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ORIGINAL ARTICLE

Quantifying Impairments in Swallowing Safety and Efficiency in Progressive Supranuclear Palsy and Parkinson's Disease

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Abstract

Dysphagia is a largely inevitable symptom in both progressive supranuclear palsy (PSP) and Parkinson's disease (PD). To date, comparative studies in these diseases have failed to detect differences in the severity of impairments in swallowing safety or efficiency, potentially due to small sample sizes and outcome measures with low sensitivity. Therefore, this study sought to address these limitations by using novel measurement methodology to comprehensively compare swallowing safety and efficiency impairments between these populations in order to better understand whether differences may exist and guide clinical management. Twenty-four participants with PSP and 24 with PD were matched for disease duration and completed flexible endoscopic evaluations of swallowing. A visual analog scale and penetration-aspiration scale quantified swallowing safety and efficiency. Bayesian multilevel models compared the frequency, severity, and variability of swallowing impairments. Individuals with PSP demonstrated greater impairments in swallowing safety, including deeper and more variable airway invasion and more frequent vocal fold and subglottic residue. Swallowing efficiency was also more impaired among individuals with PSP, including more frequent hypopharyngeal residue (with solids) and more severe residue in the oropharynx (with thin liquids and solids) and hypopharynx (with thin liquids). When airway or pharyngeal residue was present, similar within-subject variability of the amount of residue was appreciated across anatomic landmarks. This is the first study comparing the frequency, severity, and variability of swallowing impairments between PSP and PD populations. Our findings demonstrate more pronounced impairments in swallowing safety and efficiency for PSP compared to PD. These findings provide a clinically relevant characterization of swallowing measures using novel methodological and statistical approaches attempting to resolve some limitations of prior studies.

Keywords Progressive supranuclear palsy · Parkinson's disease · Pneumonia · Dysphagia · Deglutition disorders

Introduction

Progressive supranuclear palsy (PSP) is the most common atypical parkinsonism syndrome, affecting approximately five in every 100,000 individuals over the age of 50 [1]. In addition to parkinsonism, early clinical manifestations of PSP include vertical supranuclear gaze palsy, postural instability, behavioral disturbances, and bulbar dysfunction [2]. In part, the overlapping features between early PSP and Parkinson's disease (PD) make it difficult to differentiate between these two diseases, resulting in an average delayed PSP diagnosis of four to 5 years [3, 4]. Given the clinical diversity of PSP phenotypes and the commonalities with PD, a comprehensive characterization of clinical features beyond those identified from a routine motor examination may elucidate symptoms that improve the accuracy of clinical diagnostic assessments. An earlier PSP diagnosis would provide patients with access to targeted interventions, education, and management to improve health outcomes and quality of life.

Oropharyngeal dysphagia, characterized by impairments to swallowing safety (i.e., penetration and aspiration) and efficiency (i.e., pharyngeal residue), is a common symptom in PSP [5] and PD [6] and has been associated with the development of pneumonia, a leading cause of death in these populations [7–9]. All swallowing phases (i.e., oral,

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pharyngeal, and esophageal) can be impacted by PSP, contributing to a high prevalence of swallowing impairments [5, 10–13]. Compared to PD, individuals with PSP exhibit greater atrophy of multiple neural structures implicated in swallowing, including the midbrain, pons, cerebellar peduncle, and frontal lobe [14, 15]. Recent research suggests that the location of neuroanatomical impairments might be associated with the nature of swallowing impairments in PSP [16]. For example, oral-phase dysfunction may be greater among individuals with cortical abnormalities, whereas involvement of infratentorial regions may be associated with pharyngeal dysfunction. However, the relative heterogeneity of clinical PSP variants results in distinct patterns of cortical and subcortical involvement, likely impacting swallowing in different ways.

Despite a growing body of research characterizing dysphagia among individuals with PSP [5, 12, 16–18], few studies have directly compared swallowing outcomes in this population to PD. Specifically, only three investigations have compared swallowing outcomes with objective instrumental assessments, such as videofluoroscopy [11] and flexible endoscopic evaluations of swallowing (FEES) [19, 20]. Although these studies did not report differences between PSP and PD in swallowing safety or efficiency, several limitations may have precluded their ability to detect an effect, if present. Swallowing protocols in these studies were largely limited to small bolus volumes (e.g., 5 ml), which may not have represented natural sip sizes nor challenged the swallowing system, potentially masking impairments in swallowing dysfunction. Prior studies have also relied on the worst trial to characterize swallowing dysfunction. This aggregation approach may not have adequately captured variability and impairment profiles across repeated trials, which may have affected ecological validity and statistical power. Finally, measures in these studies were limited to gross assessments of swallowing function (e.g., the presence of aspiration) and did not quantify the severity of impairments (e.g., the amount of aspiration present). Visuoperceptual FEES rating methods combined with multilevel statistical models provide an opportunity to comprehensively quantify swallowing impairments across multiple trials to determine whether swallowing impairments are more pronounced among individuals with PSP compared to PD.

Variability of swallowing performance across repeated trials is an important, yet largely unexamined, consideration in the management of individuals with dysphagia. Heightened variability of bulbar functions, such as speech [21], cough [22], and pharyngeal pressure generation during swallowing [23], has been documented in PD. However, within-subject variability of objective swallowing outcomes like swallowing safety and efficiency remains unexamined in both PD and PSP. Variability has important clinical implications, as increased trial-by-trial variability may require additional boluses in a swallowing protocol to reveal impairments. Importantly, ignoring variability across repeated trials may misrepresent swallowing dysfunction; for example, a single aspiration event may over or underestimate the severity of dysphagia.

Studies directly comparing swallowing outcomes using sensitive, comprehensive, and valid measures of swallowing dysfunction are needed to identify potential differences between PSP and PD. The present study sought to contribute to this overarching goal by first comparing measures of swallowing safety and efficiency between PSP and PD. Specifically, we compared the frequency, severity, and variability of swallowing impairments between these populations. To accomplish this aim, we used a novel visuoperceptual FEES rating method to quantify the frequency and severity of swallowing impairments [24], as well as statistical analyses that permitted the inclusion of multiple trials in a swallowing protocol [25]. Given research documenting swallowing dysfunction in both PSP and PD [5, 11, 19, 20], we hypothesized that impairments in swallowing safety and efficiency would be prevalent in both groups. However, we hypothesized a greater frequency, severity, and variability of these impairments among individuals with PSP in light of research suggesting more diffuse dysfunction and pronounced brainstem and cortical atrophy in this population compared to PD [14, 16].

Methods

Participants

Participants with PSP and idiopathic PD were prospectively recruited from New York City and surrounding areas through a variety of sources including local neurology clinics, PSP and PD support groups, and online referrals (e.g., the Michael J. Fox Foundation trial finder), and informed consent was obtained (IRB #: 17-396). Participants were enrolled in a larger study examining communication, speech, and swallowing function; therefore, participant complaints of dysphagia were not required for enrollment. A neurologist specializing in movement disorders confirmed diagnoses based on current Movement Disorder Society clinical diagnostic criteria for PSP [26] and the UK Brain Bank criteria for PD [27]. Participants with PSP were classified into PSP subtypes based on disease features. Exclusion criteria included a history of other neurological disorders, respiratory disease, head and neck cancer, or smoking within 5 years. Demographic variables were collected including age, sex, disease duration from symptom onset, activities of daily living [28], and cognition [29]. PD evaluations were performed in the 'on' medication state. Participants were

matched based on disease duration from PD or PSP symptom onset.

Flexible Endoscopic Evaluations of Swallowing (FEES)

Flexible endoscopic evaluations of swallowing (FEES) were performed by trained speech pathologists with expertise in FEES using a 3-mm-diameter flexible distal chip laryngoscope (ENT-5000; Cogentix Medical, New York, USA) and video system with an integrated LED light source LCD display. The laryngoscope was passed transnasally without the use of topical anesthetic or vasoconstrictors and positioned within the oropharynx to visualize the pharynx, larynx, and subglottis before, during, and after the swallow. Participants were unable to view their physiology during the exam and were presented with a standardized protocol of boluses, including one trial of 5-ml thin liquid (International Dysphagia Diet Standardization Initiative (IDDSI) level 0) via teaspoon, one trial of 20-ml thin liquid via medicine cup, three trials of 10-ml thin liquid via cup, three trials of 90-ml thin liquid via cup, one trial of 5-ml vanilla pudding (IDDSI 4), and one trial of a saltine cracker (IDSSI 7) [30]. The 5- and 20-ml boluses were administered with instructions to hold the bolus in their mouth and swallow when cued. Liquid boluses were dyed to maximize visualization during the FEES. Six drops (~0.2 cc) of blue dye (Chef-O-Van Food Coloring, Rockford, Ohio, USA), green dye (Chef-O-Van Food Coloring), or three teaspoons (~24 g) of barium powder (E-Z-PAQUE barium sulfate for suspension, 96% w/w; E-Z-EM Canada, Inc., Anjou, Canada) were added to each cup. The order of blue, green, and barium boluses were randomized across participants. Different colorants were used to maximize the sensitivity of the exam and optimize visibility to discern residue across bolus trials. For all boluses, bailout criteria included evidence of gross aspiration without the ability to cough and clear aspirate material to a trace amount. Clinicians administering the FEES were also able to deviate from the protocol due to perceived safety or tolerance concerns. Given the potential for differences in protocol deviations between groups, PSP participant's boluses were matched with PD to ensure volumes and colorants were identical.

Data Analysis

FEES trials were analyzed offline by speech pathologists trained in the Visual Analysis of Swallowing Efficiency and Safety rating method [24], which has demonstrated strong associations with common criterion-referenced FEES rating scales [31]. The penetration–aspiration scale was used to measure the depth of and reaction to airway invasion, with higher scores indicating worse swallowing safety [32] (Appendix Table 1). Raters used a 100-point visual analog scale (VAS) to estimate the amount of pharyngeal residue in the oropharynx and hypopharynx and the amount of penetrant or aspirate material in the laryngeal vestibule, vocal folds, and subglottis (Appendix Fig. 1). Four components of objective swallowing outcomes were examined: (A) the depth of airway invasion (penetration–aspiration scale), (B) the frequency of airway invasion or pharyngeal residue (proportion of VAS > 0), (C) the severity of airway invasion or pharyngeal residue when present (amount when VAS > 0), and (D) within-subject variability of A and C. Twenty percent of PSP and PD boluses were re-rated for inter- and intra-rater reliability. Since ratings were performed in the context of each group's larger separate study, raters were not blinded to diagnosis. However, raters were blinded to the research question and ratings of the other group. PSP and PD ratings were separated by at least four months. All trials for each outcome were included in statistical analyses.

Statistical Analysis

A priori simulation-based power analyses were performed for a Bayesian ordinal multilevel model with 24 participants in each group and an assumed participant random effect (SD = 0.25). Given these assumptions, the sample size of 24 participants in each group provided 80% statistical power to detect an effect of OR = 2.51 for the PAS. Welch's t tests and chi-square tests compared demographic characteristics with an alpha of 0.05. Two-way random effects (single measure, absolute agreement) intra-class correlation (ICC) coefficients and unweighted Cohen's kappa (κ) were used for continuous and ordinal reliability estimates.

To examine whether participants with PSP demonstrated higher PAS scores compared to PD, we fit a Bayesian cumulative logit multilevel model with PAS as the dependent variable, group as a fixed effect, and a random intercept of participant. All thin-liquid bolus volumes from the swallowing protocol were included in this model, and this non-independence was accounted for by the random effect in the multilevel model. We assumed unequal variances between groups by including an auxiliary component of the model that directly compared variability (i.e., the variance of the latent variable in the cumulative logit model) in PAS scores between groups. To explore within-subject PAS variability among participants administered at least three trials, we used the coefficient of unalikeability, which quantified how often trials differed within each participant [33], and used descriptive statistics to characterize variability in our sample.

Bayesian zero-inflated beta multilevel models determined whether the frequency and severity of residue in the oropharynx, hypopharynx, and airway (laryngeal vestibule, vocal folds, and subglottis) was different between groups. Fixed effect posterior distributions in the zero-inflated portion of the

model were multiplied by negative one so that model estimates were interpreted as the frequency of residue. Beta estimates were interpreted as the severity (i.e., amount) of residue when present. Fixed effects in this zero-inflated beta model included group, consistency (thin liquids or solids), and their two-way interaction. Among participants with at least three trials, within-subject variability was examined with the coefficient of variation, which was calculated by dividing the standard deviation by the mean of all trials with some degree of residue. Given a limited number of participants with multiple trials of residue on a given anatomic landmark, descriptive statistics were used to characterize variability.

Analyses were performed in R [34] with the *brms* package [35]. Fixed effect model parameters were assigned weakly informative priors, specifically a normal distribution with a mean of zero and standard deviation of three. This prior distribution assumed no a priori effect and constrained unrealistically large effects. Variance parameters were assigned a Cauchy distribution with a sigma of 0.15, which excluded negative values and placed a lower likelihood on standard deviations greater than four. In zero-inflated beta models, a default student's t prior distribution with a mean of zero, sigma of 2.5, and 3 degrees of freedom was used for the precision parameter.

Each model produced a posterior distribution conditioned on the data and prior distributions, representing the joint probabilities of parameter values. Five thousand iterations were run for each of the four independent Hamiltonian Markov Chain Monte Carlo [36]. The initial 2,500 warmup chains were discarded and not included in the estimation of each parameter. Chain convergence was confirmed from posterior predictive checks, the potential scale reduction factor, and the effective sample size [37]. For each parameter of interest, we summarized posterior distributions with a median point estimate and 90% credible intervals (CI) [38]. These CIs indicate which values have a 90% probability as conditioned by the model, the prior, and the data [39]. Results were considered statistically robust if 90% credible intervals excluded zero. This threshold of 90% was chosen given its ability to computationally produce more stable posterior distributions with a reasonable number of posterior samples [38]. To understand the impact of the present study's prior distributions on our inferences, we performed prior sensitivity checks after completing data analysis. This was accomplished by fitting different prior distributions and determining whether inferences remained consistent (Appendix Fig. 2).

Results

Participant Characteristics

Twenty-four participants with PSP and 24 with PD met inclusion criteria. Trial frequencies by group, bolus volume, and consistency are provided in Appendix Table 2. There were no significant differences in age, sex, or disease duration between groups ($p > 0.05$). Participants with PSP demonstrated more profound cognitive deficits ($p = 0.002$), as well as greater impairments in activities of daily living ($p < 0.001$) compared to PD (Table 1). Three participants with PSP reported solid diet modifications (2 with IDDSI level 4, 1 with IDDSI level 6) and two of these participants also reported liquid modifications (IDDSI level 4). Two participants with PD reported solid diet modifications (IDDSI level 6). All participants with PD were on unrestricted liquid diets. One participant with PD had a bilateral deep brain stimulation procedure 5 years before enrollment.

Table 1 Demographic characteristics

	PSP ($n = 24$)	PD ($n = 24$)	p-value
Age (years)	71.10 (7.34)	70.90 (6.86)	.991
Sex	Male = 16 Female = 8	Male = 19 Female = 5	.330
MoCA	20.70 (6.81)	25.90 (3.21)	.002
Disease Duration from Symptom Onset (years)	5.05 (2.19)	5.22 (2.59)	.819
Schwab and England activities of Daily Living	51.70 (21.50)	79.10 (15.40)	< .001
PSP Subtype (freq)	PSP–RS: 16 PSP–P: 7 PSP–F: 1		

Mean (SD) are reported for continuous variables

PD Parkinson's disease, *PSP* Progressive supranuclear palsy, *MoCA* Montreal Cognitive Assessment, *PSP-RS* Progressive supranuclear palsy-Richardson's Syndrome, *PSP-P* Progressive supranuclear palsy-Parkinsonism, *PSP-F* Progressive supranuclear palsy-Frontal Presentation

Protocol Deviations

Not all participants completed the entire FEES protocol. Deviations were common for participants with PSP and reasons for which clinicians deviated included gross aspiration per bailout criteria ($n = 10$), poor exam tolerance ($n = 4$), and clinician judgment ($n = 6$). For PD, protocol deviations were less common and included gross aspiration ($n = 2$) and poor exam tolerance ($n = 1$). As described in the above methodology, boluses from PSP participants were matched with PD participants since deviations were common for participants with PSP. This ensured that volumes, colorants, and trial frequencies were identical.

Table 2 Distribution of maximum penetration-aspiration scale scores

Maximum PAS score	PSP ($n=24$)	PD ($n=24$)
1	3 (13%)	5 (20.8%)
2	0 (0%)	0 (0%)
3	3 (13%)	9 (37.5%)
4	1 (4%)	0 (0%)
5	7 (29%)	5 (20.8%)
6	1 (4%)	0 (0%)
7	2 (8%)	1 (4.2%)
8	7 (29%)	4 (16.7%)

Maximum penetration–aspiration scale scores were derived from thin-liquid boluses and are provided here for descriptive purposes. All trials with this outcome were included in multilevel statistical models

Penetration-Aspiration Scale: Depth of Airway Invasion

Eighty-seven percent of individuals with PSP and 79% with PD demonstrated abnormal, unsafe swallowing, defined as a PAS > 2 on at least one thin-liquid trial (Table 2). Across all thin-liquid boluses, individuals with PSP were more likely (OR = 4.82; 90% CI: 1.25–12.73) to have deeper airway invasion (i.e., higher PAS scores) compared to PD with a 98% probability for the presence of an effect (Fig. 1).

To explore trial-by-trial variability in PAS scores, the coefficient of unalikeability was calculated on a subset of participants with at least three trials of 10-ml (6 PSP, 7 PD) and 90-ml (1 PD, 1 PSP) thin-liquid boluses. On 10-ml trials, four participants with PD demonstrated no within-subject variability, whereas all six participants with PSP had variable PAS scores (Appendix Fig. 3). On 90-ml trials, one participant with PD demonstrated variable PAS scores, whereas one participant with PSP did not.

For solid boluses (IDDSI 4 and 7), airway invasion (PAS > 1) was not commonly appreciated. In PD, there was one instance of penetration above the level of the vocal folds (PAS 3) and two instances of silent aspiration (PAS 8) with these consistencies. PSP demonstrated two instances of transient penetration above the level of the vocal folds (PAS 2). Given the infrequency of airway invasion events with solid boluses, inferential statistics examining swallowing safety were not performed with this consistency.

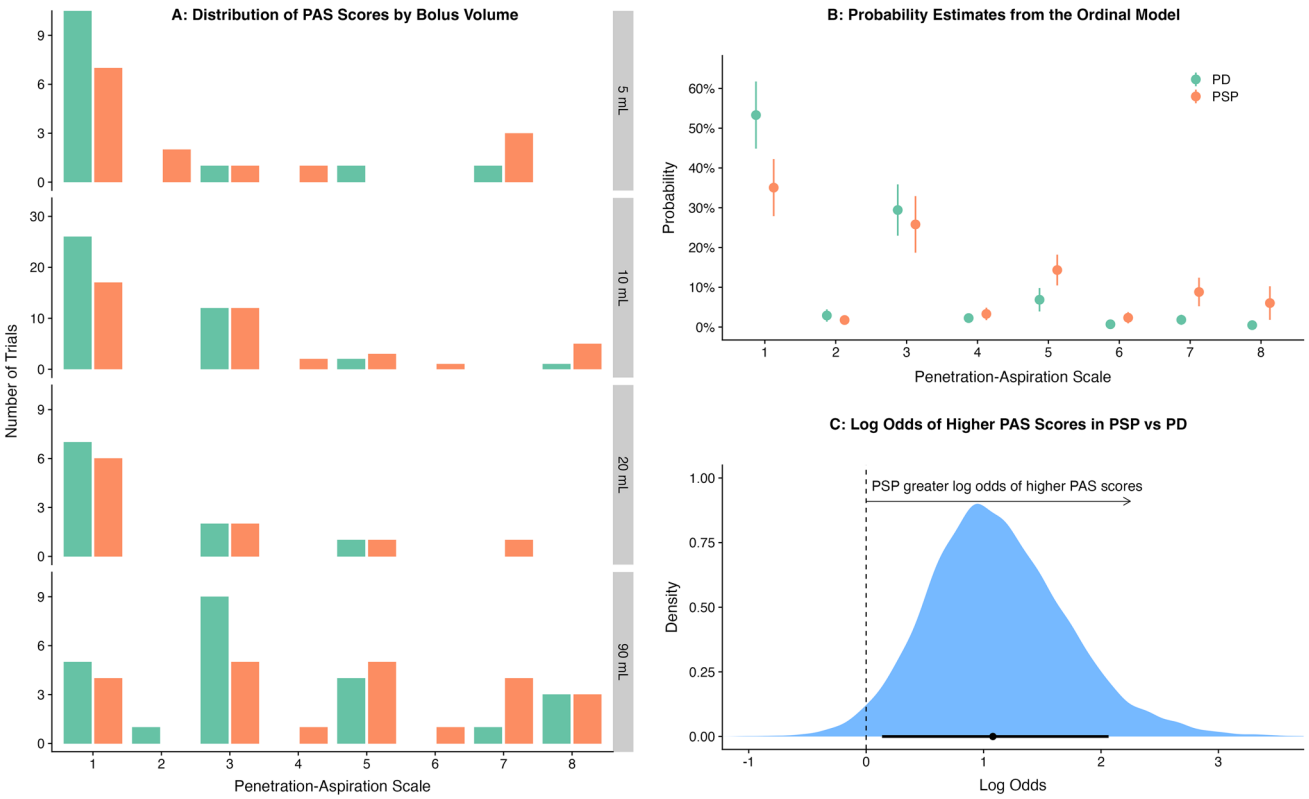

Fig. 1 Airway invasion in progressive supranuclear palsy and Parkinson's disease; *PD* Parkinson's disease, *PSP* progressive supranuclear palsy, *PAS* penetration–aspiration scale; **A** Shows the distribution of penetration–aspiration scale (PAS) scores by bolus volume. Probability and posterior estimates in (**B**) and (**C**) are across all thin-liquid bolus volumes in the cumulative link ordinal model. **B** visualizes the relative probabilities of each PAS score by group. **C** shows the log odds of worse airway invasion (i.e., higher PAS scores) with positive log odds indicating PSP has higher odds. The median and 90% credible intervals are shown in black

Laryngeal Vestibule: Frequency and Severity of Airway Invasion

The frequency of residue in the laryngeal vestibule was not statistically different between individuals with PSP and PD (Appendix Table 3). When laryngeal vestibule residue was present, there were no statistically robust differences in residue severity between individuals with PSP and PD (Fig. 2). Among participants with multiple trials of laryngeal vestibule residue, individuals with PD demonstrated higher within-subject variability (65%) compared to individuals with PSP (39%) (Appendix Fig. 4).

Vocal Folds: Frequency and Severity of Airway Invasion

Individuals with PSP were more likely to have more frequent vocal fold residue compared to PD (OR = 3.75, 90% CI 1.20–8.56) with a 98% probability for the presence of an effect. When vocal fold residue was present, the severity of residue between individuals with PSP and PD was not statistically different from zero. Since only one participant with PD had multiple trials with vocal fold residue, comparisons of within-subject variability were not examined (Appendix Fig. 4).

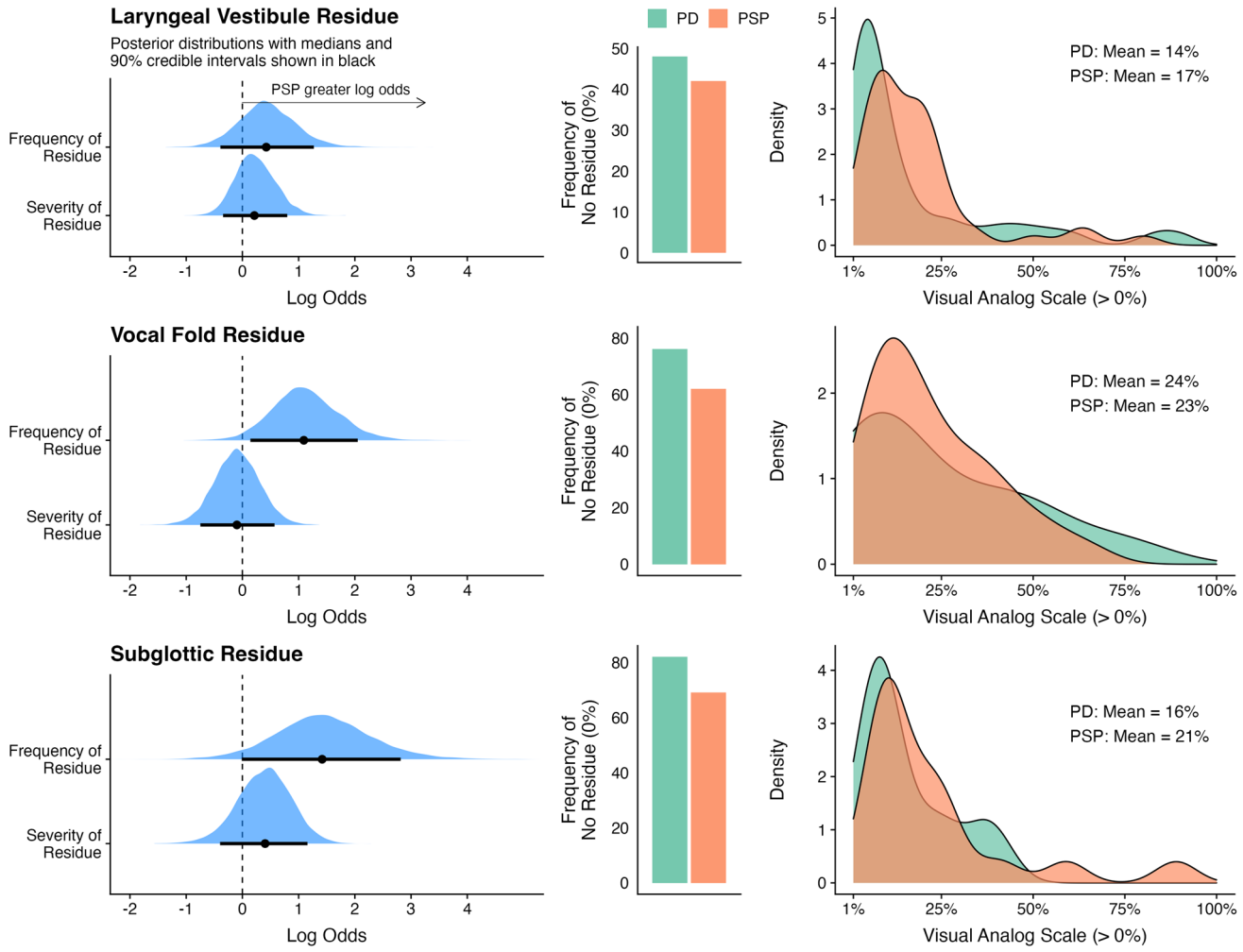

Fig. 2 Frequency and severity of airway invasion in progressive supranuclear palsy and Parkinson's disease; *PD* Parkinson's disease, *PSP* progressive supranuclear palsy; Only thin liquids (IDDSI 0) were included in airway severity models. For frequency posterior distributions, positive log odds indicate an increased likelihood of airway residue (> 0%) for PSP. For severity posterior distributions, positive log odds indicate more severe residue ratings for PSP when present. Posterior distributions from model coefficients are shown on the far-left panel. A descriptive visualization of the zero-inflated portion of the statistical model is shown in the middle panel, whereas the beta regression portion of the model is shown on the far-right panel. Mean proportions on the far-right panel were obtained from statistical models

Subglottis: Frequency and Severity of Airway Invasion

Individuals with PSP were more likely to have more frequent subglottic residue compared to PD (OR = 6.21, 90% CI 1.09–17.59) with a 96% probability for the presence of an effect. When subglottic residue was present, the severity of residue between individuals with PSP and PD was not statistically different (Fig. 2). Since no participants with PD had multiple trials with subglottic residue, comparisons of within-subject variability were not examined (Appendix Fig. 4).

Oropharynx: Frequency and Severity of Pharyngeal Residue

There was not a statistically robust between-group difference in the frequency of oropharyngeal residue for solid boluses (OR = 4.82; 90% CI: 0.76–14.08; Appendix Table 4). When oropharyngeal residue was present on thin liquids, individuals with PSP showed more severe residue than PD (OR = 3.71; 90% CI: 2.80–4.81, PP: 100%). In the presence of oropharyngeal residue on solid boluses, individuals with PSP showed more severe residue than PD (OR = 1.97; 90% CI: 1.30–2.81, PP: 99.73%; Fig. 3). On thin liquids, within-subject variability between PD (60%) and PSP (50%) was descriptively similar.

Hypopharynx: Frequency and Severity of Pharyngeal Residue

Individuals with PSP was more likely to demonstrate some degree of hypopharyngeal residue on solid boluses compared to PD (OR = 7.37; 90% CI: 1.24–21.28, PP: 97.21%). When hypopharyngeal residue was present on thin liquids, individuals with PSP showed more severe residue than PD (OR = 2.45; 90% CI: 1.93–2.99, PP: 100%). In the presence of hypopharyngeal residue on solid boluses, the severity of residue between individuals with PSP and PD was not statistically different (OR = 1.05; 90% CI: 0.77–1.39, PP: 56.69%). On thin liquids, within-subject variability between PSP (47%) and PD (46%) was descriptively similar.

Inter- and Intra-Rater Reliability

Inter-rater reliability was $\kappa = 0.63$ (76% absolute agreement) for PAS, ICC = 0.67 for oropharyngeal residue, ICC = 0.67 for hypopharyngeal residue, ICC = 0.71 for laryngeal vestibule residue, ICC = 0.69 for vocal fold residue, and ICC = 0.67 for subglottic residue. Intra-rater reliability was $\kappa = 0.87$ (89% absolute agreement) for PAS, ICC = 0.80 for oropharyngeal residue, ICC = 0.69 for hypopharyngeal residue, ICC = 0.87 for laryngeal vestibule residue, ICC = 0.77 for vocal fold residue, and ICC = 0.90 for subglottic residue.

Discussion

Dysphagia in PSP and PD is associated with increased morbidity and mortality, likely due to its contribution to the development of pneumonia [7–9]. Although swallowing dysfunction is highly prevalent in both populations, no studies to date have documented differences in swallowing safety or efficiency impairments. Therefore, this study aimed to compare swallowing safety and efficiency, including the frequency, severity, and within-subject variability of these impairments, between individuals with PSP and PD. This provided a comprehensive examination of how often, how much, how deep (for penetration-aspiration), and how variable swallowing dysfunction was between these two populations. Overall, our findings demonstrate that individuals with PSP largely have more pronounced impairments in both swallowing safety and efficiency compared to PD.

For swallowing safety, individuals with PSP were more likely to have deeper airway invasion and more frequent vocal fold and subglottic residue compared to PD, as well as prior reference values in healthy adults [40]. Furthermore, individuals with PSP descriptively showed greater trial-by-trial variability in the depth of these airway invasion events, suggesting that swallowing safety was not only more severe in PSP but also more variable across swallowing repetitions of a 10-ml bolus. Although previous research has not identified worse swallowing safety in PSP compared to PD [11, 19, 20], the methodology used in our study may have allowed for a more sensitive analysis of swallowing outcomes to detect an effect. Collectively, our findings suggest that the severity of swallowing safety impairments may be a subtle clinical feature that differentiates PSP from PD. Additionally, these data support the early assessment and intervention of swallowing safety among individuals with PSP, which is necessary given the concomitant cough dysfunction and known prevalence of pneumonia and mortality [41, 42].

In the context of swallowing inefficiency, our findings demonstrate more frequent and severe pharyngeal residue in PSP, depending on the anatomic location and consistency of the bolus. Specifically, individuals with PSP showed more frequent hypopharyngeal residue with solid boluses, as well as more severe residue in the oropharynx (with thin liquids and solids) and hypopharynx (with solids). When residue was present across multiple trials, both PSP and PD showed high within-subject variability, suggesting that the severity of residue in the oropharynx or hypopharynx was inconsistent across repetitions. However, within-subject variability was descriptively similar between these groups.

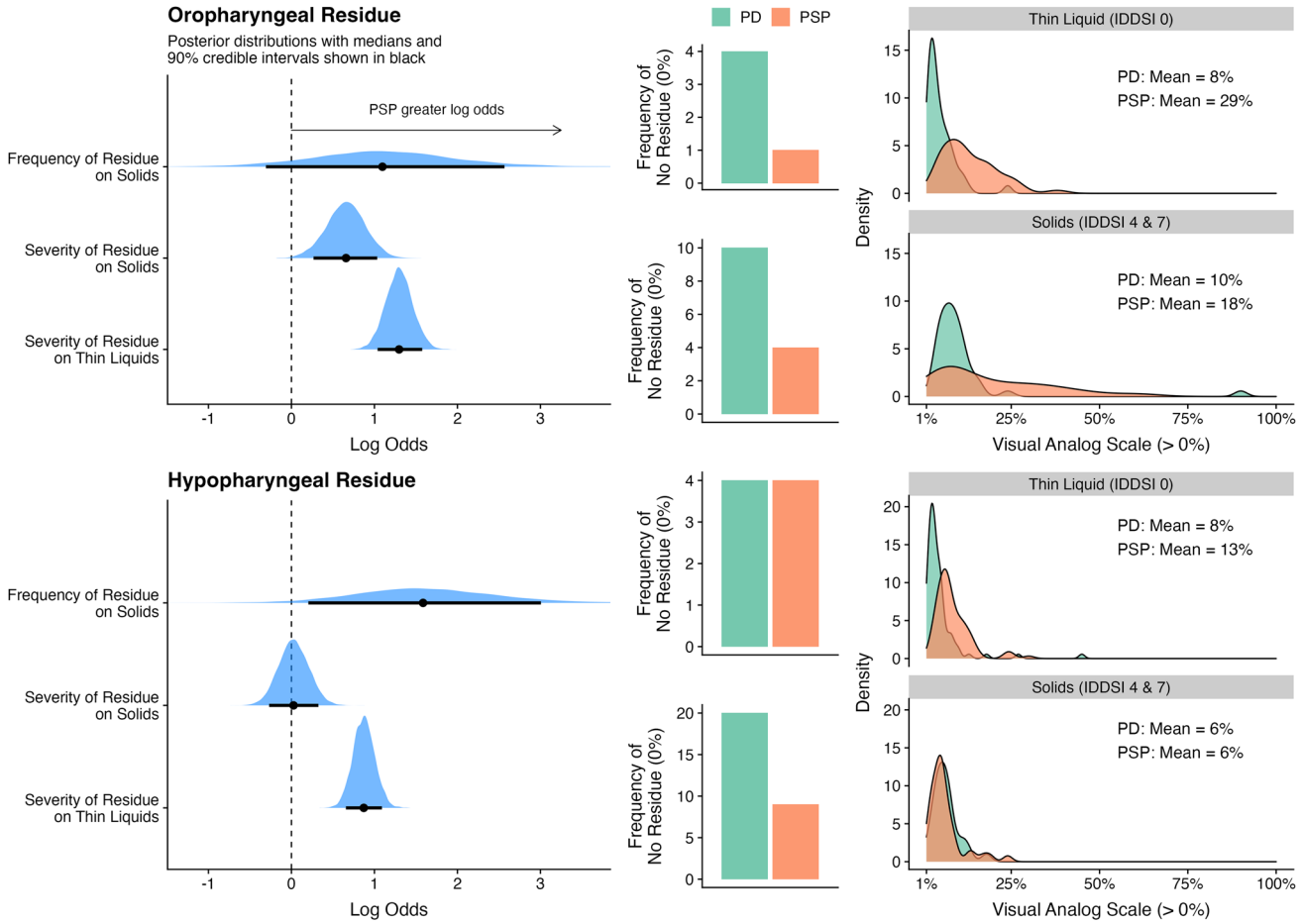

Fig. 3 Frequency and severity of pharyngeal residue in progressive supranuclear palsy and Parkinson's disease; *PD* Parkinson's disease, *PSP* progressive supranuclear palsy; For frequency posterior distributions, positive log odds indicate an increased likelihood of some degree of pharyngeal residue for PSP. For severity posterior distributions, positive log odds indicate more severe residue ratings for PSP when present. A descriptive visualization of the frequency of no residue events (i.e., zero-inflated model) is shown in the middle figures, whereas the distribution of the severity of residue events (i.e., beta model) is shown in the far-right figures. Note that posterior distributions for the frequency of thin-liquid residue was not examined due to a low number of zero (i.e., no residue) events

These variability findings highlight the need for comprehensive protocols and analyses that capture performance across multiple repetitions. Overall, these results suggest that pharyngeal residue may be more severe among individuals with PSP compared to PD. Given that swallowing inefficiency can affect mealtime parameters (i.e., oral intake), nutritional outcomes, quality of life, and risk of airway invasion [43, 44], pharyngeal residue may represent an important treatment target for individuals with PSP in future rehabilitation paradigms.

This study is not without limitations. Since our sample was predominantly composed of the Richardson syndrome subtype of PSP (PSP-RS), larger studies including a higher representation of other PSP subtypes will be necessary to determine whether swallowing impairments vary by subtype. Given inherent limitations of FEES, the present study was unable to examine pathophysiology underlying swallowing impairments in these populations. Future research will be necessary to identify physiologic mechanisms that differ between these populations. Although the present study used a standardized swallowing protocol, deviations may have introduced sampling bias, such that participants with less severe dysphagia were presented with more trials than those with more profound swallowing impairments. Participants in each group were matched by bolus characteristics, in addition to age and disease severity, which may have reduced its impact on our results. Additionally, results related to within-subject variability should be interpreted with caution given the potential for bias in our sampling procedure (i.e., only participants with at least three trials of airway invasion or pharyngeal residue were included in the analysis) and boluses included (i.e., only thin-liquid boluses). Although the use of a standardized protocol during FEES allowed for visualization and measurement of objective

swallowing outcomes (i.e., airway invasion and pharyngeal residue), this procedure does not allow for an assessment of oral-stage deficits, which may be an important consideration for future research given frequent observations of impulsive feeding behaviors in PSP [12]. Results should be interpreted in the context of its cross-sectional design, which will inform future longitudinal studies that examine causal relationships between the onset and severity of dysphagia and PSP diagnosis. Suboptimal agreement between raters may also have introduced measurement error in our ratings, though the present study's reliability estimates are consistent with prior FEES research [45–49]. Finally, one benefit of a Bayesian analysis framework is the quantification of uncertainty, which is expressed in the width of credible intervals. Although our study provided preliminary evidence that differences in objective swallowing outcomes exist between PSP and PD, our results exhibited a high degree of uncertainty in the magnitude of these differences. This uncertainty, coupled with a lack of clinically meaningful thresholds for our outcomes, warrants caution in interpreting the strength of reported effect sizes. Future research in large patient populations will be necessary to provide more accurate estimates of the magnitude of these differences, as well as identify clinically meaningful thresholds.

Conclusions

Although dysphagia is highly prevalent in both PSP and PD, differences in swallowing outcomes between these diseases remain poorly characterized. Our results demonstrate deeper and more frequent airway invasion in PSP compared to PD, as well as more frequent and severe impairments to swallowing efficiency. These findings provide a clinically relevant comparison of swallowing impairments among individuals with PSP and PD matched for disease duration, highlighting an increased severity of swallowing dysfunction in PSP. Although this study provides preliminary support for more profound impairments to swallowing safety and efficiency in PSP, future studies with larger, representative cohorts are necessary.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00455-023-10560-7.

Author Contributions JCB: Research project: Conception; Organization; Execution; Manuscript Preparation: Writing of the first draft; Review and Critique. JSS: Research project: Conception; Statistical Analysis: Review and Critique; Manuscript Preparation: Review and Critique. JAC: Research project: Execution; Statistical Analysis: Review and Critique; Manuscript Preparation: Review and Critique. NVA: Research project: Organization; Execution; Statistical Analysis: Review and Critique. Manuscript Preparation: Review and Critique. MST: Research project: Conception; Organization; Execution; Statistical Analysis: Design; Review and Critique. Manuscript Preparation: Review and Critique.

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Declarations

Conflicts of interest All authors have no conflicts of interest to disclose.

Ethical Approval All procedures performed were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Approval was obtained from the Institutional Review Board.

Informed Consent Informed consent was obtained from all participants prior to enrollment in this research study.

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