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Original article

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Tongue Strength and Swallowing Dynamics in Chronic Obstructive Pulmonary Disease

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Summary

In this novel study of swallowing dynamics in COPD we observed airway invasion during swallowing of liquids, a delayed inhibitory occlusion reflex in inspiratory muscles of the COPD group, and no differential tongue weakness compared to healthy controls.

Abstract

Background

Swallowing disorders occur in chronic obstructive pulmonary disease (COPD), but little is known about tongue strength and mastication. This is the first assessment in COPD of tongue strength and a test of mastication and swallowing solids (TOMASS).

Methods

Anterior tongue strength measures were obtained in 18 people with COPD, aged 73±11 years (mean±SD), and 19 healthy age-matched controls, aged 72±6 years. Swallowing dynamics were assessed using an eating assessment tool (EAT-10), timed water swallow test (TWST), and TOMASS. Swallowing measures were compared to an inhibitory reflex in the inspiratory muscles to airway occlusion (IR; recorded previously in the same participants).

Results

Tongue strength was similar between COPD and controls (*P*=0.715). Self-assessed scores of dysphagia EAT-10 were higher (*P*=0.024) and swallowing times were prolonged for liquids (*P*=0.022) and solids (*P*=0.003) in the COPD group. During TWST, ~30% of COPD group showed clinical signs of airway invasion (cough and wet voice), but none in the control group. For solids, the COPD group had ~40% greater number of chews (*P*=0.004), and two-fold-higher number of swallows (*P*=0.0496). Respiratory rate was 50% higher in COPD group than controls (*P* <0.001). The presence of an IR was not related to better swallowing outcomes, but signs of airway invasion were associated with a delayed IR.

Conclusion

Dysphagia in stable COPD is not due to impaired anterior tongue strength, but rather swallowing-breathing discoordination. To address dysphagia, aspiration, and acute exacerbations in COPD, therapeutic targets to improve swallowing dynamics could be investigated further.

Introduction

Chronic obstructive pulmonary disease (COPD), a major public health problem globally [1], is a progressive lung condition that causes airflow obstruction, chronic cough, shortness of breath, and excess secretions in the airway.

Impaired swallowing (dysphagia), typically related to disruptions in breathing-swallowing coordination [2], has been documented in 20% of people with stable COPD [3], and in up to 56% of COPD exacerbations [4]. Most healthy adults swallow during expiration, and the positive intrathoracic pressure serves as an airway protective mechanism to expel any misdirected material from the laryngeal vestibule [5, 6]. In contrast, tachypnoeic COPD patients usually inspire during or immediately after swallowing, increasing their risk of aspiration and acute exacerbations [7].

COPD commonly occurs in advanced age [4, 8], but oropharyngeal muscle weakness as a mechanism for dysphagia has not been well explored. Fifteen percent of older adults (>65 years) have dysphagia [9], that is frequently attributed to oropharyngeal sarcopenia (loss of skeletal muscle mass and strength) [5]. As tongue strengthening, a treatment for oropharyngeal weakness, may prevent aspiration, the primary aim of this study was to evaluate tongue strength in COPD. Swallowing efficiency, mastication and clinical signs of airway invasion were also evaluated. The association between swallowing dynamics, participant anthropometrics and lung function were assessed.

We also assessed the relationship between swallowing and the short-latency inhibitory reflex in inspiratory muscles (IR) which is a protective response evoked by airway occlusion [10]. We hypothesised COPD participants with alterations in IR may have clinical signs of aspiration and more severe dysphagia.

Methods

Ethics:

University of New South Wales Human Research Ethics Committee approved the study (#HC17762). Written informed consent was obtained. All procedures were conducted according to the Declaration of Helsinki (2013), except for database registration (clause 35).

Participants:

Eligible participants had moderate to severe COPD or were healthy age-matched controls without chronic respiratory or neurological disease. The participants were either referred from colleagues at the Prince of Wales Private Hospital based on previous diagnosis of COPD or had previously volunteered in our laboratory and given permission to be contacted again. We used the GOLD criteria [30] to select people with moderate to severe COPD. Controls were recruited from the Neuroscience Research Australia Research Volunteers Registry or had previously volunteered. All participants with COPD were well at the time they were studied, i.e. during stable COPD.

In the same participants, we had previously measured the reflex responses to brief airway occlusion (see below for details) [11]. We compare the reflex results to the outcomes of the swallowing tests in the current study.

Spirometry:

Pre-bronchodilator spirometry was performed while seated, using a hand-held spirometer (One Flow FVC Memo; Clement Clarke, Harlow UK). At least three attempts of spirometry were performed, until two values of forced expiratory volume in 1 second (FEV_1), force vital capacity (FVC) and peak expiratory flow (PEF) were within 10% [12]. The highest values were presented as a percent predicted; derived using the European Respiratory Society Global Lung Initiative Calculator [13].

Swallowing dynamics:

A standardised eating assessment tool (EAT-10) was used for self-assessment of swallowing [14]. High EAT-10 scores (>22, from maximal score of 40) indicate profound dysphagia, EAT-10 scores ≥3 suggest a possible issue with swallowing, and EAT-10 scores ≥15 a possible aspiration risk [14, 15].

Anterior tongue strength measures were obtained using the Iowa Oral Performance Instrument (IOPI), with participants instructed to elevate their tongue, and press the air-filled bulb on the hard palate following a standardised procedure [16]. The best of 3 consistent trials was recorded (2 within 10%).

Swallowing efficiency tests were performed using TWST for liquids [17], and TOMASS for solids [18], with audio-visual recordings of jaw and neck region. We monitored for cough, during or after (for 1 minute) the tests, and also signs of a wet-sounding gurgly voice. TWST was performed twice with 150 ml of water (> 1-minute between tests). TOMASS was performed once, with participants instructed to eat ¼ of Arnott's Salada cracker (5x5 cm) "as quickly and comfortably as possible".

Inspiratory muscle reflexes:

Comfortably seated participants wearing a nose clip breathed through a mouthpiece connected to a bacterial filter, pneumotachograph (Series 3813; Hans Rudolph, Kansas City, KS) and a two-way valve (Series 2600; Hans Rudolph). The respiratory rate was calculated during quiet breathing. Then, a balloon valve in the inspiratory port of the two-way valve occluded the airway for 250 ms on random breaths until 30-40 occlusions were recorded [10,11]. Surface electromyography activity (EMG) was recorded from the scalene muscles bilaterally using a standardized electrode placement [19], and over the right costal diaphragm at the 7th / 8th

intercostal space with clear-trace electrocardiogram electrodes (ConMed Corp., Utica, NY, USA) [11] and the EMG signals were rectified and averaged across occlusions.

Statistical Analysis:

Tongue strength and swallowing dynamics were compared between the COPD and control groups. Tongue strength results were compared with published normative data [16]. t-Tests or the Mann–Whitney rank sum tests were used to compare swallowing results between and within the groups using Stata version 14 - StataCorp College Station, Texas 77845. Spearman and Pearson's correlations were used to analyse the associations between anthropometric and swallowing data. Normality (Shapiro-Wilk tests), and correlation tests were performed using GraphPad Prism 8.4.3. Data are expressed as mean±SD or median (interquartile range). Statistical significance was set at $P < 0.05$ in this exploratory study, and Bonferroni corrections were not applied.

Results

We recruited 18 participants with moderate to severe COPD and 20 healthy control (Figure 1). One control participant was excluded due to inconsistent spirometry. Additionally, one COPD participant had an EAT-10 score of 16, and therefore did not proceed with TWST and TOMASS, but tongue strength was assessed. Two control participants did not have adequate reflex data for comparison with the swallowing tests (Figure 1).

There were 11 female participants in each group [61% (COPD) and 57.9 % (control)]. Groups were matched for age (73±11, and 72±6 years, Table 1). Spirometry parameters were significantly lower in the COPD group than in control, FEV_1/FVC for COPD 50±16% and controls 79.9±5.7% ($P < 0.001$). PEF was 164±55.1 l/s and 289 ± 85.2 l/s, respectively ($P < 0.001$), (Table 1).

Tongue strength assessment

Anterior tongue strength was similar between the COPD and control groups (45.2±15.5 and 46.8±11.0 kPa, respectively, *P*=0.715, Table 1). Neither the COPD nor control group were underweight (BMI<18.5, Table 1). There were no associations of tongue strength with TWST time, (*P*=0.297 and *P*=0.766), or TOMASS time, (*P*=0.746 and *P*=0.120), for COPD and control groups, respectively (Table 3B). However, compared to weighted averages of previously published tongue strength data using the IOPI [16], both COPD and control groups had lower tongue strengths compared to older controls aged >60 years, 57.4±13.0 kPa [16] (P=0.005 versus P=0.001, respectively), and younger controls aged 20-39 years, 65.7±13.0 kPa [16] (P<0.001 versus P<0.001, respectively).

Swallowing efficiency and mastication assessment

EAT-10 scores were significantly higher in the COPD group [1.5 (1.0, 6.0)] than in controls [0.0 (0.0, 2.0)], (P=0.024, Figure 2), indicative of a higher level of self-reported dysphagia in COPD. Among the COPD participants, 7 (~40%), compared to 2(~11%) control participants had EAT-10 scores ≥3, suggesting the presence of dysphagia. Total TWST times were 50% longer, and TOMASS times 31% longer in the COPD group than in the control group, (*P*=0.022 and *P*=0.003, Figure 3A and B, Table 2). Total TWST times correlated positively with TOMASS times in the COPD group (R=0.686, *P*=0.003, Figure 3C), but not the control group (R=0.318, *P*=0.185). The EAT-10 score correlated positively with higher TOMASS number of swallows in the COPD group (R=0.557, *P*=0.022, Figure 3D), but not the control group (R=-0.046, *P*=0.852). No association was observed between EAT-10 and BMI, TWST or spirometry in the COPD or control groups (see Table 3A).

The COPD group took a longer time to swallow 150 ml of water, taking 17.0 (9.4, 27.3) s compared to 9.0 (7.5, 13.2) s in the control group (*P*=0.022). COPD group had a lower liquid swallowing efficiency than control group 10.7±6.6 ml/s vs 15.6±5.1 ml/s (*P*=0.019). The time per liquid swallow was 2.0 (1.5, 2.6) s in the COPD group compared to 1.4 (1.3, 1.8) s in control group (*P*=0.020, Table 2). There was a negative correlation between the TWST time and FEV_1 %predicted in the COPD group (R=-0.721, *P*=0.002; Figure 4C) but not in control group (R=-0.179, *P*=0.464). This indicates a lower efficiency of swallowing liquids in more severe COPD.

TOMASS times were longer in the COPD group [56.7 (53.1, 80.4) s] than the controls [43.4 (29.3, 52.1) s, *P*=0.003, Table 2]. The COPD group had a higher number of chews (68.5±22.5) than the control group (48.7±13.2) (*P*=0.004, Table 2). Total number of swallows was two-fold higher in the COPD than the control group (*P*=0.0496, Table 2). There was no difference between the COPD and control groups in the other TOMASS variables (Table 2). A negative correlation was observed between TOMASS time and FEV_1 %predicted in the COPD group (R=-0.498, *P*= 0.044; Figure 4D), but not the control group (R=-0.219, *P*=0.367; Figure 4D).

Events during the swallowing tests

Five of the COPD participants (29.4%) had clinical signs of airway invasion during the TWST (i.e. events: cough and wet voice), but none was observed in the control group. Among the COPD participants 1/17 (6%) coughed during, 3/17 (18%) coughed after the TWST, and 1/17 (6%) had a wet voice quality immediately after the test, which recovered within a minute. No clinical signs of airway invasion were noted during or after the TOMASS. In the COPD group, 2/17 (12%) had dentures which they kept in during the tests, and another participant chewed the cracker with front teeth as they did not have molars. There were no differences in the total time for TOMASS (*P*=0.169), TWST (*P*=0.114), EAT-10 (*P*=0.085), or tongue strength (*P*=0.805) tests between patients with or without events, except for greater number of bites (5±1.1 vs 3±1.2, *P*=0.002), and less chews per bite in the TOMASS test; 22.3(16.1, 25.3) vs 14.6(10.0, 15.8), see Table 4.

Respiratory Rate correlations

The COPD group had a 50% higher respiratory rate than the control group, with 18 versus 12 breaths per minute ($P<0.001$). The EAT-10 score positively correlated with respiratory rates in the COPD group (R=0.517, P=0.028), but not the control group (R=0.126, P=0.607). No association was observed between the respiratory rate and total time of TWST and TOMASS in either the COPD (R=0.231, P=0.369 and R=0.112, P=0.667, respectively) or AMC groups (R=0.069, P=0.781 and R=-0.224, P=0.357, respectively; Table 3C). No correlations were observed between respiratory rate and TWST volume per swallow or volume per second, and there was no association with FEV_1 %predicted or FEV_1, in either the COPD or control groups (Table 3C).

Within-group comparison of swallowing data with inspiratory muscle reflexes

Inhibitory reflexes were observed in the COPD and control groups, but not in all participants and muscles [11]. The short-latency inhibitory reflex (IR) in either the scalene or diaphragm muscles was present in 15/18 (83%) participants with COPD versus 7/17 (41%) participants in the control group, (P= 0.010) (Epiu et al, manuscript under review 2021). Participants in the COPD group who had events during TWST had a delayed IR onset time in the diaphragm, when compared to those who did not have signs of airway invasion, (85±14.1 ms vs 58±7.9 ms, P=0.007). No other parameter of the reflex differed between participants with or without clinical signs of airway invasion (Table 4).

Discussion

We have shown no difference in tongue strength between stable COPD and healthy age-matched controls, despite an increased level of dysphagia in the COPD group. This suggests that anterior tongue strength is not the mechanism of dysphagia in this COPD group. Prolonged times for swallowing both solids and liquids in the COPD group compared to control indicate that the COPD group had a reduced swallowing efficiency and impaired masticatory ability. Longer times in both swallowing tests were associated with COPD severity. Additionally, a greater peak of the reflex inhibition in inspiratory muscles positively correlated with COPD severity [11].

Disruption to breathing-swallowing coordination is the most common cause of dysphagia in COPD [20-22] and would be aggravated by a higher respiratory rate seen here and by others [8, 23]. The COPD participants had a 50% higher respiratory rate, greater number of swallows (solids and liquids), and ~30% showed clinical signs of airway invasion (cough and wet voice), but none in the control group.

In contrast to our hypothesis, the presence of an inhibitory reflex was not related to better swallowing function, but rather we did observe a delayed onset of the IR in participants who showed clinical signs of airway invasion.

Dysphagia in COPD

Swallowing problems are considered a major risk factor for acute exacerbations of COPD (AECOPD) which present as an abrupt worsening of COPD symptoms, compromised lung function, decreased ventilation-perfusion ratios, and lower oxygen saturation [24, 25]. Dysphagia observed here with the bedside TWST and TOMASS is consistent with video-fluoroscopy studies in COPD which reveal that airway penetration or aspiration is associated with tachypnoea, reduced hyoid elevation, post-swallow pharyngeal residue and more frequent hospitalizations [26, 27]. Aspiration may contribute to a higher morbidity in people with COPD by aggravating AECOPD, which together reduce the quality of life, and increase health-related costs [27-30].

Poor swallowing efficiency is linked to a higher risk of post-swallow aspiration, especially in the presence of shortness of breath. Changes in ventilatory pattern can alter swallowing and compromise swallowing coordination [5, 31-33]. Tachypnoea may lead to a shorter pause (typical apnoea period 0.5-1 s), and higher chance of a post-swallow inspiration which increases the risk of aspiration [26], as may have occurred in ~30% of participants in the COPD group who had a cough or wet voice. However, a limitation of this study is that silent aspirations would have been missed during the TWST and TOMASS tests. To detect silent aspirations specialized evaluations are required (i.e. video-fluoroscopy and/or endoscopy).

The higher number of swallows for solids in the COPD group may indicate the presence of pharyngeal residue, prompting additional swallows. This aligns with previous research that showed pharyngeal residue in COPD patients with instrumental assessment [27]. Additionally, the COPD group swallowed less liquid (volume/second) than controls, which may be a compensatory mechanism to enhance swallowing safety. The prolonged overall time for swallowing solids in the COPD group is probably due to the increased number of chews or reduced swallowing efficiency. This may be linked to a greater self-awareness of their difficulty swallowing as indicated by the high EAT-10 score in the COPD group. While an EAT-10 ≥3 indicates swallowing difficulties in our elderly participants, another potential limitation is that the EAT-10 score may have been affected by recall bias in which participants reported less severe swallowing difficulties. Nonetheless, the overall EAT-10 scores were higher in COPD than controls.

A second possibility for the prolonged time for swallowing solids in the COPD group may be oropharyngeal weakness, reduced masticatory efficiency, or poor dentition with 12% of the COPD group reporting poor dentition. We did not measure bite strength, but anterior tongue strength was comparable in both groups, as was the strength of the inspiratory muscles (maximal inspiratory pressure) which had been measured previously in the same participants [11].

Swallowing Dynamics and the Inhibitory Reflex

The inspiratory muscle inhibitory reflex (IR) in response to airway occlusion was more prevalent in COPD compared to control group [11]. Here, the same COPD group also had higher EAT-10 scores, and lower swallowing efficiency of liquids and solids. Previous findings from repetitive saliva swallowing tests also suggest that abnormal swallowing reflexes were increased in COPD and those predisposed to exacerbations [8].

In COPD participants who showed clinical signs of airway invasion when swallowing water, the onset time for the IR in the diaphragm was longer, compared to those with COPD who did not exhibit signs of airway invasion. If the onset of the IR is delayed, then the reflex may be less protective against aspiration. In other words, a delayed decrease in negative (inspiratory) thoracic pressure may allow pharyngeal residue to be sucked into the airway.

While the sample sizes for these analyses were small, a delayed IR may be a marker to identify those at risk of AECOPD, if delayed inspiratory muscle reflexes can aggravate underlying swallowing problems indicated clinically by a cough, wet voice and/or aspiration. This needs to be explored further. Since the IR is believed to be mediated by intramuscular receptors in the inspiratory muscles rather than airway mucosa or lung afferents [10, 34], any delay in the onset of IR is unlikely to be explained by any decrease in pharyngeal sensation [35]. In future studies, the relationship between the IR as a possible airway protective mechanism and the occurrence of airway invasion should be evaluated using endoscopy or video-fluoroscopy to provide clearer insight into this relationship.

Tongue Strength and Dysphagia

Dysphagia can be due to impaired neurological, muscular or psychogenic components of deglutination, and most dysphagia symptoms in COPD are related to impaired pharyngeal protective mechanisms [36]. Oropharyngeal dysphagia affects more than 60% of elderly institutionalized patients [5], commonly associated with age-related atrophy of the tongue, geniohyoid muscle, and the pharynx [37-39]. We found no difference in the tongue strength between the COPD and healthy controls (mean ages 73 and 72 years for the COPD and control groups, respectively), both lower than weighted averages of older (> 60 years) and young (20-39 years) controls [16]. While we enrolled people with stable COPD, some reports have shown that oropharyngeal dysphagia is more common during AECOPD [24]. Additionally, the similar BMI in the COPD and control groups suggests our COPD group did not have cachexia. Therefore, to address these complex swallowing dynamics in stable COPD, improving respiratory-swallowing coordination (e.g. using biofeedback, as piloted in a head and neck cancer cohort [40]) rather than tongue strengthening exercises may be more beneficial.

Conclusion

Our results confirm that people with COPD have swallowing difficulties, but decreased anterior tongue strength is unlikely to be a contributing factor in stable COPD. The higher incidence of airway invasion in COPD, a factor that may lead to frequent AECOPD, was linked to a delayed inhibitory reflex in the inspiratory muscles. Training methods to improve swallowing-breathing coordination, and the impaired occlusion reflex could be implemented to reduce exacerbations, hospitalization costs, and improve the quality of life for people with COPD.

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Author Contributions

All authors contributed to the study conception. I.E, A.H, and C.B.R performed the experiment at Neuroscience Research Australia. I.E. analyzed the data and drafted the manuscript. All authors interpreted the data and revised the manuscript. All authors approved the final version of the manuscript.

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Disclosure statements

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Table 1. Summary of anthropometric, respiratory, and spirometry data

	COPD (n=18)	Control (n=19)	P Value
Age (Years)	73 ± 11	72 ± 6	0.799
Female Gender – N (%total)	11 (61)	11 (58)	0.842
BMI (kg/m^2)	23.0 (20.1, 24.8)	26.5 (22.1, 28.7)	0.056
Smoking Pack years/Day	18.3 (2.0, 30.0)	0.1 (0.0, 1.0)	**0.002***
FEV_1 (L)	1.2 ± 0.4	2.3 ± 0.5	**<0.001***
FEV_1 (%pred)	55.7 ± 18.4	89.8 ± 12.4	**<0.001***
FVC (L)	2.4 ± 0.7	2.9 ± 0.7	0.057
FVC (%pred)	80.4 ± 20.4	86.1 ± 11.7	0.310
PEF (l/s)	164 ± 55.1	289 ± 85.2	**<0.001***
FEV_1/FVC (%)	50.4 ± 15.5	79.9 ± 5.7	**<0.001***
Respiratory rate (breaths/minute)	18 ± 4.8	12 ± 10.3	**<0.001***

Anthropometric and spirometry data as well as the eating assessment tool score, tongue strength, and respiratory rate for the chronic obstructive pulmonary disease (COPD) and the age-matched control groups (shown as mean ± (SD) for parametric data and as median (IQR) for non-parametric data). Student t-Tests and Mann-Whitney tests were used to compare between groups. Abbreviations: COPD = chronic obstructive pulmonary disease; IQR = interquartile range; N (% total) = sample size (percentage of total sample); BMI =body mass index; %pred = percent predicted for age, sex and ethnicity; FEV_1 =forced expiratory volume in 1 second; FVC =forced vital capacity; PEF =peak expiratory flow. * and bold text indicates $P < 0.05$

Table 2 Swallowing data analysis

		COPD (n=17)	CONTROL (n=19)	P Value
TWST (Liquids)	Total Time (s)	17.0 (9.4, 27.3)	9.0 (7.5, 13.2)	**0.022***
	No. Swallows	7.0 (7.0, 10.0)	6.0 (5.0, 8.0)	0.053
	Volume/sec (ml/s)	10.7 ± 6.6	15.6 ± 5.1	**0.019***
	Volume/Swallow (ml)	21.4 (15.0, 21.4)	25.0 (18.8, 30.0)	0.053
	Time/Swallow (s)	2.0 (1.5, 2.6)	1.4 (1.3, 1.8)	**0.020***
TOMASS (Solids)	Total Time (s)	56.7 (53.1, 80.4)	43.4 (29.3, 52.1)	**0.003***
	No. Swallows	4.0 (2.0, 4.0)	2.0 (2.0, 4.0)	**0.0496***
	No. Bites	4.0 (3.0, 5.0)	3.0 (2.0, 3.0)	0.079
	No. Chews	68.5 ± 22.5	48.7 ± 13.2	**0.004***
	Chews/Bite	18.2 (15.8, 23.0)	18.0 (12.8, 27.0)	0.739
	Swallow/Bite	1.0 (0.8, 1.3)	1.0 (0.7, 1.3)	0.547
	Time/Bite	18.7 (16.3, 22.7)	14.6 (10.8, 21.2)	0.132
	Time/ Chews	1.01 (0.8, 1.2)	0.9 (0.8, 1.0)	0.199
	Time/Swallow	18.7 (13.6, 21.0)	14.6 (13.0, 26.9)	0.635

Results of TWST and TOMASS assessments in COPD and age matched control groups, shown as mean ± standard deviation (SD) for parametric data and as median (IQR) for non-parametric data. Student t-Tests and Mann-Whitney tests were used to compare between groups. Abbreviations: COPD = chronic obstructive pulmonary disease; IQR = interquartile range; s = second; TWST = Timed Water Swallow Test; TOMASS = Test of Mastication and Swallowing of Solids. * and bold text indicates $P < 0.05$

Table 3. Correlations between eating assessment tool (EAT-10), tongue strength (IOPI), respiratory rate (RR) with spirometry, BMI, TWST and TOMASS variables for the COPD and control groups.

		COPD			Controls		
		R	R (95% CI)	P Value	R	95% CI	P value
A.EAT-10	BMI Kg/m^2	-0.014	-0.489 to 0.468	0.957	-0.180	-0.596 to 0.312	0.462
	TWST total time (s)	0.156	-0.364 to 0.602	0.546	0.115	-0.371 to 0.551	0.639
	TWST No. Swallows	0.014	-0.470 to 0.491	0.957	0.367	-0.105 to 0.704	0.123
	TOMASS No. swallows	**0.557**	**0.088 to 0.823**	**0.022***	-0.046	-0.501 to 0.430	0.852
	TOMASS Total time (s)	0.218	-0.308 to 0.641	0.399	-0.043	-0.500 to 0.431	0.861
	FEV_1/FVC ratio (%)	0.461	-0.023 to 0.770	0.054	-0.034	-0.492 to 0.438	0.889
	FEV_1 (l)	0.057	-0.433 to 0.521	0.823	0.119	-0.367 to 0.554	0.627
	FEV_1 %pred	-0.147	-0.584 to 0.357	0.561	0.366	-0.120 to 0.711	0.123
B.IOPI							
	BMI Kg/m^2	-0.436	-0.773 to 0.092	0.092	0.233	-0.276 to 0.640	0.352
	TWST total time (s)	0.268	-0.259 to 0.672	0.297	-0.073	-0.521 to 0.406	0.766
	TWST No. Swallows	0.478	-0.019 to 0.786	0.054	0.203	-0.290 to 0.611	0.404
	TWST Vol/ Swallow	-0.478	-0.786 to 0.019	0.054	-0.203	-0.611 to 0.290	0.404
	TOMASS No. Chews	-0.002	-0.494 to 0.491	0.993	-0.323	-0.686 to 0.168	0.177
	TOMASS No. swallows	0.091	-0.420 to 0.558	0.727	0.327	-0.163 to 0.689	0.172
	TOMASS Total time (s)	-0.085	-0.554 to 0.426	0.746	-0.369	-0.712 to 0.117	0.120
C.RR							
	EAT-10	**0.517**	**0.051 to 0.798**	**0.028***	0.126	-0.361 to 0.559	0.607
	TWST total time (s)	0.231	-0.295 to 0.650	0.369	0.069	-0.410 to 0.518	0.781
	TOMASS Total time (s)	0.112	-0.403 to 0.573	0.667	-0.224	-0.625 to 0.270	0.357
	TWST Volume/Sec	-0.212	-0.628 to 0.200	0.415	-0.107	-0.535 to 0.365	0.664
	TWST Volume/Swallow	-0.199	-0.620 to 0.311	0.443	0.443	-0.537 to 0.363	0.655
	FEV_1 (l)	-0.216	-0.620 to 0.279	0.389	-0.149	-0.565 to 0.327	0.542
	FEV_1 %pred	0.176	-0.317 to 0.594	0.486	-0.052	-0.495 to 0.412	0.833

Results of associations between **A.** Self-assessed scores of dysphagia (EAT-10), **B.** Tongue strength (IOPI), **C.** Respiratory rate (RR), with BMI, TWST, TOMASS or Spirometry variables. We used Spearman and Pearson correlation (R) to compute the non-parametric and parametric correlations, respectively. Abbreviations: COPD = chronic obstructive pulmonary disease; TWST = Timed Water Swallow Test; TOMASS = Test of Mastication and Swallowing of Solids; BMI = body mass index; RR= respiratory rate; IOPI = Iowa Oral Performance Instrument (Tongue Strength); EAT-10 = eating assessment tool scores; %pred = percent predicted for age, sex and ethnicity; FEV_1 =forced expiratory volume in 1 second; FVC =forced vital capacity; R=Spearman and Pearson correlation; CI= confidence interval. * and bold text indicates $P < 0.05$

Table 4: within-group analysis of signs of airway invasion (events)

		No events	Yes events	P Value
	SAMPLE SIZE	**COPD n=12**	**COPD n=5**	
A.TWST (Liquids)	Total Time (s)	13.8(8.1, 20.6)	27.3 (15.7, 41.6)	0.114
	No. Swallows	7.7 ± 2.46	10.8 ± 4.1	0.067
	Volume/sec (ml/s)	12.5 ± 6.8	6.2 ± 3.9	0.073
	Volume/Swallow (ml)	21.7 ± 16.9	15.6 ± 8.5	0.124
	Time/Swallow (s)	1.7 (1.4, 2.4)	2.2 (2.0, 2.6)	0.092
B.TOMASS (Solids)	Total Time (s)	63.8 ± 26.1	87.3 ± 40.6	0.169
	No. Swallows	7.0 (5.5, 10.0)	10.0 (7.0, 14.0)	0.134
	No. Bites	3.1 ± 1.2	5.4 ± 1.1	**0.002***
	No. Chews	65.7 ± 18.7	75.2 ± 31.5	0.445
	Chews/Bite	22.3 (16.1, 25.3)	14.6 (10.0, 15.8)	**0.011***
	Swallow/Bite	1.2 ± 0.6	0.9 ± 0.9	0.330
	Time/Bite	19.0 (18.0, 27.4)	13.4 (11.5, 16.3)	0.058
	Time/ Chews	1.0 ± 0.3	1.2 ± 0.4	0.225
	Time/Swallow	18.4 (15.4, 24.7)	14.2 (13.6, 20.1)	0.598
C. IOPI	Tongue Strength	42.6 ± 16.1	50.2 ±15.6	0.805
D. EAT-10	Self-assessed dysphagia score	1.0 (0.5, 2.0)	6.0 (3.0, 10.0)	0.085
	SAMPLE SIZE (2SD Criteria)	**COPD n=9**	**COPD n=4**	
E. IR Scalenes	IR Onset	56.2 ± 9.7	60.9 ± 11.2	0.461
	IR Duration	62.3 ± 28.6	75.2 ± 32.6	0.485
	IR Area M	14.5 (10.0, 17.7)	15.3 (13.3, 32.3)	0.643
	IR Peak %	62.1 (60.4, 70.1)	60.2 (47.3, 66.7)	0.643
	IR Peak time	82.0 (76.0, 94.5)	93.5 (89.3, 108)	0.142
	SAMPLE SIZE (2SD Criteria)	**COPD n=6**	**COPD n=3**	
F. IR Diaphragm	IR Onset	58.0 ± 7.9	86.0 ± 14.1	**0.007***
	IR Duration	71.2 ± 24.5	63.7 ± 34.9	0.715
	IR Area	19.3 ± 8.9	21 ± 18.2	0.854
	IR Peak %	62.4 (53.6, 64.7)	61.4 (36.8, 78.8)	0.796
	IR Peak time	101 (95.0, 110)	104 (104, 115)	0.294

Within group analysis of participants with COPD who had clinical signs of airway invasion (events) during TWST test for swallowing liquids. Abbreviations, COPD = chronic obstructive pulmonary disease; TOMASS= test for mastication and swallowing of solids; TWST= timed water swallow test; IR= inhibitory reflex; EAT-10 = eating assessment tool. The presence of an IR in the Scalene and Diaphragm muscles was assessed using a 2SD Criteria, i.e. airway occlusion evoked a decrease in inspiratory muscle electromyographic activity (EMG) of 2SD below pre-occlusion EMG levels, that lasted 10ms or more [11]. * Indicates P < 0.05 for t-test comparisons and Spearman's correlations within the COPD group

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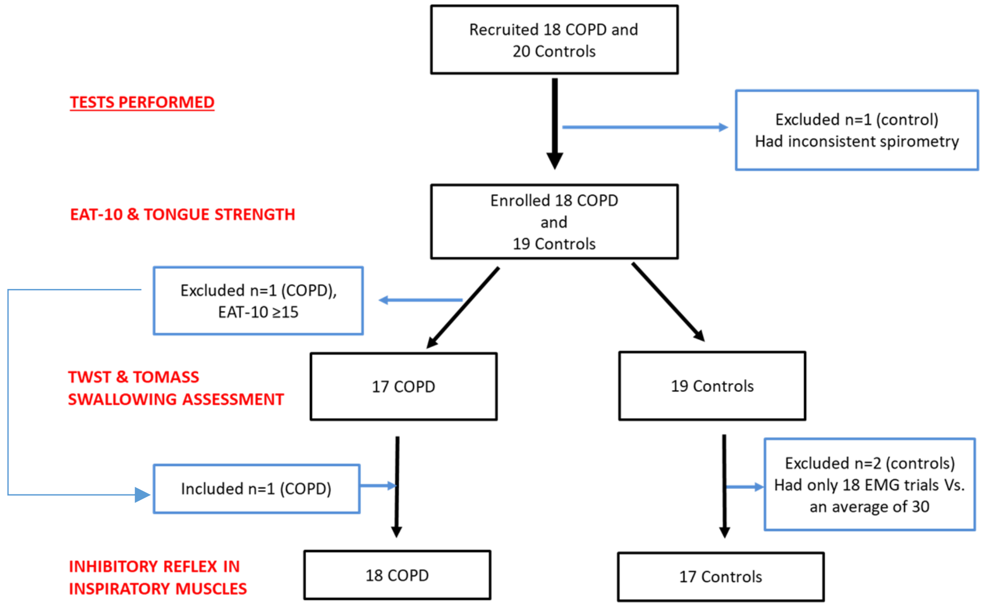
Figure 1: Flow chart of study participants' recruitment for experiments



Enrolment of participants with chronic obstructive pulmonary disease (COPD) and age-matched controls ('Controls') for swallowing tests and comparison with previously published inhibitory reflex data [11]. An EAT-10 score (self-assessed score of dysphagia) of ≥15 indicates a higher aspiration risk and we excluded such participants from the TWST AND TOMASS assessments [14, 15]. A score of ≥3 indicates possible issue with swallowing, and here we proceeded with caution. Abbreviations: COPD = chronic obstructive pulmonary disease; TWST=Timed Water Swallow Test; TOMASS = Test of Mastication and Swallowing of Solids; EMG=Electromyography; EAT-10 = eating assessment tool; n = number included or excluded. The timing of the tests performed is indicated on the left in red text.

Figure 2. EAT-10 scores for participants with COPD and age-matched controls.

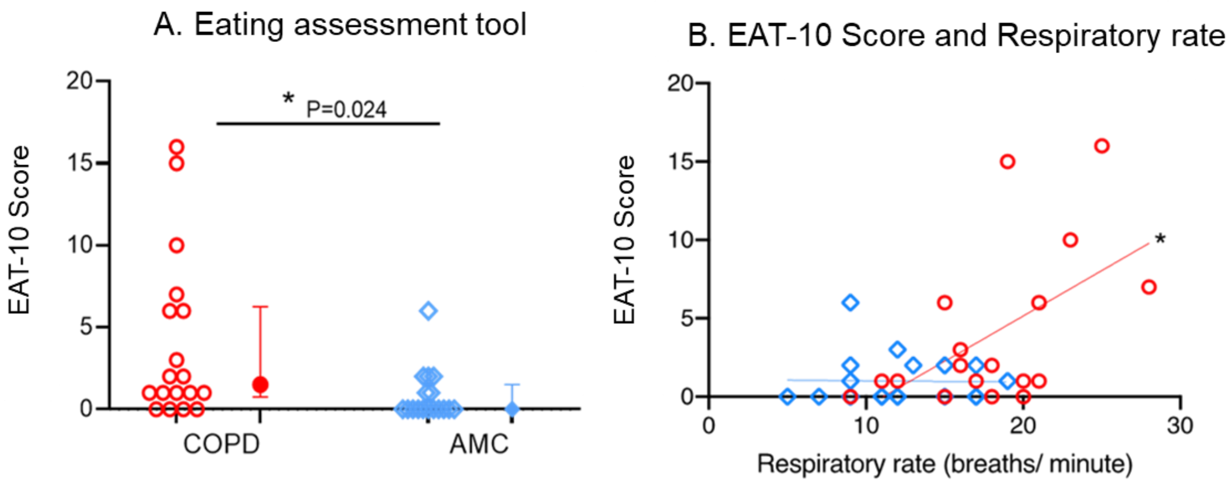
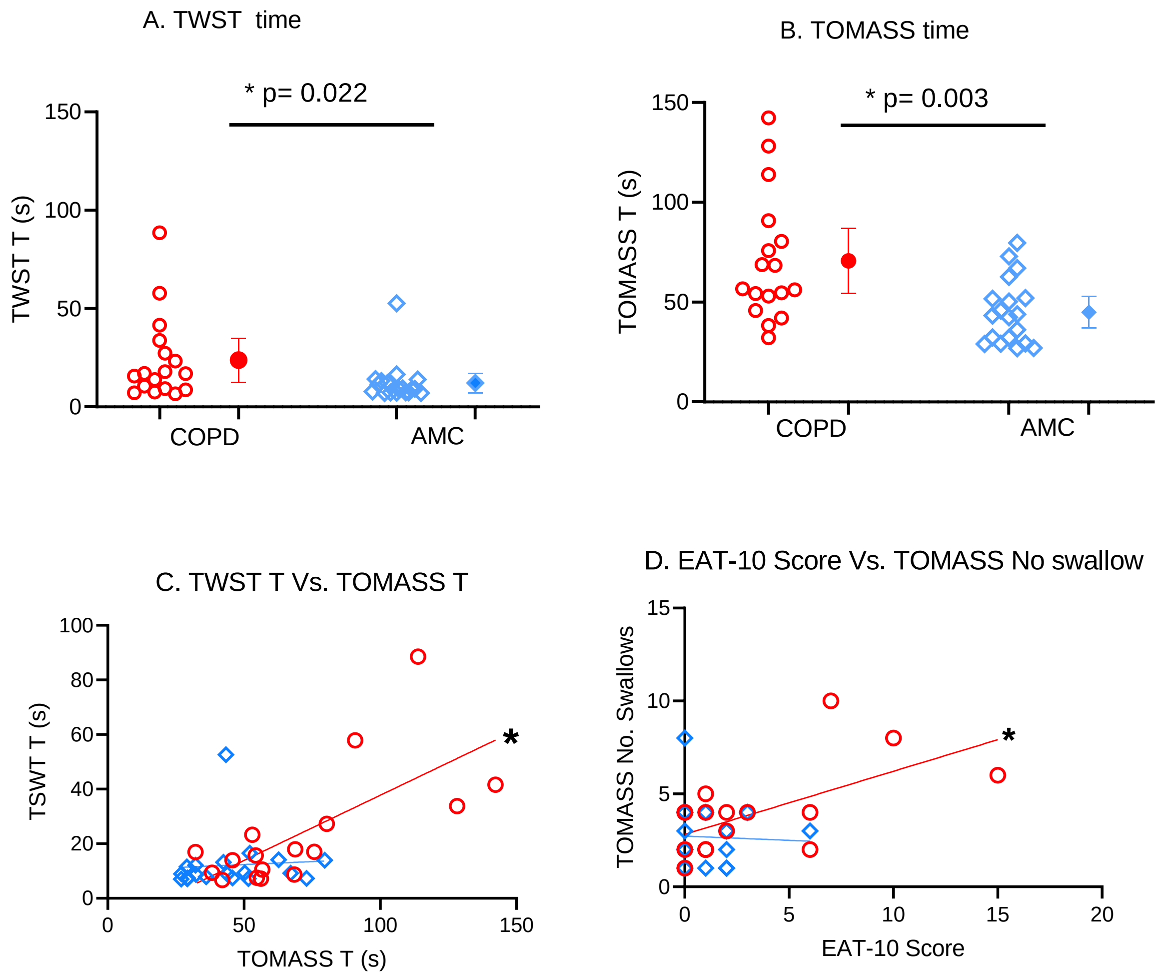


Figure 2A. Individual data (open symbols) and median and IQR (closed symbols) for participants with COPD (n=18, red circles) and age-matched controls (n=20, blue diamonds). 2B. Correlations between respiratory rate and EAT-10 for those with COPD (red circles) and age-matched controls (blue diamonds). Abbreviations, T= Time; COPD = chronic obstructive pulmonary disease; AMC = age-matched control; EAT-10 = eating assessment tool. * Indicates P < 0.05 for t-test comparisons and Spearman's correlations within the COPD group

Figure 3. TWST and TOMASS total time and correlation with EAT-10 Scores



Panels A and B show individual data (open symbols) and mean ± 95% Confidence Intervals (closed symbols) for participants with COPD (n=18, red circles) and age-matched controls (n=20, blue diamonds) for TWST and TOMASS times, respectively. Panels C and D show correlations between TOMASS and TWST times (C) and EAT-10 score and TOMASS number of swallows (D) for those with COPD (red) and age-matched controls (blue). Abbreviations, T= Time; COPD = chronic obstructive pulmonary disease; AMC = age-matched control; TOMASS= test for mastication and swallowing of solids; TWST= timed water swallow test; EAT-10 = eating assessment tool. * Indicates $P < 0.05$ for t-test comparisons and Spearman's correlations within the COPD group

Figure 4 Correlations between TWST/ TOMASS and Spirometry

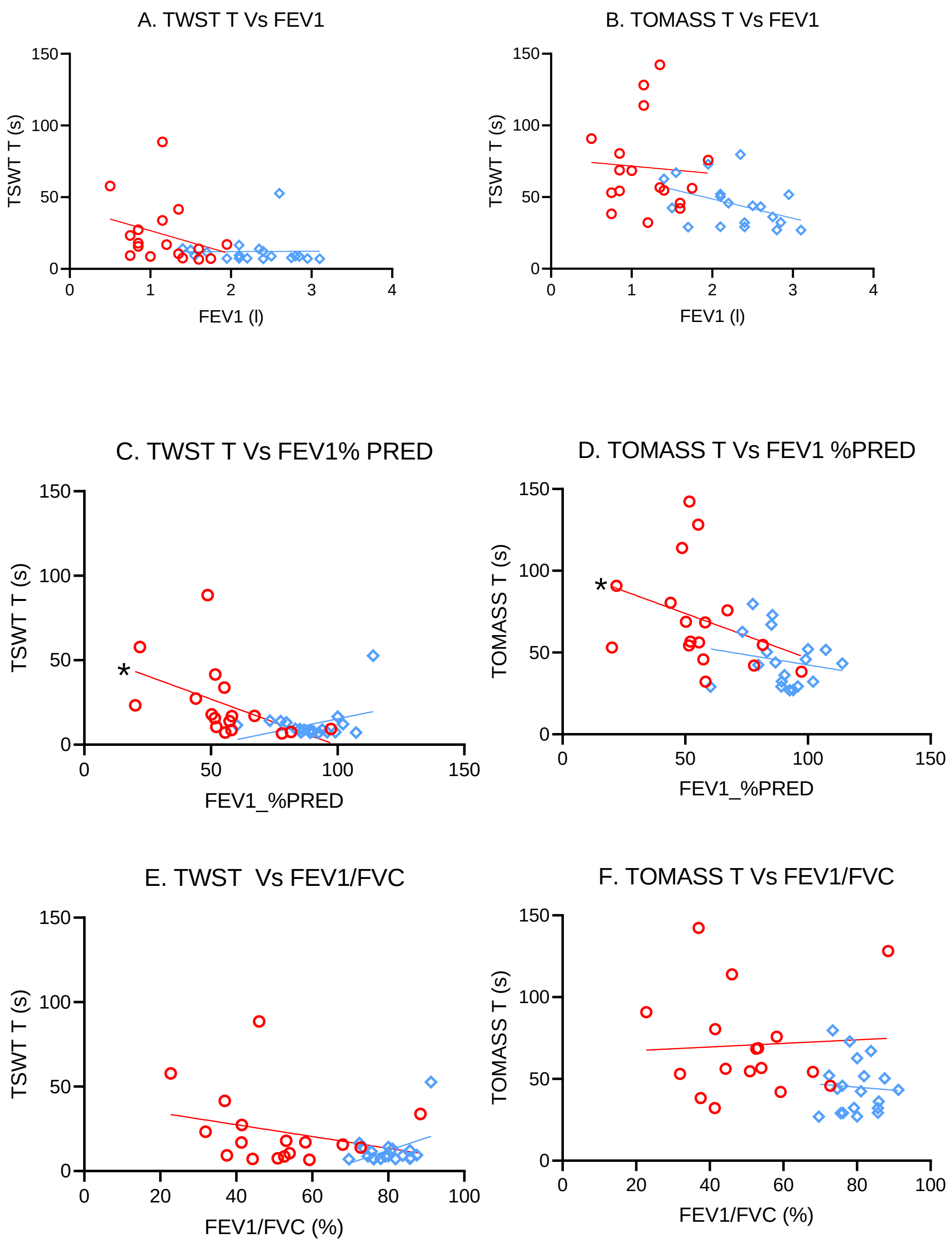


Figure 4 Panel A-F show correlations between total times for TOMASS and TWST and the spirometry measures for those with COPD (red) and age-matched controls (blue). We used Spearman and Pearson correlation (R) to compute the non-parametric and parametric correlations, respectively. Abbreviations, T= Time; COPD = chronic obstructive pulmonary disease; AMC = age-matched control; %PRED = percent predicted for FEV_1; FEV_1 =forced expiratory volume in 1 second; FVC =forced vital capacity; TOMASS= test for mastication and swallowing of solids; TWST= timed water swallow test. * Indicates $P < 0.05$ for Spearman's correlations within the COPD group.