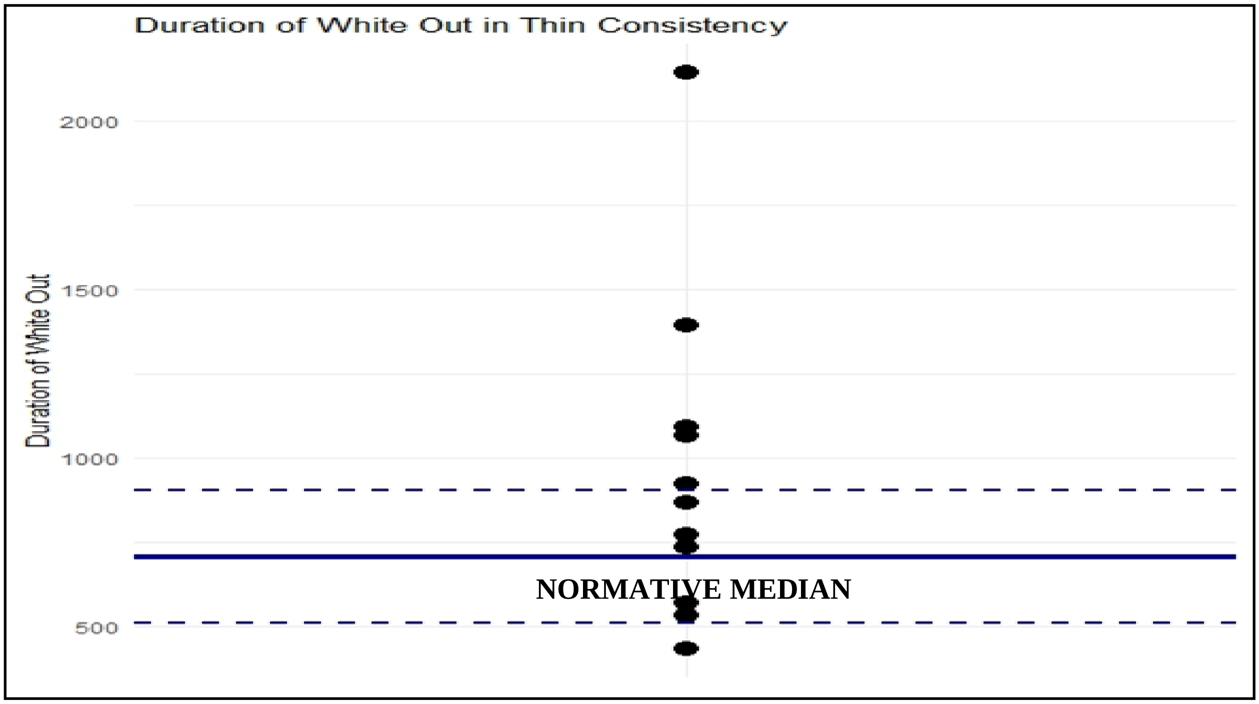
The individual data points in the neurogenic group remained widely distributed, with several participants continuing to exhibit delayed and inconsistent swallow triggering in solid bolus (Figure 3). While previous literature has reported that increased bolus viscosity may enhance sensory input and improve swallowing safety in neurological populations (Clavé et al., 2006; Newman et al., 2016), such facilitative effects were not consistently observed in the present study. These findings may be suggestive of impaired sensory–motor integration and reduced efficiency in pharyngeal swallow initiation irrespective of bolus consistency in neurogenic dysphagia.

Duration of Whiteout

Similar to the previous, swarm plots were generated to visually compare the individual duration of white-out in the neurogenic dysphagia cohort with the normative median obtained from healthy adults across bolus consistencies in milk (Figure 4), curd (Figure 5), and solid boluses (Figure 6). These figures illustrate the visual plot of the duration of white-out in neurogenic cohorts compared to the median duration of white-out obtained from a group of healthy adults in similar boluses. The horizontal lines denote the normative median range, whereas the individual data points indicate the individual values from the neurogenic cohort.

Figure 4.

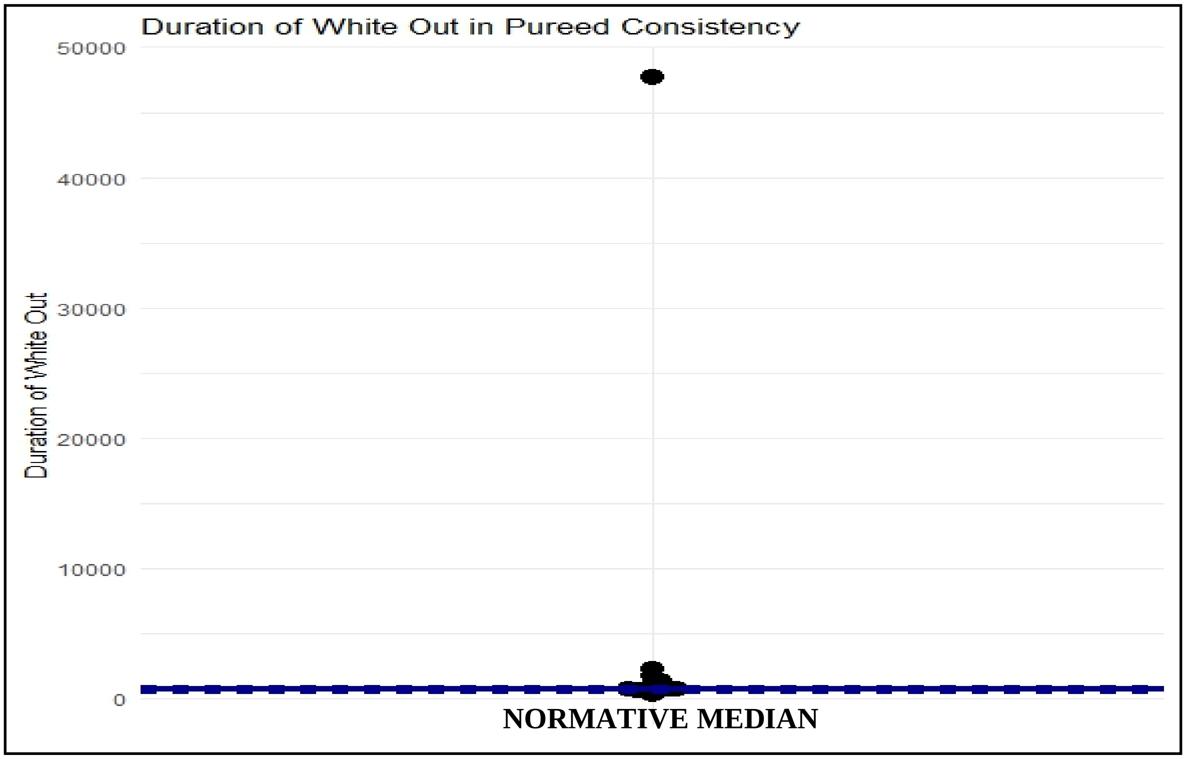
Duration of White-out in Thin-Consistency (Milk) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median and range of the duration of whiteout during milk swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the duration of white out during milk swallows in the neurogenic cohort included in the current study.

Figure 5.

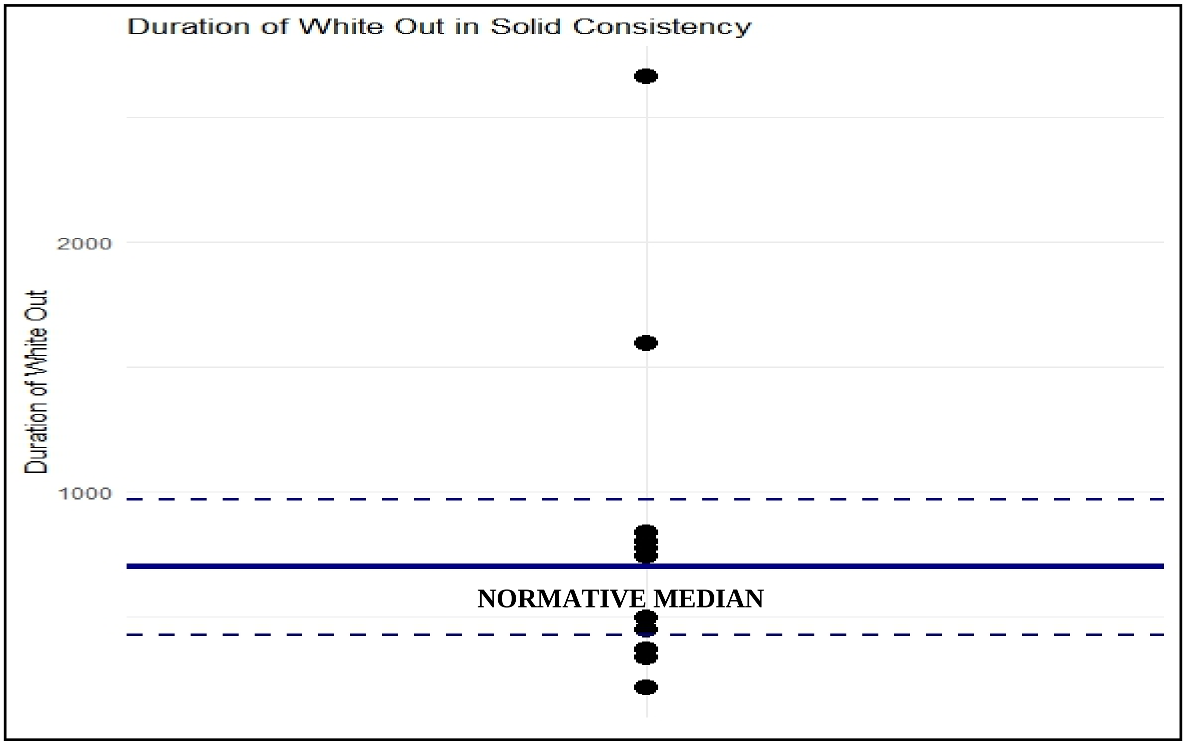
Duration of White-Out in Puree Consistency (Curd) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of duration of whiteout during pureed swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the duration of whiteout during pureed swallows in the neurogenic cohort included in the current study.

Figure 6.

Duration Of Whiteout in Solid Consistency Swallows Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median and range of duration of whiteout during solid swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the duration of whiteout during solid swallows in the neurogenic cohort included in the current study.

The white-out phenomenon during FEES evaluations refers to the brief loss/disturbance in the endoscopic image that is caused by strong pharyngeal constriction around the endoscope during a pharyngeal swallow. Literature identifies white-out as an important physiological marker of pharyngeal swallow initiation (Menon, 2022) and pharyngeal constriction (Schindler et al., 2022). The presence of a timely, strong, coordinated white-out phenomenon is clinically relevant for clinicians in interpreting swallow timing and airway protection events (Mozzanica et al., 2019). The duration and characteristics of white-out have also been explored in objective dysphagia diagnostic measures using instrumental evaluations (Betito et al., 2024; Mozzanica et al., 2019; Sutton et al., 2024).

In the current study, the duration of white-out was measured from the onset of complete white-out (WO) to the first frame in which the hypopharynx became visible (Table 2). Figure 4 to 6 are visual plots of the duration of whiteout in thin, puree, and solid consistency bolus across the neurogenic cohort and the healthy cohort. Comparing these figures, the individual data on duration of white-out was more variable and dispersed in thin liquid (milk) consistency than in other thicker boluses (Figure 4). Few individuals diagnosed with neurogenic dysphagia performed within the range of typical healthy individuals, while there were individual variations on either scale of the normative range. The dispersion and variability were minimal for puree consistency (Figure 5), with most individuals with neurogenic dysphagia performing within the ‘typical’ range for this bolus consistency. Solid bolus, though less dispersed than liquid bolus, had individuals performing at the higher and lower ends of the typical range, suggesting individual variability in the duration of the white-out phenomenon in thin and solid consistencies in neurogenic dysphagia.

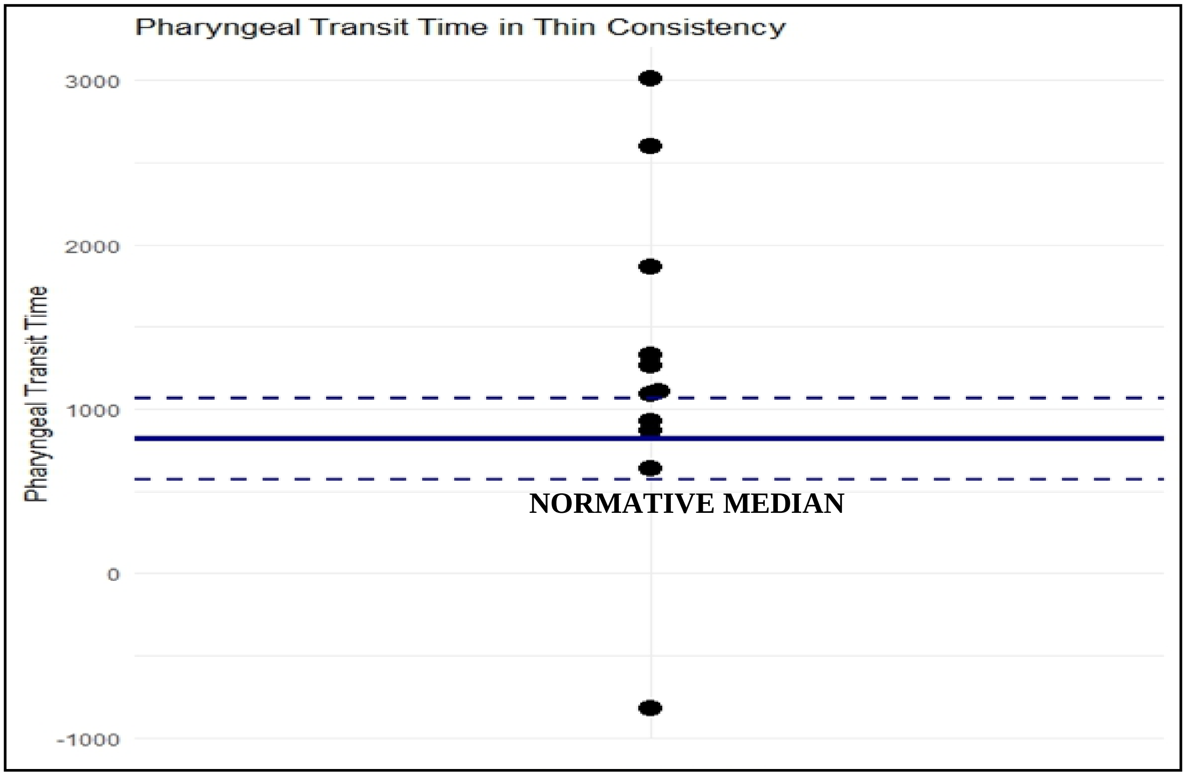
Several studies have demonstrated that pureed boluses have greater cohesiveness, reduced flow velocity, and improved oral and pharyngeal control compared to thin liquids, thereby reducing the likelihood of premature spillage and airway invasion (Bolivar-Prados et al., 2019). Increased bolus viscosity provides greater oropharyngeal sensory input and prolongs bolus transit through the swallowing system, allowing additional time for neuromuscular mechanisms involved in swallowing to initiate and coordinate an effective pharyngeal response (Liu et al., 2023). The rheological characteristics of pureed consistencies, including better cohesiveness, extensibility, and yield stress, contribute to improved bolus stability and swallowing efficiency while reducing aspiration risks (Nishinari et al., 2019). Consistent with this finding, Ismael-Mohammed et al.,(2023)reported that the cohesiveness of thick pureed bolts remains stable throughout the oral processing, thereby facilitating bolus integrity during swallowing. Thicker boluses are consequently recommended for individuals with delayed pharyngeal swallow initiation for improved swallowing performance (Logemann, 1995). The findings of the present study are consistent with the prevailing literature, with the duration of the white-out during puree swallows comparable to the normative median obtained from healthy adults. This suggested relatively preserved pharyngeal swallowing performance and airway-protective function for this bolus consistency in the neurogenic cohort.

Pharyngeal Transit Time

Swarm plots were generated to visually compare the individual pharyngeal transit time in the neurogenic dysphagia cohort with the normative median obtained from healthy adults across bolus consistencies in milk (Figure 7), curd (Figure 8), and solid boluses (Figure 9). These figures illustrate the visual plot of the pharyngeal transit time in neurogenic cohorts compared to the median measure obtained from a group of healthy adults in similar boluses. The horizontal lines denote the normative median range, whereas the individual data points indicate the individual pharyngeal transit times obtained from the neurogenic cohort in the current study.

Figure 7.

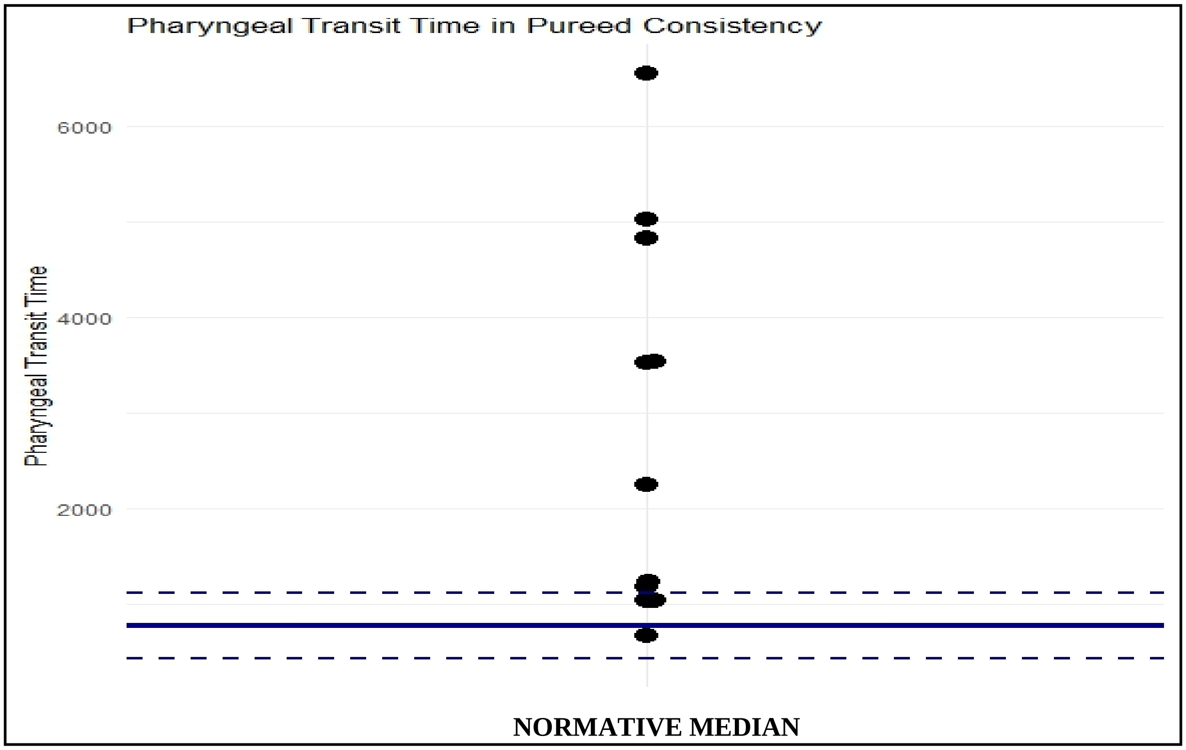
Pharyngeal Transit Time in Thin Bolus Consistency (Milk) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of pharyngeal transit time during milk swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the pharyngeal transit time during milk swallows in the neurogenic cohort included in the current study.

Figure 8.

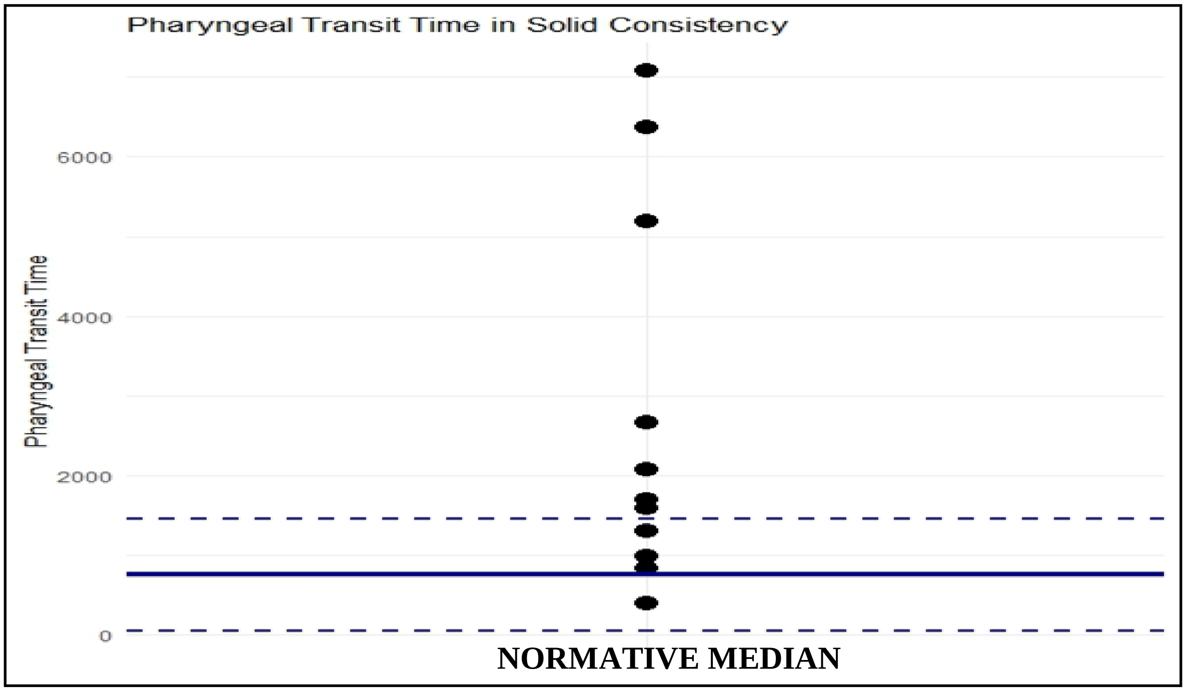
Pharyngeal Transit Time in Pureed Bolus Consistency (Curd) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of pharyngeal transit time during pureed swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the pharyngeal transit time during pureed swallows in the neurogenic cohort included in the current study.

Figure 9.

Pharyngeal Transit Time in Solid Bolus Consistency Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of pharyngeal transit time during solid swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the pharyngeal transit time during solid swallows in the neurogenic cohort included in the current study.

Pharyngeal transit time (PTT) is traditionally defined as the duration required for the bolus to pass through the pharynx. It is typically measured from the initiation of the pharyngeal swallow (identified with white-out frame in FEES evaluation) to the entry of bolus into the upper esophageal sphincter (visualized in VFSS, but not visualized in FEES) (Labeit et al., 2023).. Using the VFSS technology, various researchers have explored the clinical utility of pharyngeal transit time in dysphagia diagnostics (Yang et al., 2018). Prolonged PTT is an important indicator of impaired pharyngeal swallowing efficiency and delayed bolus clearance (Bingjie et al., 2010). Prolonged PTT may be associated with reduced pharyngeal constriction, weakness of the pharyngeal musculature, delayed swallow initiation, impaired sensory-motor integration, and discoordination of swallowing musculature in neurogenic dysphagia (Henderson et al., 2016; R. J. Leonard et al., 2000; Yip et al., 2006). Association between transit times and increased pharyngeal residue, reduced swallowing efficiency, and a higher risk of penetration and aspiration has been reiterated by previous reports (Im et al., 2012; Nordio et al., 2020; R. Leonard, 2019). This measure has also been shown to adapt as per the pharyngeal flow conditions related to tissue strength as well as bolus properties (Nascimento et al., 2015). Therefore, quantification of pharyngeal transit time was expected to provide valuable objective information regarding swallowing timing, coordination, and airway safety in neurogenic dysphagia evaluation.

From table 2, the prevalidated definition for pharyngeal transit time as visualized in clinical FEES evaluation was calculated as 'the time interval from the earliest frame showing either bolus head presence in the pharynx or white-out onset (whichever occurs first) to the first frame demonstrating minimal residue after the white-out phase (Offset-Onset).' This definition was derived as per the visual frames available in the FEES evaluation. The frames selected in the definition were closest to the frames traditionally used with VFSS data. From figures 7-9, the neurogenic dysphagia cohort deviated from the typical PTT measure in thin liquid, puree, and solid consistency boluses, though not without individual variability in this measure. Prolonged PTT was common in the neurogenic dysphagia cohort across all consistencies.

Pharyngeal transit time (PTT) reflects the efficiency of bolus transport through the pharynx and is governed by the coordinated interaction of bolus characteristics, sensory input, neuromuscular control, and pharyngeal biomechanics. Bolus viscosity and volume are known to influence transit duration, with thicker consistencies generally producing slower but more controlled bolus flow because of increased resistance and altered propulsion demands (Im et al., 2012; Sia et al., 2018). Efficient pharyngeal transit depends on the timely initiation of the swallow response and the coordinated physiological performance (Kahrilas et al., 1992; R. Leonard et al., 2023). Neurological impairment may compromise one or more of these mechanisms, resulting in delayed bolus propulsion and prolonged PTT (Robbins et al., 1993). Matsuo and Palmer (2008) further reported that reduced tongue base retraction and diminished pharyngeal constrictor activity in neurogenic dysphagia populations compromised pharyngeal driving forces. This delayed oropharyngeal transit and increased pharyngeal residue in their population. Additional influences such as fatigue, cognitive status, respiratory–swallow coordination, posture, and compensatory adaptations may further modify pharyngeal transit dynamics (Bülow et al., 2003; Daniels et al., 2007; Logemann, 1995)

Existing evidence regarding the effect of bolus consistency on PTT remains mixed. Steele & Lieshout (2004) reported only minor variations in lingual kinematics across liquid viscosities, suggesting limited consistency-related adaptation in certain swallowing measures. Cassiani et al. (2011) noted no significant differences in oral or pharyngeal transit time between liquid and paste consistencies, while Nascimento et al. (2015) highlighted the relative stability in the temporal relationship between pharyngeal clearance duration and hyoid movement duration across variations in bolus volume and consistency. In contrast, Im et al. (2012) found that the pharyngeal transit duration was influenced by age, sex, and bolus viscosity, with longer transit times observed in older adults, females, and thicker consistencies. When viewed collectively, these findings suggest that PTT is a multifactorial measure influenced not only by bolus properties but also by individual physiological and neurological factors, which may outline the variability observed across clinical populations.

From the literature, pharyngeal transit time can be considered a functional consequence of multiple physiological and biomechanical properties related to the swallowing process. The current study is in concordance with the known dimensions of pharyngeal transit time with large inter-subject variability in the measure across consistencies in the neurological cohort included in the study. In the present study, one individual with neurogenic dysphagia demonstrated a pharyngeal transit time that was shorter than the normative reference range during thin-liquid swallowing (Figure 7). Although prolonged transit time is more commonly reported in neurogenic dysphagia, a shortened transit duration may reflect altered bolus flow characteristics rather than improved swallowing efficiency. One possible explanation is premature posterior spillage of the bolus into the pharynx prior to the initiation of the pharyngeal swallow, resulting in an apparently shorter measured transit interval.

Schaefer et al. (2024) reported that premature spillage was among the most frequent swallowing abnormalities observed in individuals with isolated cerebellar stroke, indicating a disruption in the coordination of bolus control and transfer resulting in fragmented bolus propulsion.

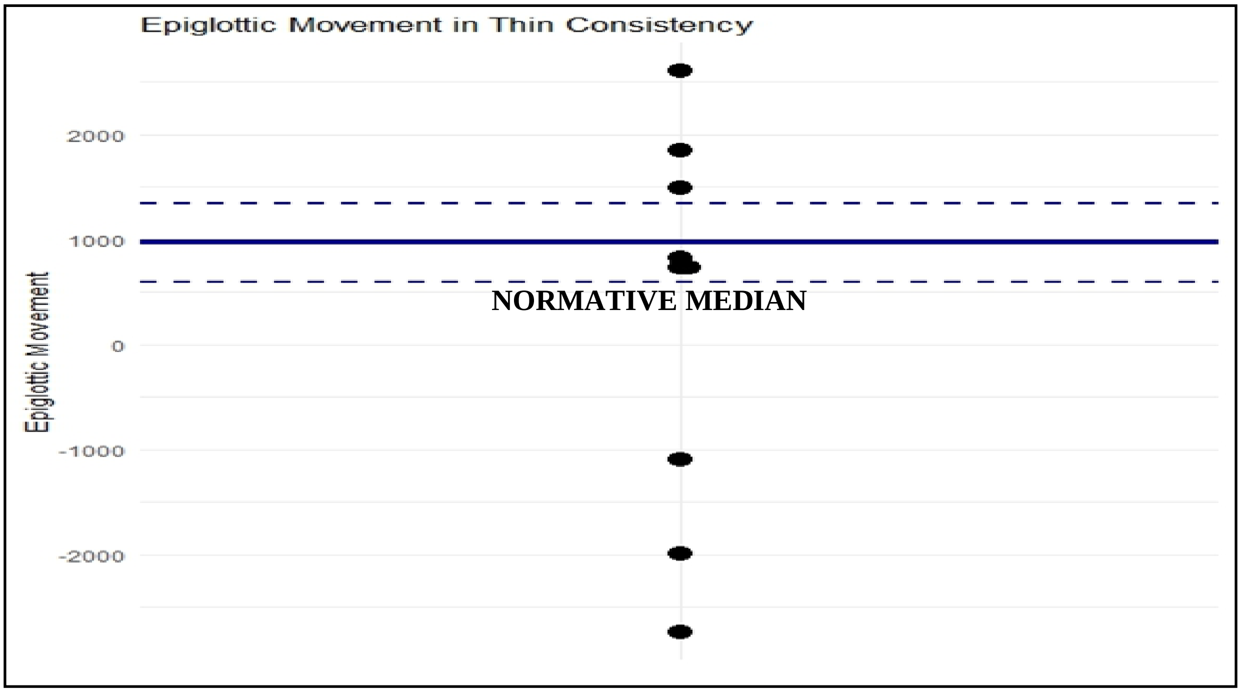
In agreement with this, studies of post-stroke dysphagia have shown that the premature spillage occurs secondary to reduced oral bolus control, impaired tongue-based retraction, reduced pharyngeal contractility, upper esophageal sphincter dysfunction, bulbar and pseudobulbar involvement, and deficits in cortical control of swallowing (Labeit et al., 2023). Previous investigations have also reported premature spillage as a common finding in acute and supratentorial stroke populations (Suárez-Escudero et al., 2022). Consistent with these observations, premature spillage was identified in the present neurogenic cohort, suggesting impaired bolus containment and delayed swallow initiation. Therefore, the shortened pharyngeal transit time observed in this participant should not necessarily be interpreted as superior swallowing performance but rather as a potential marker of impaired sensorimotor control resulting in early bolus entry into the pharynx.

Time taken for the return of the epiglottis post-swallow

The analysis of time taken for the return of the epiglottis post-swallow yielded comparatively fewer analyzable data due to difficulties in visualizing the frames of reference for the calculation of this outcome as per the pre-validated definition (Table 2). Figure 10-12 are swarm visual plots of the epiglottic movement measure during a swallow in the population with neurogenic dysphagia compared to the median measure obtained from a group of healthy adults in a different research study by Preethi et al. (unpublished dissertation).

Figure 10.

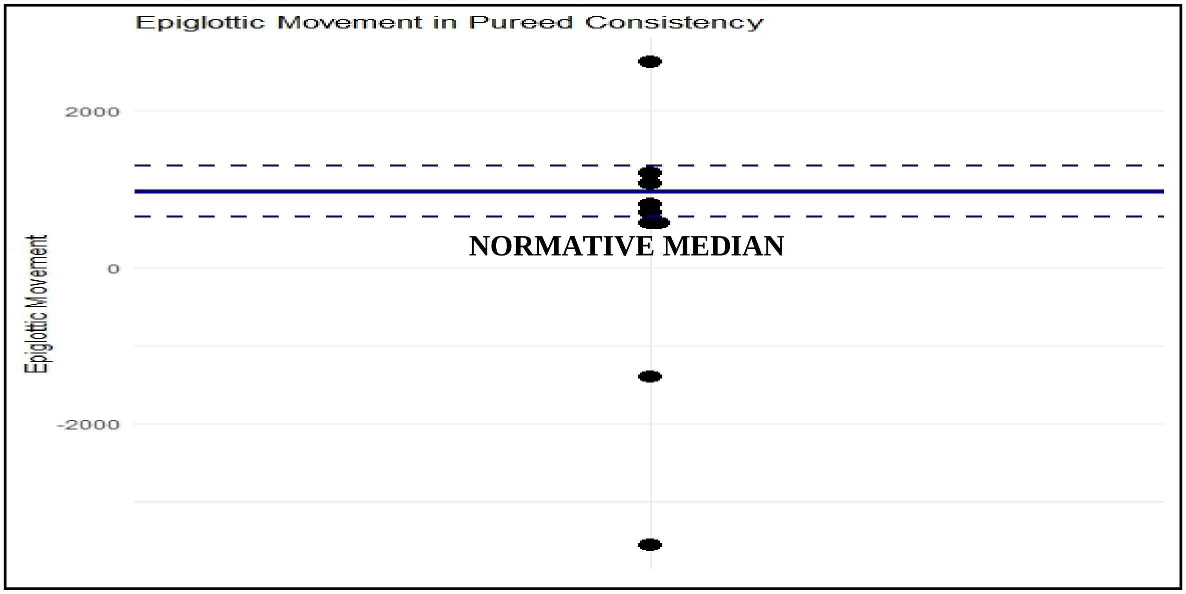
Time Taken for the Return of the Epiglottis Post-Swallow in Thin Bolus Consistency (Milk) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of time taken for the return of the epiglottis post-swallow during milk swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the time taken for the return of the epiglottis post-swallow during milk swallows in the neurogenic cohort included in the current study.

Figure 11.

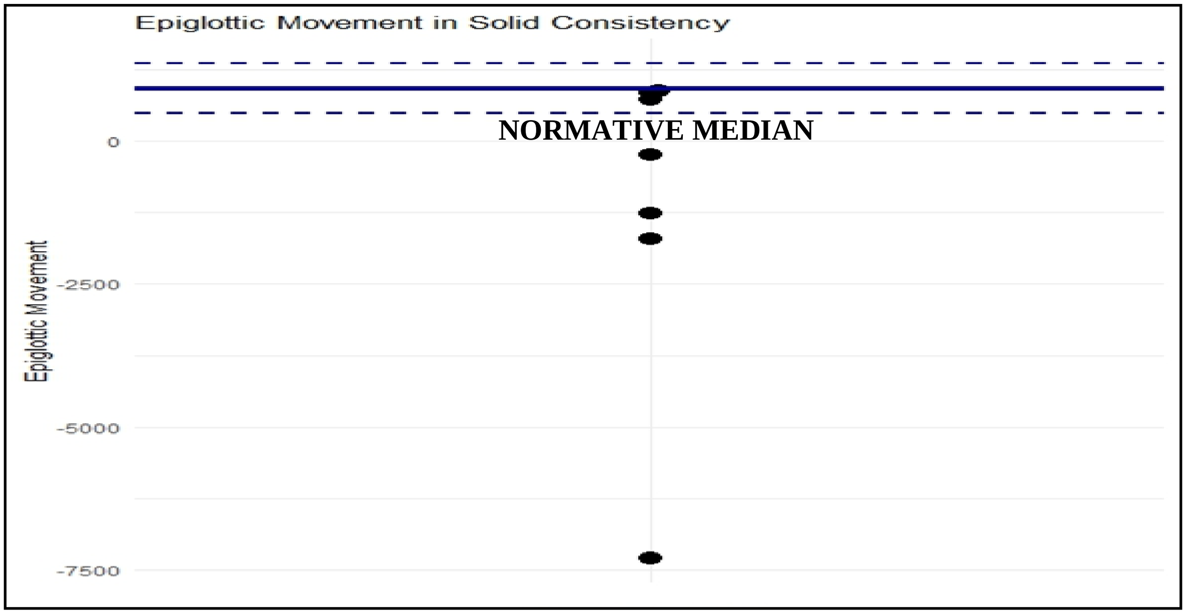
Time Taken for the Return of the Epiglottis Post-Swallow in Pureed Bolus Consistency (Curd) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of time taken for the return of the epiglottis post-swallow during pureed swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the time taken for the return of the epiglottis post-swallow during pureed swallows in the neurogenic cohort included in the current study.

Figure 12.

Time Taken for the Return of the Epiglottis Post-Swallow in Solid Bolus Consistency Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of time taken for the return of the epiglottis post-swallow during solid swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the time taken for the return of the epiglottis post-swallow during solid swallows in the neurogenic cohort included in the current study.

The current study defined epiglottic movement as the 'time interval from the initiation of epiglottic downward movement over the airway to the final frame of anterior epiglottic movement toward the base of the tongue after white-out (Offset-Onset).' This required visualization of the frame that initiated inversion and also the last frame after the return of the epiglottis after the whiteout. In individuals with neurogenic dysphagia, visualization of these frames was inconsistent due to premature spillage, the onset of white-out before visualization of epiglottic movement, or pharyngeal residue after white-out. Therefore, the number of data points available for comparison across neurogenic dysphagia and healthy cohorts was less than in other outcome measures considered in this study.

From figure 10-12, a pattern of dispersion of the temporal measurement of time taken for epiglottic movement during swallowing was evident across consistencies. In thin liquid swallows, the epiglottis showed varied timing of epiglottic movement, with temporal measures comparable to, less than, and longer than the median measure in healthy individuals (Figure 10). Whereas, in thicker boluses (curd), the number of individuals with deviant temporal measures for epiglottic movement during swallowing was lower, with the majority of available data within the healthy range (Figure 11). In the solid bolus, individual data points in the neurogenic dysphagia group were less than the norm-reference range, suggesting a shorter duration for epiglottic inversion (Figure 12). This deviation in performance may contribute to compromised airway protection and increased risk of penetration/aspiration in individuals with neurogenic dysphagia.

Epiglottic inversion is considered a largely passive biomechanical event that occurs secondary to superior–anterior hyolaryngeal excursion and tongue base retraction during the pharyngeal swallow. Reduced tongue base retraction and impaired laryngeal elevation have been associated with incomplete epiglottic inversion and altered airway protection mechanisms (Pearson et al., 2016). Computational and physiological studies further suggest that adequate hyolaryngeal movement and tongue base movement are essential contributors to complete epiglottic deflection and laryngeal vestibule closure (Vose & Humbert, 2019). During normal swallowing, airway protection is achieved through coordinated closure of the laryngeal vestibule by a sphincteric pattern closure created by the arytenoid approximation toward the epiglottic base, while anterior and superior displacement of the hyoid bone and larynx facilitates inversion of the epiglottis over the laryngeal inlet (Logemann, 1995). Consequently, impaired epiglottic inversion may result in incomplete laryngeal vestibule closure, thereby increasing the risk of penetration and aspiration and reducing the pharyngeal pressure drive for the bolus clearance resulting in post-swallow pharyngeal residue in individuals with neurogenic dysphagia (Matsuo & Palmer, 2008).

Previous VFSS-based research on epiglottic kinematics and airway protective mechanisms during swallowing has reported considerable variability in epiglottic movement patterns and timing across swallows (Logemann et al., 1992) and individuals (Garon et al., 2002). The variability may be a reflection of the natural adaptation of normal swallowing physiology in response to bolus properties and individual biomechanical characteristics (Pearson et al., 2016; Steele et al., 2019). There was wide variability in the performance of the neurogenic dysphagia population of the current study in the time taken for epiglottic movement during swallowing, probably as an adaptive behavior or as a compensatory strategy. Individual variability was particularly evident during liquid swallows, possibly indicating heterogeneous compensatory adaptations among participants with neurogenic dysphagia. While some individuals may prolong epiglottic movement to enhance airway protection, others may demonstrate inadequate compensatory responses due to impaired sensory-motor integration and reduced pharyngeal biomechanics.

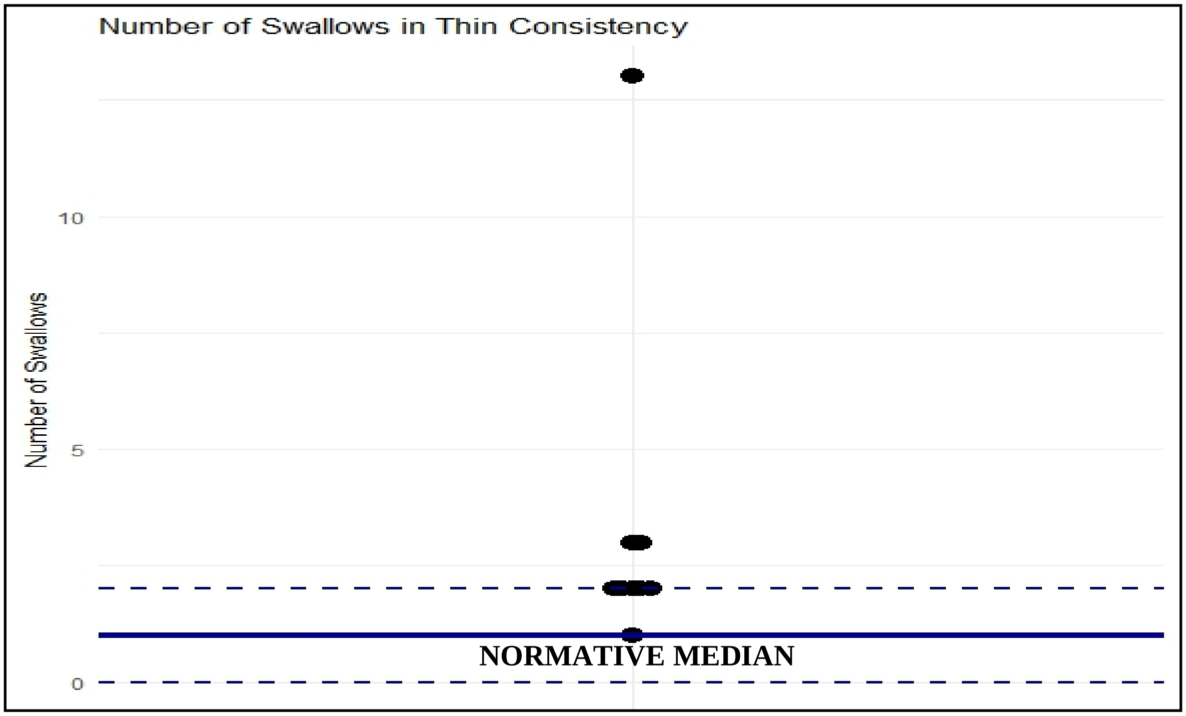
From the results of the present study, the duration of epiglottic inversion for thicker liquid consistency (curd) in neurogenic dysphagia was comparable with that of healthy cohorts, suggesting relatively preserved or compensatory airway protective performance for this specific bolus type. This finding supports the ‘safety’ of thicker liquids/semi-solids in individuals with neurogenic dysphagia (Clavé et al., 2006). However, with increasing bolus consistency toward solid textures, a reduction in epiglottic inversion duration was observed in the neurogenic cohort, indicating biomechanical inefficiency and increased swallowing safety concerns during solid bolus transit (Palmer et al., 1992). This finding supports the previous studies that found increased swallowing safety and efficiency concerns in solid bolus swallows in individuals with dysphagia (Matsuo & Palmer, 2008), and the current finding adds to the probable contributing physiology to these previous reports.

Number of Swallows

The number of 'spontaneous' swallows for each bolus trial was calculated from the clinical FEES evaluation dataset. On retrospective analysis, few individuals with neurogenic dysphagia had to be cued for multiple swallows for bolus clearance. These data had to be eliminated to maintain data reliability in the current analysis. Therefore, the number of data points for the measure 'number of swallows' was less than the total number of participants in the neurogenic group. Figure 13-15 are visual plots of the number of swallows for each bolus trial in the population with neurogenic dysphagia compared to the median number of swallows for similar bolus obtained from a group of healthy adults in another parallel investigation by Preethi et al. (unpublished dissertation).

Figure 13.

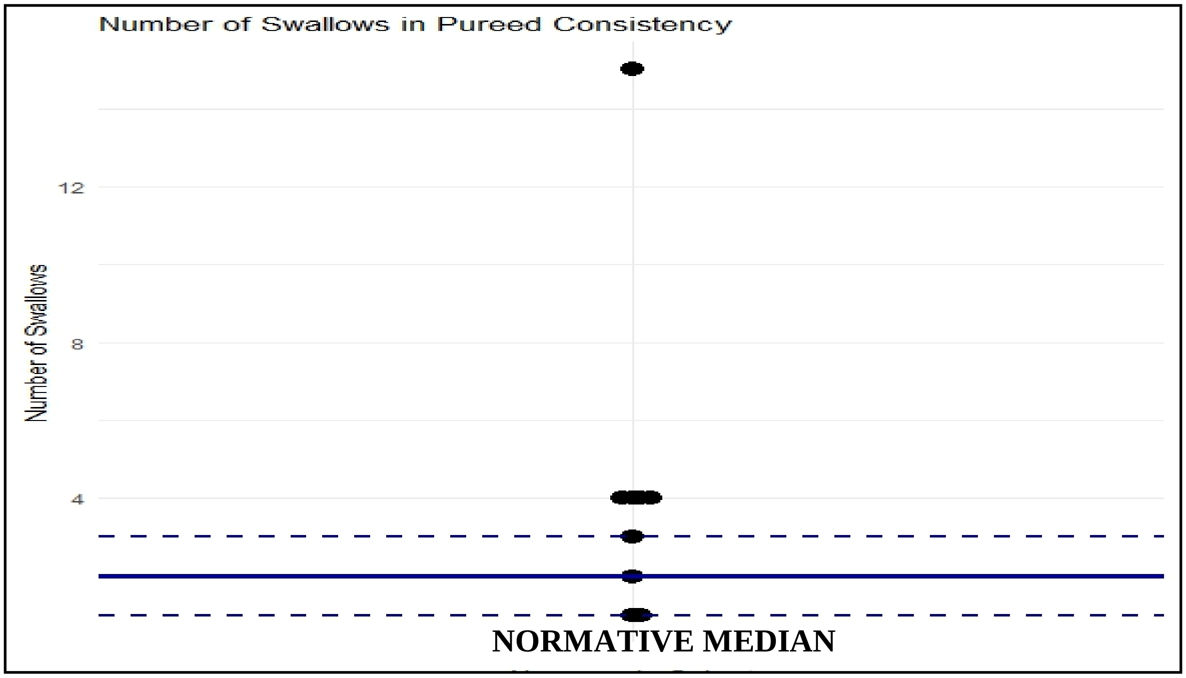
Number of Swallows in Thin Bolus Consistency (Milk) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of number of swallows during milk swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the number of swallows during milk swallows in the neurogenic cohort included in the current study.

Figure 14.

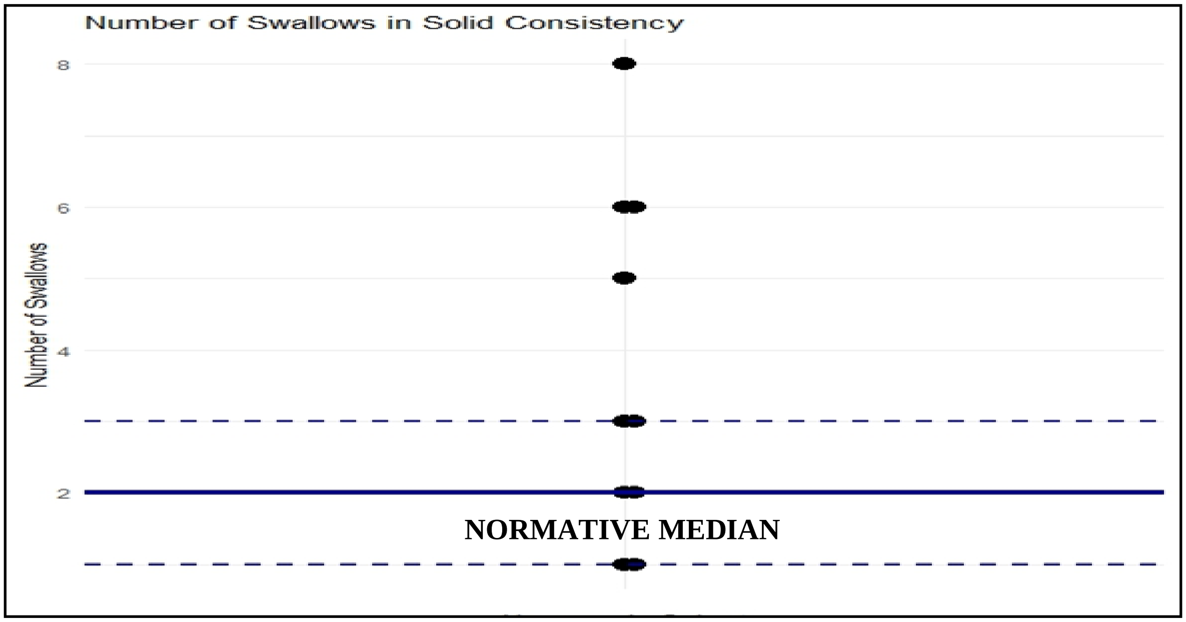
Number of Swallows in Pureed Bolus Consistency (Curd) Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of the number of swallows during pureed swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the number of swallows during pureed swallows in the neurogenic cohort included in the current study.

Figure 15.

Number of Swallows in Solid Bolus Consistency Swallows Across Neurogenic Dysphagia and Healthy Individuals.



Note: The blue horizontal lines denote the normative median range of number of swallows during solid swallows in a healthy cohort (Preethi et al., unpublished dissertation). The individual data points denote the number of swallows during solid swallows in the neurogenic cohort included in the current study.

The number of swallows per bolus is an important indicator of bolus manipulation and pharyngeal clearance efficiency (Santos et al., 2022). Sensory feedback mechanisms strongly mediate this function to continuously regulate swallowing safety and bolus propulsion. Sensory input from the oral, pharyngeal, and laryngeal receptors contributes to adaptive modulation of swallow volume and frequency based on the perceived safety limits and biomechanical capacity of the swallowing system (Steele & Miller, 2010). An increased number of swallows may therefore represent a sensory-mediated compensatory response to impaired bolus clearance, reduced swallowing efficiency, or concerns related to airway protection (Donohue et al., 2023).

During thin liquid swallows, the number of swallows in the neurogenic cohort was comparable to that of healthy individuals (Figure 13). Most participants demonstrated swallowing frequencies that were comparable to, or in the higher range of norm-reference from the healthy cohort, suggesting that individuals with neurogenic dysphagia did not substantially modify swallow volume or employ multiple swallows for thin liquid bolus swallows. Although a few participants demonstrated increased swallow frequency, the majority remained within or near the normative range, indicating a relatively preserved number of swallows and less swallow adaptation for liquid consistencies in neurogenic dysphagia.

A gradual increase in the number of swallows was observed with an increase in bolus consistency. Several participants demonstrated a greater number of swallows that were outside the normative reference range, although a subset continued to exhibit comparable performance to healthy adults (Figure 14). Increased bolus cohesiveness and prolonged oral containment associated with thicker consistencies (Hadde et al., 2019; Hiiemae & Palmer, 1999) may have contributed at least partially to the increased number of thicker bolus swallows. At this point, it can only be hypothesized that the cohesiveness of thicker boluses may require multiple swallows in individuals with significant oral transit-related concerns (Cichero & Murdoch, 2006; Hiiemae & Palmer, 1999). Further increase in bolus consistency resulted in greater variability in swallow frequency, with the majority of individuals with neurogenic dysphagia demonstrating a higher number of swallows compared to the reference range (Figure 15). All individual data points in the neurogenic cohort revealed increased numbers of swallows compared to typical adults, suggesting compensatory multiple-swallow behavior to facilitate bolus clearance and compensate for impaired swallowing efficiency.

Rademaker et al. (1994) reported that individuals with dysphagia required a greater number of swallows per bolus across multiple consistencies in relation to healthy controls, reflecting reduced swallowing efficiency and the need for adaptive clearance mechanisms. Ertekin et al. (1996) introduced the concept of the dysphagia limit, defined as the maximum bolus volume that can be safely swallowed in a single swallow, and demonstrated that individuals with dysphagia frequently require multiple swallows because of reduced swallowing capacity. This interpretation is supported by evidence from neurogenic populations. Belo et al. (2014) reported that individuals with Parkinson's disease demonstrated reduced volume per swallow and increased swallowing frequency, suggesting a compensatory reduction in bolus size to accommodate impaired swallowing physiology. Multiple swallows are widely recognized as an indicator of reduced swallowing efficiency and are commonly associated with incomplete bolus clearance, pharyngeal residue, and increased swallowing effort (Palmer, 2020). Increased swallow frequency has also been reported in individuals with multiple sclerosis and Devic's syndrome, particularly during solid bolus intake, where repeated swallows were interpreted as compensatory responses to increased swallowing effort and impaired bolus clearance (Milewska et al., 2020). Therefore, rather than representing a pathological event in isolation, repeated swallows are often interpreted as an adaptive compensatory strategy intended to improve bolus clearance and maintain swallowing safety in individuals with dysphagia.

The influence of bolus characteristics further supports this interpretation. Hiiemae and Palmer (1999) reported that solid foods often require sequential swallows even in typical swallowing because of the greater demands associated with mastication, bolus formation, and oral clearance.

Cichero and Murdoch (2006) reported a case study of an individual with cerebral palsy who required multiple swallows to clear solid bolus, due to his pronounced impairment in oral and pharyngeal phases. This study pointed out the increased physiological demands for the solid consistency. Previously reported evidence also supports this finding. Hadde et al. (2019) documented that poor cohesive boluses are prone to fragmentation, pharyngeal residue and the need for repeated swallows. Whereas, a bolus with greater cohesiveness maintains the bolus integrity during bolus transit. These boluses are cleared more efficiently, hence, an increased number of swallows serve as a marker for the identification of compensatory adaptations. This reflects the individual's attempt to overcome reduced swallowing capacity and maintain effective bolus clearance when swallowing more demanding bolus consistency.

In the present study, despite variations in swallow frequency across consistencies, the neurogenic cohort did not demonstrate substantial differences in several temporal swallowing measures. Previous literature has similarly reported that certain temporal parameters may remain relatively stable across bolus consistencies.

Comparison of Glottic Status Before and After Swallow Across Different Bolus Consistencies. The frame immediately before and after the whiteout was identified, and the status of glottic closure before and after the swallow was documented. From the data, four distinct types of closure patterns were suggested depending on whether the glottis was open (O) or closed (C). The patterns were categorized as closed-to-closed (C–C), closed-to-open (C–O), open-to-open (O–O), and open-to-closed (O–C) for each bolus trial in the retrospective data set. The frequency of occurrence of each pattern was calculated across bolus conditions (Table 4)

Table 4

Frequency of occurrence of each pattern of glottic status across bolus trials in neurogenic dysphagia

	O-O (%)	O-C (%)	C-O (%)	C-C (%)	**Total swallows by bolus type**
Milk	2 (33.33)	-	4 (66.67)	-	**6**
Puree	3 (52.38)	-	4 (57.14)	-	**7**
Biscuit	2(33.33)	-	3 (50.00)	1 (16.66)	**6**
Total swallows by glottic type	**7 (36.84)**	**-**	**11(57.89)**	**1 (5.26)**	**19**

From table 4, the C–O pattern (closed before and open after whiteout) demonstrated the highest frequency of occurrence across all consistencies in neurogenic dysphagia. Second in order of frequency of occurrence is the O-O pattern (open before and after the white-out) in all consistencies. The C-C pattern was also rare, with only one instance of a closed glottis before and after a solid swallow being observed. There was no occurrence of the O-C pattern observed among neurogenic dysphagia in the current study. These findings reflect the variability in glottic closure patterns in neurogenic dysphagia cohorts.

Respiratory–swallow coordination is an essential component of swallowing safety. The typical pattern of respiration during the swallowing process in healthy adults is characterized by expiration before and after the swallow (Ex/EX, Hiss et al., 2001). This pattern of expiration followed by expiration after swallow is considered physiologically protective; the post-swallow exhalation assists in clearing the residue from the laryngeal vestibule (Martin-Harris et al., 2005). This can in turn reduce the likelihood of airway invasion following the bolus passage. Previous investigations of respiratory–swallow coordination have identified four principal respiratory phase patterns: expiration/expiration (EX/EX), expiration/inspiration (EX/IN), inspiration/expiration (IN/EX), and inspiration/inspiration (IN/IN) (Martin-Harris et al., 2005). These patterns may be represented as close-close (C-C), close-open (C-C), open-close (O-C) and open-open (O-O) glottic configurations in relation to the swallowing events (Brancatisano et al., 1983; Sasaki et al., 2005). In the study, the EX/EX pattern was more prevalent in healthy adults, thereby regarded as the most airway protective pattern, whereas EX/IN and IN/IN patterns occurred less frequently (Martin-Harris et al., 2005).

Effective airway protection during deglutition relies on timely vocal fold and glottic closure (Logemann, 1995). During a normal swallow, the inferior-superior progression of events for airway protection results in a coordinated sequence of vocal fold adduction, false vocal fold approximation, laryngeal elevation, and epiglottic inversion to prevent penetration and aspiration (Logemann, 1995). With resumption of respiration, there is a rapid reopening of the glottis after swallow completion (Kawasaki et al., 2001; Logemann et al., 1992; Ohmae et al., 1995; Van Daele et al., 2005). Although the importance of glottic closure for swallowing safety is well established, the precise temporal characteristics of glottic closure and reopening remain difficult to quantify during routine clinical examinations due to variability and image obstruction during the swallowing process. Hence, the present study focused on profiling patterns of glottic status before and after the white-out rather than measuring the exact timing of closure. This variable may be more appropriately interpreted as a swallowing performance outcome than a true temporal measure.

The predominance of the closed–open (C–O) pattern across bolus consistencies in the present neurogenic dysphagia cohort (Table 4) may suggest relatively preserved airway protective behavior in at least a proportion of individuals with neurogenic dysphagia. The observed pattern of glottic closure in the current study is consistent with the physiological sequence described in healthy swallowing (Matsuo & Palmer, 2009). However, the relatively frequent occurrence of the open–open (O–O) pattern across consistencies in neurogenic dysphagia is clinically noteworthy. Maintenance of an open glottic configuration before and after swallowing may contribute to reduced effectiveness of lower airway protection, increasing the risk of penetration or aspiration in individuals with impaired sensorimotor control. This interpretation is supported by evidence demonstrating increased swallowing safety concerns in populations with vocal fold paresis and other conditions affecting glottic competence (Cates & Kuhn, 2019; Ha, 2020; Onwordi & Al Yaghchi, 2026).

The differences in the glottic response patterns denote the increased sensorimotor demands caused by the changes in bolus volume and viscosity (Dantas et al., 1990). Neurological impairment may further alter airway protective strategies and disrupt the coordination between respiratory and swallowing events (Hadjikoutis, 2000). These findings suggest that while glottic closure patterns appear relatively preserved in individuals with neurogenic dysphagia, the increased occurrence of non-protective glottic closure patterns may be an important mechanism contributing to airway safety concerns in this population.

Association between objective temporal measures and subjective measures of safety and efficiency of swallow.

The swallowing safety and efficiency of swallows were measured using the penetration-aspiration scale (Rosenbek et al., 1996) and Yale pharyngeal residue scale (Neubauer et al., 2015) for clinical purposes. These are ordinal scales of measurement, while the temporal measures are ratio scales of measurement. Also, the number of samples that could be successfully included for measurement was limited (n=15). Hence, Spearman's rank-order correlation was performed separately for each bolus consistency across the specific temporal measure and each ordinal scale. This analysis was expected to reveal any relationship between objective temporal swallowing measures and subjective swallowing scores (PAS and Yale residue scores). The raw subjective data on swallowing safety and efficiency are provided in Table 5.

Table 5

Swallowing Safety and Efficiency Scores of the Neurogenic Cohort Included in the Current Study.

Sl no.	*Age*	*Gender*	*Type of dysphagia*	*PAS*			*Yale Residue score*		
				Thin	*Pureed*	*Solid*	*Thin*	*Pureed*	*Solid*
1	63	Male	OPD	2	2	1	2	1	0

2	66	Male	PD	1	1	1	0	1	0
3	45	Female	OPD	-	4	-	-	3	-
4	68	Male	OPD	1	1	1	1	1	3
5	55	Male	OPD	-	-	1	-	-	2
6	18	Male	OD	1	1	1	0	1	0
7	60	Male	PD	1	-	-	0	-	-
8	79	Male	PD	1	1	1	1	0	0
9	62	Male	OPD	-	1	1	-	2	2
10	81	Male	OPD	2	1	1	2	1	1
11	72	Male	OPD	3	-	-	0	-	-
12	65	Female	OPD	2	1	-	3	2	-
13	50	Male	OPD	1	1	1	2	2	3
14	75	Male	OPD	2	2	3	1	1	2
15	82	Male	OPD	-	5	5	-	3	3

Note: OPD- Oropharyngeal dysphagia, OD- Oral dysphagia, PD- Pharyngeal dysphagia

Spearman's correlation was run for each temporal measure with the PAS and YPRS scores in thin liquid consistency (Table 6).

Table 6

Results of Spearman's Correlation Between Each Temporal Measure and PAS Scores/ Yale Scores in Thin Consistency

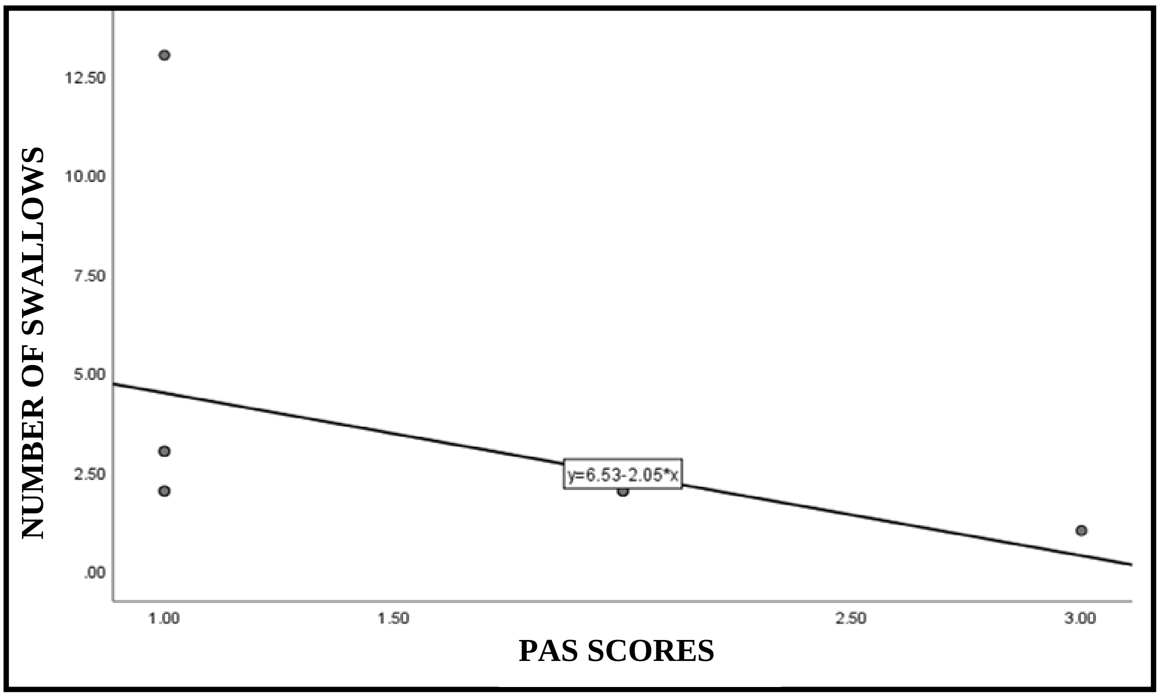
Temporal measure	**Penetration Aspiration Scale Scores**		**Yale Pharyngeal Residue Scores**	
	Spearman rho (ρ)	p value	Spearman rho (ρ)	p value
Latency of Swallow Reflex	-0.153	0.654	-.242	.474
White Out Duration	0.382	0.246	.213	.529
Pharyngeal Transit Time	0.153	0.654	.057	.868
Time Taken for the Return of the Epiglottis Post-Swallow	0.219	0.571	-0.339	0.373

Number of swallows	-0.739	0.023*	0.142	0.715

*Note: * indicates p <0.05*

Figure 16.

Scatter Plot of the Number of Thin Liquid Swallows and PAS Scores in Neurogenic Dysphagia



Note: PAS- Penetration Aspiration Scale

From Table 6, no significant correlation was obtained between residue scores and temporal measures in the current study. The small sample size and/or the characteristics of the temporal measures considered in the current study may have contributed to this result. Interestingly, a statistically significant strong negative correlation was obtained between the number of swallows and that of penetration-aspiration score (ρ= -0.739, p= 0.02). This may be interpreted as a reduction in PAS scores with an increase in the number of thin-liquid swallows in individuals with neurogenic dysphagia. The same is represented in the scatterplot to reveal the pattern of association between the number of swallows and PAS scores (Figure 16). From this figure, it may be inferred that a lesser number of swallows (spontaneous/compensatory) may be associated with an increased risk of aspiration (higher PAS scores).

There is a growing body of evidence that suggests a close association between swallowing frequency and swallowing safety and that it reflects the integrity of the sensorimotor mechanisms underlying airway protection. Although spontaneous swallowing frequency and bolus-related swallowing frequency represent distinct constructs, both are influenced by sensory input, central swallowing control, and the efficiency of airway clearance mechanisms. Crary et al. (2013) demonstrated that reduced spontaneous swallowing frequency was a strong indicator of dysphagia in individuals with acute stroke, proposing swallow frequency as a simple and non-invasive marker of swallowing impairment. Carnaby et al. (2019) reported that reduced swallowing frequency was significantly associated with persistent dysphagia and poorer swallowing outcomes. Supporting these findings, the systematic review by Bulmer et al. (2021) concluded that lower spontaneous swallowing frequency is consistently associated with increased dysphagia risk, despite methodological heterogeneity across studies.

From a physiological perspective, an increased swallowing frequency may represent an adaptive response that facilitates bolus clearance and reduces pharyngeal residue, enhancing airway protection through repeated activation of swallowing and laryngeal closure mechanisms. Reduced swallowing frequency may then reflect impaired sensory awareness of pharyngeal residue, diminished swallowing drive, or reduced compensatory capacity, increasing the likelihood of airway invasion, consequently. These observations are consistent with the findings of the present study, where participants demonstrating fewer swallows for thin-liquid boluses exhibited higher PAS scores, suggesting that reduced swallowing frequency may be associated with compromised airway protection and increased risk of penetration–aspiration in individuals with neurogenic dysphagia.

Similar analysis was conducted between temporal measures and swallowing safety and efficiency scores in puree bolus consistency, and the results are presented in Table 7. Similar to the thin bolus swallows, there was a statistically significant strong positive correlation across the number of swallows and PAS scores ($\rho = 0.723$, $p = 0.043$), indicating that the more swallows required for a puree-consistency bolus swallow were associated with greater risk of airway intrusion in individuals with neurogenic dysphagia (Figure 17).

Using videofluoroscopic swallow study revealed enhanced swallow safety with increasing bolus viscosity, with safe swallowing observed in 80.6% of patients for pudding consistency, compared to 52.1% for nectar-thick liquids and only 32.9% for thin liquids (Clavé et al., 2008). Ferris et al. (2018) documented that piecemeal deglutition alters the swallowing biomechanics, and an increased number of swallows indicated better bolus management and clearance strategies. Further, Omari et al. (2022) investigated multiple swallow behaviours across different bolus volumes and consistencies and reported this behaviour as a normal adaptive response to increased bolus volume and thickness. From their study, piecemeal deglutition is predominantly observed in IDDSI level 4 (pureed/extremely thick). These findings suggest that pureed consistency can facilitate better swallowing safety, thereby reducing the risk of aspiration and penetration. The findings of this study pointed out that an increased number of swallows in pureed consistency may reflect reduced swallowing efficiency and incomplete bolus clearance, which requires repeated swallowing attempts and eventually contributes to a greater risk of aspiration/penetration in the neurogenic population.

Table 7

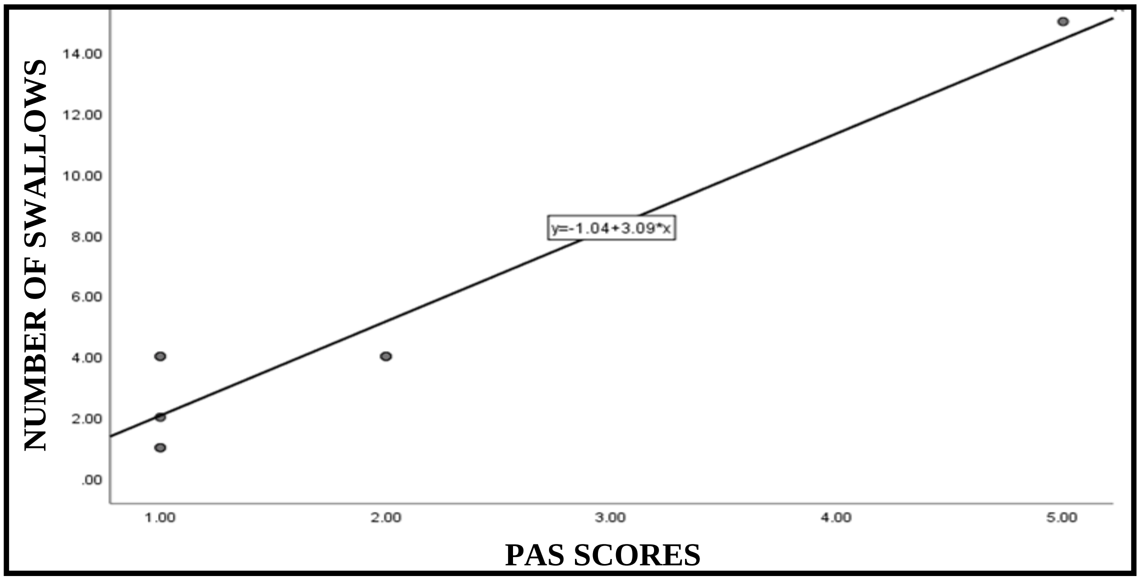
Results of Spearman's Correlation Between Each Temporal Measure and PAS Scores/ Yale Scores in Pureed Consistency

Temporal measure	**PAS Scores**		**Yale Pharyngeal Residue Scores**	
	Spearman rho (ρ)	p value	Spearman rho (ρ)	p value
Latency of Swallow Reflex	-.035	.919	.226	.505
White Out Duration	-.075	.826	.030	.930
Pharyngeal Transit Time	-.338	.339	.010	.977
Time Taken for the Return of the Epiglottis Post-Swallow	.016	.971	-.319	.441
Number of Swallows	0.723	.043*	.059	.891

*Note: * indicates p <0.05*

Figure 17.

Scatter Plot of the Number of Pureed Swallows and PAS Scores in Neurogenic Dysphagia



Note: PAS- Penetration-Aspiration Scale

There was no significant association between the temporal measures and residue rating, suggesting that these measures may be independent of each other. However, the results need to be interpreted with caution, considering the small sample size and variability in the number of data points across the measures that dilute the absolute statistical effect size.

Exploring the relationship between objective and subjective measures in solid boluses (Table 8), unlike the thin and pureed boluses, there was a marginally statistically significant moderately strong positive correlation between latency of swallow and PAS scores ($\rho = 0.607$, $p = 0.048$). This suggests that the higher the latency of swallowing a solid bolus, the higher the risk of airway intrusion (Figure 18). Similar to the other bolus consistencies, there was no significant correlation across temporal measures and pharyngeal residue rating, suggesting that swallowing efficiency was independent of the temporal measures included in the current study. Again, the results need to be interpreted with caution, owing to the small sample size and heterogeneity of the data.

Table 8

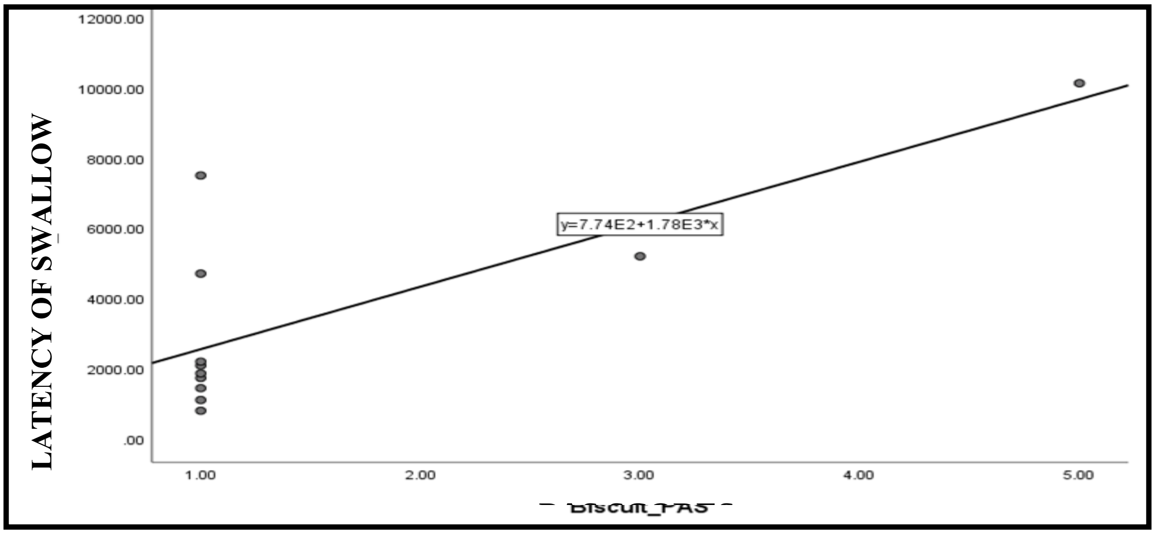
Results of Spearman's Correlation Between Each Temporal Measure and PAS Scores/ Yale Scores in Solid Consistency

Temporal measure	**PAS Scores**		**Yale Pharyngeal Residue Scores**	
	Spearman rho (ρ)	p value	Spearman rho (ρ)	p value
Latency of Swallow Reflex	.607	.048*	.455	.159
White Out Duration	.310	.353	.213	.529
Pharyngeal Transit Time	.391	.234	.313	.349
Time Taken for the Return of the Epiglottis Post-Swallow	.490	.264	-.019	.968
Number of Swallows	-.257	.474	.070	.847

*Note: * indicates p <0.05*

Figure 18.

Scatter Plot of the Latency of Swallow Reflex in Solid Consistency and PAS Scores in Neurogenic Dysphagia



Note: PAS- Penetration-aspiration scale

The present study explored the relationship between objective temporal swallowing measures and clinically relevant indicators of swallowing safety and efficiency, namely the Penetration–Aspiration Scale (PAS) and Yale Pharyngeal Residue Severity Rating Scale (YPRSRS). Previous literature has indicated the influence of bolus properties on swallowing physiology (Pena, 2024). Hence, correlation analysis was performed separately for each bolus consistency.

Pharyngeal residue is a multifactorial outcome that reflects the combined influence of multiple swallowing physiologies such as tongue base retraction, pharyngeal constriction, hyolaryngeal excursion, upper esophageal sphincter opening, bolus characteristics, and overall swallowing strength, pressure, and coordination (Chitose et al., 2024; Knigge & Thibeault, 2016; Steele et al., 2011; Stokely et al., 2015). These factors drive the bolus effectively through the pharynx, and an impairment in these processes reduces the driving force, reducing swallowing efficiency and clearance. In the current study, no significant association was observed between the temporal swallowing measures and pharyngeal residue ratings across any bolus consistencies. This may suggest that the temporal parameters examined in the current study may not directly predict pharyngeal residue severity in neurogenic dysphagia. In concurrence with the previous reports, the presence of pharyngeal residue may therefore represent the cumulative effect of multiple physiological events rather than a single temporal measure of swallowing. However, the relatively small sample size and variability in the number of measurable swallows across participants may have reduced statistical power and limited the detection of subtle relationships across the subjective and objective variables.

In contrast to swallowing efficiency, significant associations were identified between swallowing safety and swallow frequency measures. For thin-liquid swallows, a strong negative correlation was observed between the number of swallows and PAS scores. Participants who demonstrated fewer swallows per thin bolus were more likely to exhibit higher PAS scores, indicating greater airway invasion. From Figure 13-15, the number of swallows in neurogenic dysphagia was more than that of healthy individuals. This was justified as a spontaneous adaptive behavior to compensate for swallowing difficulty, especially in the highly demanding thin liquid swallows. Interpreting the correlation result in this context, individuals with poor adaptive compensation through an increased number of liquid swallows had an increased risk of airway intrusion. This finding highlights the role of spontaneous or compensatory multiple swallows as a protective strategy to improve bolus clearance and maintain airway safety (Palmer, 2020).

Instead of representing impairment alone, an increased number of swallows may indicate preserved sensory awareness of residue or incomplete clearance, facilitating additional swallows before airway invasion occurs.

This interpretation is substantiated by previous studies examining the spontaneous swallowing frequency. Crary et al. (2013) reported that reduced spontaneous swallowing frequency is a strong indicator of dysphagia in acute stroke, and it may serve as a clinically useful screening marker.

Carnaby et al. (2019) further reported that reduced swallowing frequency was associated with poorer swallowing outcomes in post-stroke individuals. In a more recent systematic review by Bulmer et al. (2021), lower spontaneous swallowing frequency was consistently associated with increased dysphagia risk despite methodological differences across studies. Together, these findings strongly complement the results of the current study, reiterating that swallow frequency may reflect the integrity of sensory-motor swallowing networks and the individual's ability to generate protective swallowing responses. The present findings extend this evidence by demonstrating that individuals with neurogenic dysphagia who exhibited fewer swallowing attempts during thin-liquid intake were more likely to demonstrate impaired airway protection.

The results of Spearman's correlation analysis revealed a significant positive correlation between the number of swallows and PAS scores in pureed bolus consistency. Increased airway invasion was observed for individuals who required multiple swallows for pureed bolus consistency. Due to the cohesive nature, slower bolus characteristics and improved sensory stimulation, pureed bolus were considered safer compared to liquids (Steele et al., 2015). Increased viscosity reduces the bolus velocity and provides additional sensory input to the oropharynx, facilitating more timely swallow initiation and enhanced airway protection.

Previous studies by Clavé and colleagues (2008) documented that thicker consistencies improve swallow safety in neurogenic dysphagia by reducing penetration and aspiration events while improving bolus control. Pureed consistency is often recommended clinically as a compensatory diet modification for patients with impaired oropharyngeal control and airway protection (Steele et al., 2015).

Considering the rheological advantages of pureed boluses, the need for multiple swallows to clear the bolus may be an indicator of reduced swallowing efficiency rather than a beneficial compensatory strategy. There may be underlying deficits in pharyngeal propulsion and bolus driving force in individuals who require multiple swallows for a cohesive and easy-to-control bolus; these factors increase the risk of airway intrusion. This can explain the positive association between swallow frequency and PAS scores for pureed bolus in the present study. Thus, while the multiple swallows may be protective for thin consistency, an increased number of swallows for pureed consistency may indicate greater physiological impairment and reduced swallowing efficiency

Unlike the thinner boluses, a moderately strong positive correlation was identified between latency of swallow initiation and PAS scores during solid bolus swallowing. Participants with a longer delay in triggering the pharyngeal swallow reflex were more likely to exhibit higher PAS scores (increased risk) and greater airway invasion. This finding is physiologically reasonable. According to the process model of swallowing, solid boluses are transported through a stage II transport, wherein portions of the prepared bolus may enter the oropharynx before the initiation of the pharyngeal swallow (Hiiemae & Palmer, 1997,1999). Delayed initiation of swallow prolongs the duration of bolus dwelling in the pharynx before airway closure mechanisms are fully activated (J.-W. Park et al., 2016; Perlman et al., 1994). Compared to thin liquids and pureed consistencies, solid boluses impose substantially greater sensorimotor demands on the swallowing system

Successful swallowing of solids depends on effective sensory recognition of bolus characteristics, timely triggering of the pharyngeal swallow, adequate mastication, bolus formation, saliva incorporation, and sustained oral containment before transfer to the pharynx (Palmer, 1998; Palmer et al., 1992). In contrast, pureed boluses are considered generally more cohesive and easier to control, while thin liquids flow rapidly through the oral cavity and may rely on different compensatory mechanisms

Earlier research has identified delayed swallow initiation as a major contributor to aspiration and penetration risk in the neurological population (Han et al., 2016). Individuals with delayed swallow initiation demonstrated premature spillage of bolus into the pharynx and laryngeal vestibule before the airway protection was established (Han et al., 2016).

Within the neurological population assessed in this study, delayed swallow initiation reflects a greater impact on swallowing safety for solid bolus intake, where the combined demands of bolus preparation, transport, and airway protection are the greatest.

While significant associations observed in the current study provide insights into the relationship between swallowing measures and safety, the findings need to be interpreted with caution. The present study was exploratory in nature, and it relied on retrospective analysis of the clinical data. The final sample size was limited, the neurogenic cohort was heterogeneous, and not all temporal measures could be reliably extracted from every swallow. All these factors influence both correlation strength and statistical significance.

Certain temporal measures, particularly latency of swallow reflex and number of swallows, have better clinical utility in understanding the swallowing safety in neurogenic dysphagia. Future studies can incorporate larger sample size, broader diagnostic group efficiency, and more temporal measures to establish the relationship and to provide clinically meaningful outcomes of swallowing safety and efficiency.

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CHAPTER V

SUMMARY AND CONCLUSIONS

Fiberoptic Endoscopic Evaluation of Swallowing (FEES) is one of the most widely utilized instrumental procedures for the assessment and management of dysphagia across diverse clinical populations. The procedure provides direct visualization of pharyngeal and laryngeal structures and enables experienced clinicians to evaluate swallowing safety, efficiency, secretion management, and the effectiveness of therapeutic interventions through standardized protocols. Despite its extensive clinical utility, FEES interpretation remains highly dependent on clinician expertise, subjective judgment, and rating scales. There is a growing demand for objectivity in FEES evaluations to improve reliability and diagnostic accuracy. In neurogenic dysphagia, there is temporal incoordination. of swallowing processes that are suggested as a significant factor leading to swallowing safety and efficiency concerns. Therefore, the current study explored the possibility of quantifying temporal measures of swallowing and related endoscopic events based on pre-validated definitions and explored their clinical significance across bolus characteristics and swallowing outcomes.

The study was carried out in different phases. The first phase reviewed the literature for systematically listing, developing, proposing, and validating specific temporal measures. From a total of 18 proposed measures, 17 were validated by seven SLPs through the Delphi method. These definitions were then applied to a dataset of clinical FEES evaluations to explore the applicability and clinical utility. The dataset of individuals with neurogenic dysphagia was selected from the archived FEES database from the Centre for Swallowing Disorders. Following a systematic methodology for inclusion and exclusion and multi-tier data screening, a total of 15 FEES evaluations were included in the analysis. Each pre-validated definition was applied for the identification of reference frames, and their time of onset and offset was tabulated. Temporal measures were then derived and compared against normative reference values obtained from Preeti et al. (2026, unpublished dissertation). Objective temporal measures included latency of swallow reflex, pharyngeal transit time, duration of white-out, epiglottic inversion duration, respiratory–swallow coordination patterns, glottic closure patterns, and number of swallows. Subjective swallowing safety and efficiency were evaluated using the Penetration–Aspiration Scale (PAS) and Yale Pharyngeal Residue Severity Rating Scale (YPRSRS). Correlation analyses were conducted to explore associations between objective temporal measures and subjective clinical ratings. The significant outcomes of the current study are mentioned below:

1. A set of 17 definitions was pre-validated with 80% agreement across seven expert SLPs who served as judges. The detailed definitions are provided in Table 1.
2. The study demonstrated the feasibility of quantifying and extracting the temporal swallowing measures from FEES recordings using the pre-validated operational definitions.
3. Several temporal measures could be reliably identified and quantified across bolus consistencies.
4. Certain frames of reference could not be reliably identified in all individuals with neurogenic dysphagia, and these measures had to be excluded in spite of the pre-validation of their definitions. This led to heterogeneity and unequal data sets across boluses and outcome measures.
5. ‘Latency of response to airway intrusion’ and ‘latency of response to residue’ were not consistently measurable because of silent aspiration, absent physiological responses, compensatory maneuvers, and retrospective video limitations in the current study. These

temporal measures may require future prospective clinical validation through protocol-controlled recording conditions. The current study provides the derivation protocol and standardized definitions for these future trials.

6. ***Latency of Swallow Reflex:*** Individuals with neurogenic dysphagia demonstrated prolonged latency of swallow reflex compared to median norm reference values. Considerable inter-individual variability was observed, probably highlighting the heterogeneous nature of neurogenic dysphagia. Thickened consistencies appeared to facilitate swallow initiation in some participants, although this effect was not a uniform response from all individuals included in the study. Delayed swallow initiation remains an important physiological marker associated with aspiration risk in neurogenic populations.

7. ***Pharyngeal Transit Time*:** Pharyngeal transit time remained stable across bolus consistencies. Most of the patients showed prolonged PTT compared to the normative median. Increased transit time can be associated with impairments in the physiology of swallowing that reduce the bolus flow drive and force. Due to premature spillage and poor bolus containment in the oral phase, one participant showed unusually short PTT.

   The findings support the multifactorial nature of pharyngeal transit time and its adaptability with bolus properties, sensory feedback, and swallowing biomechanics.

8. ***White-Out Duration:*** The duration of white-out was successfully quantified across bolus consistencies; however, large variability was observed in its values among the neurogenic dysphagia dataset. Pureed boluses produced white-out durations most comparable to normative references, emphasizing the near-normal biomechanical performance during the swallow of this consistency.

9. ***Epiglottic Inversion Duration:*** Significant variation was observed among participants for epiglottic inversion duration. For pureed consistency, the duration of epiglottic movement was similar to that of the normative median. For solid consistency, reduced epiglottic inversion duration was reported, which indicated increased risk of airway intrusion and poor swallowing efficiency. The use of different compensatory strategies across individuals may be the reason for the individual variability.
10. ***Number of Swallows:*** Multiple-swallow behavior increased progressively with bolus consistency. Thin liquid swallows generally require swallow frequencies comparable to those of healthy individuals. Pureed boluses demonstrated modest increases in swallow frequency. Solid boluses showed the greatest variability and consistently required multiple swallows beyond normative expectations. Increased swallow frequency may reflect the sensory-mediated compensatory behavior to overcome swallowing limitations. This spontaneous compensation may aid bolus clearance in persons with neurogenic dysphagia. The findings align with the concept of the 'dysphagia limit,' which explains the reduction in bolus volume per swallow when swallowing capacity is compromised.
11. ***Glottic Patterns:*** The most frequently observed glottic configuration pattern was the physiologically expected closed-to-open sequence. This observation suggested relative preservation of fundamental airway protection mechanisms in many participants with neurogenic dysphagia. However, open-to-open patterns occurred with notable frequency across consistencies, indicating co-occurrence of atypical patterns that could increase the vulnerability to airway invasion during swallow in individuals with neurogenic dysphagia.
12. ***Relationship Between Objective and Subjective Measures:*** No significant association was observed between temporal measures and residue ratings across bolus consistencies in the

current dataset. This suggested that swallowing efficiency may be influenced by physiological factors not captured by the temporal measures included in the study.

a. ***Thin Liquid vs temporal measures correlation:*** A strong negative correlation was observed between the number of swallows and PAS scores. Participants demonstrating fewer swallows tended to exhibit higher PAS scores. Increased swallowing frequency may therefore represent a protective compensatory mechanism.

b. ***Puree liquid vs. temporal measures correlation:*** A strong positive correlation was observed between the number of swallows and PAS scores. Individuals requiring multiple swallows for a cohesive and safe bolus consistency, such as puree, demonstrated increased airway invasion risk, probably associated with underlying swallowing impairment rather than successful compensation.

c. ***Solid bolus vs temporal measures correlation:*** A moderately strong positive correlation was identified between latency of swallow reflex and PAS scores. Delayed swallow initiation was associated with increased airway invasion during solid bolus swallowing.

The current study successfully demonstrated the feasibility of extracting objective temporal swallowing measures from FEES recordings using validated operational definitions. However, all the temporal measures may not be derivable for all individuals. There was notable deviations in temporal measures of individuals with neurogenic dysphagia from norm-referenced swallowing performance in swallow initiation latency, pharyngeal transit characteristics, epiglottic inversion behavior, and swallowing frequency. The results of the current study reinforce the complex and multifactorial nature of neurogenic dysphagia. Correlation analyses revealed selective relationships between objective temporal measures and swallowing safety outcomes. Specific physiological timing measures may provide clinically meaningful information regarding aspiration risk. The findings support the importance of combining objective temporal quantification with traditional perceptual assessment approaches.

Clinical Implications

The results of the present study provided

a) A set of standardized temporal measures of swallowing and related events as seen in FEES evaluations. The measures have the potential to enhance the diagnostic precision and inter-rater reliability of the procedure of FEES beyond subjective assessment.

b) The objective measures of the FEES examination complement the subjective judgements on swallowing safety and efficiency in the neurogenic population.

c) The current study supports the application of temporal measures of swallow as an outcome for individualized diagnostic documentation.

d) The objective data could serve as a reliable marker for rehabilitation progress over time. With further prospective research studies on clinical utility, progress tracking may be made more evidence-based with quantifiable outcome measures, unlike the wider subjective assessment markers.

e) By analyzing the scope of quantification of FEES data, the study has contributed to the overall patient-centric progress and development of more comprehensive technology-based assessment of FEES protocols

Limitations of the Study

a) All the validated temporal measures could not be obtained for every participant due to safety concerns. Administration of certain bolus consistencies had to be restricted because of the risk of aspiration, patient fatigue, reduced medical stability, or poor tolerance to the procedure. Some swallow-related frames for the derivation of temporal parameters could not be consistently visualized. This resulted in missing data points, heterogeneity, and unequal data distribution across participants. This limits large-scale inferential statistics and estimation of statistical power of observations.

b) As the proposed study was retrospective, all bolus consistencies required for the given objectives could not be obtained. The effective sample size was consequently small, which limited the ability to establish definitive or robust reference patterns and constrained generalizability.

c) Retrospective data included a 5 ml bolus volume uniformly, and only this bolus was included in the analysis. In spite of the previous literature that suggests the influence of volume on the temporal measure of swallow and methods of airway protection, this analysis could not be explored due to the retrospective nature of the study.

d) As an initial exploration, the study included a heterogeneous group of conditions that resulted in neurogenic dysphagia. The nature of these disorders may have contributed to increased variability in swallowing performance and may have masked any relationships.

Future directions

Future studies should aim at overcoming the limitations of the present study with well-controlled prospective experimentation of temporal analysis of swallow and related events. The clinical validity of all the outcome measures needs to be established through prospective trials and longitudinal designs to determine the progress in subjective and objective measures of swallowing performance. The predictive nature of these measures and patterns of recovery may be of significant importance in clinical practice. Integration of temporal, spatial, and kinematic parameters may be useful for a more comprehensive and multidimensional framework for quantitative FEES analysis. If future research is aimed at addressing these significant gaps, there is a possibility of automation of FEES analysis using machine learning and artificial intelligence techniques to improve efficiency, objectivity, and clinical usability.

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