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Biomechanical Quantification of Mendelsohn Maneuver and Effortful Swallowing on Pharyngo-Esophageal Function

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Abstract

Objective

To quantify the effects of two swallowing maneuvers used in dysphagia rehabilitation, the Mendelsohn maneuver and effortful swallowing, on pharyngo-esophageal function using novel, objective pressure-flow analysis.

Study Design

Evaluation of intervention effects in healthy control cohort

Setting

Pharyngo-esophageal motility research laboratory in a tertiary education facility

Subjects

Twelve young healthy subjects (9 females, 28.6 ± 7.9 years) from the general public, without swallowing impairment volunteered to participate in this study

Methods

Surface electromyography from the floor of mouth musculature and high resolution impedance manometry based pressure flow analysis were used to assess floor of mouth activation and pharyngo-esophageal motility, respectively. Subjects performed 10 non-effortful control swallows, Mendelsohn maneuver swallows and effortful swallows each, swallowing a 5ml viscous bolus. Repeated Measures Analyses of Variance was used to compare outcome measures across swallowing conditions.

Results

Effortful and Mendelsohn swallows generated greater floor of mouth contraction ($p=0.001$) and pharyngeal pressure ($p < 0.0001$) compared to control swallows. There were no changes at the level of the upper esophageal sphincter, except for a faster opening of the sphincter to maximal diameter during maneuver swallows ($p = 0.01$). The proximal esophageal contractile integral was reduced during Mendelsohn swallows ($p = 0.001$).

Conclusion

Effortful and Mendelsohn maneuver swallows significantly alter the pharyngo-esophageal pressure profile. Fast opening of the upper esophageal sphincter may facilitate bolus transfer during maneuver swallows, however, reduced proximal esophageal contractility during Mendelsohn maneuver swallows may impair bolus flow and aggravate dysphagic symptoms.

Introduction

Impaired swallowing (dysphagia) is a common consequence of neurological or anatomical impairment of the oropharyngeal tract. The most frequent complications include aspiration and aspiration pneumonia, choking and malnutrition or dehydration, all of which significantly affect patients' and carers' quality of life, self-worth and social participation[1]. A suite of swallowing rehabilitation maneuvers is available, designed to compensate for, or restore, impaired swallowing function[2, 3]. Several of these maneuvers rely on increased effort during swallowing, including the effortful swallow, designed to generate greater pharyngeal pressure through increased contact between base of tongue with the posterior pharyngeal wall[3]. Similarly, the Mendelsohn Maneuver involves maintaining suprahyoid contraction at the peak of hyolaryngeal excursion to increase laryngeal displacement and prolong upper esophageal sphincter (UES) opening[2]. Both maneuvers are widely employed in dysphagia rehabilitation practice and have been shown to increase floor of mouth muscle activation[4,5,6,7] and pharyngeal contractile strength[8,9,10,11,12]. Effortful swallowing also reduces nadir UES relaxation pressure in some[4,12], but not all studies[13,14,8] and increases duration and radiological width of UES opening[15,16]. Similarly, the Mendelsohn Maneuver increases the magnitude and duration of the pharyngeal pressure profile[8,9], reduces peak UES contraction pressure[8] and increases the UES relaxation interval[2,9] , however, may also produce greater esophageal intrabolus pressure or impede esophageal peristalsis[17]. Clinically, understanding the differential impact of each maneuver on pharyngeal and esophageal swallowing physiology is essential for developing patient-specific management regimens, especially in light of potential negative effects on esophageal motility[17]. We employed novel high-resolution impedance manometry (HRIM) based pressure flow analysis[18,19,20,21], which can now provide detailed and objective analysis of pharyngeal-esophageal swallowing biomechanics in terms of occlusive and distension pressure generation, luminal diameter changes and flow timing relationships. This state-of-the-art methodology was employed to assess the biomechanical changes produced by effortful and Mendelsohn maneuver swallowing in healthy subjects.

Methods

Participants

In line with previous studies[9], twelve young healthy volunteers (9 females, mean age ± standard deviation [SD], 28.6 ± 7.9y; 21-48 years) were recruited to the study. This sample size allowed detection of an effect size of r = 0.65 at a power of 0.8. None of the participants verbally reported a history or current symptoms of dysphagia, neurological impairment, head and neck cancer or head and neck surgeries, and/or drug use potentially affecting their neurological or swallowing function. All participants provided written informed consent and the study was approved by the Southern Adelaide Clinical Human Research Ethics Committee.

Procedures

Prior to data collection, participants were instructed by an experienced speech pathologist in the correct execution of the effortful swallowing and Mendelsohn maneuvers and practiced under guidance of online visual biofeedback (sEMG of FOM) until mastery was demonstrated, as judged independently by two speech pathologists. Task instructions for the effortful swallows were “As you swallow, squeeze hard with all your muscles”[4]. For the Mendelsohn maneuver, participants were asked to feel their larynx rise during swallowing and instructed “When you swallow, you will feel your Adam’s apple rising. Hold your swallow when your Adam’s apple has reached its highest point for at least two seconds”.

Surface electromyographic recordings

A triode surface electrode (EMG, Triode$^{\text{TM}}$ Electrode Thought Technology Ltd) was adhered superficially to the floor of mouth muscle group, with the positive and negative electrodes placed at midline and the reference electrode positioned laterally on the left side. Digitised 12-bit samples were obtained with a sampling frequency of 500Hz. The raw signal was band-pass filtered (50-250 Hz) and rectified using Signal software (Version 4.08, Cambridge Electronic Design Ltd., Cambridge, UK).

High resolution impedance manometry

Prior to insertion of the manometric catheter (Insight™ High Resolution Impedance Manometry (HRIM) System, Sandhill Scientific, Highlands Range, Denver, USA), a small amount of topical anaesthesia (Co-phenylcaine Forte Spray, ENT Technologies Pty Ltd, VIC, Australia) was applied to the most patent nasal passage. The manometric catheter (diameter 3.2mm) incorporated 32 solid state, circumferential pressure sensors spaced at 1cm intervals, with 16 adjoining impedance segments spaced at 2cm intervals. Prior to each study, the catheter pressure transducers were calibrated from 0 to100 mmHg using externally applied pressure in a calibrated pressure chamber. The lubricated catheter was then inserted trans-nasally and positioned so that the sensors straddled the entire pharyngo-esophageal segment and fixed to the nose with tape. Participants then rested for 10 minutes to adjust to the catheter *in situ.*

Pressure and impedance data were acquired at 50 Hz (Insight Acquisition System; Sandhill Scientific, Denver, CO, USA) and were displayed on an integrated computer system, BioVIEW Analysis Suite (Sandhill Scientific Inc.).

Experimental tasks

Floor of mouth sEMG and HRIM data were acquired simultaneously during ten swallows of 5ml viscous conductive jelly (EFT Viscous Sandhill Scientific, Highlands Ranch, CO, USA) using each swallowing maneuver as well as non-effortful control swallows. Non-effortful swallowing was performed first in order to prevent potential carry over effects of the swallowing maneuvers. The order of the maneuver swallows was counterbalanced across participants. All boluses were administered orally via a syringe and participants swallowed on command.

Data Processing and Analysis

Manometric and sEMG data were digitally recorded for offline analysis. Pressure and impedance signals were analysed to derive swallow function variables using Sandhill Bioview software (Sandhill Scientific, Highlands Range, Colorado, USA) and purpose designed software (*AIMplot*, copyright T Omari) which was written in Matlab (The MathWorks, Natick, MA, USA). *AIMplot* analysis utilised exported text data files. The analyst opened each swallow as a standard pressure isocontour plot and then selected six space–time landmarks as previously described elsewhere. These landmarks included timing of UES opening and closure, and the proximal margins of the velopharynx and pharynx, UES apogee and distal UES margin. This procedure has been repeatedly shown to be reliable for deriving swallow function variables[20,22,23]. Sixteen swallow function variables were defined as in Table 1 (see also Appendix 1).

Swallowing Risk Index

In addition to the outcome variables described in Table 1, a swallow risk index (SRI) was calculated for each swallow using the following formula:

- $$SRI = \frac{(IBP*BPT)}{(PeakP*(DCL+1)} *100$$

where IBP is the pressure at maximal hypo-pharyngeal admittance at 1cm superior to the UES apogee, BPT is the period of bolus related elevated admittance, recorded at 1cm superior to the UES apogee position, PeakP is the average maximal pressure from superior pharyngeal constrictor margin to UES proximal margin and DCL is the latency between maximal distension and peak pressure in the pharynx (Table 1).

This formula has previously been shown to be a useful marker of swallowing dysfunction, bolus residue and aspiration risk and was developed based on the iterative evaluation of pressure and impedance variables[18,19,20]. Clinically, an SRI above 15 indicates significant risk for aspiration[18]. Using this technique, clinically relevant changes in swallowing biomechanics during swallowing maneuvers can be determined.

Statistical Analysis

General linear model repeated measures Analyses of Variance (RM-ANOVA) was employed to identify within- subject differences using the Statistical Package for the Social Sciences (SPSS) version 22. All outcome variables were subjected to separate RM-ANOVAs with Swallowing Condition (normal swallowing, effortful swallowing, and Mendelsohn swallowing) as the independent variable. When significant main effects were present, Bonferroni-corrected post-hoc paired samples t-tests were performed to explore the strength of the main effect and compare each maneuver to the non-effortful control swallows.

Results

Effects on floor of mouth sEMG profile

Floor of mouth contraction (sEMG peak amplitude and sEMG integral) was significantly higher during Mendelsohn maneuver and effortful swallows compared to non-effortful control swallows. See Table 2 for all means and confidence intervals and Table 3 for all statistically significant comparisons. Floor of mouth sEMG peak amplitudes did not differ between Mendelsohn Maneuver swallows and effortful swallows; in contrast, the sEMG integral was significantly larger during Mendelsohn maneuver swallows compared to effortful swallows.

Effects on pharyngeal pressure profile

The velopharyngeal (VCI) and pharyngeal contractile integral (PhCI) were significantly greater during Mendelsohn maneuver and effortful swallows compared to non-effortful control swallows. Both VCI and PhCI were greater during Mendelsohn Maneuver swallows compared to effortful swallows. In line with this, peak pharyngeal pressure (PeakP) was also significantly greater during both maneuvers compared to non-effortful control swallows, although there was no difference between Mendelsohn Maneuver and effortful swallows. Hypo-pharyngeal intrabolus pressure (IBP) ($F_{(2,20)} = 0.19$; p=0.829) or bolus presence time (BPT) ($F_{(2,22)} = 1.31$; p=0.291) did not differ across swallowing conditions.

Effects on upper esophageal sphincter pressure profile

Upper esophageal sphincter opening latency (OL) was significantly shorter during both maneuvers compared to non-effortful control swallows, whereas UES closure latency (CL) was signficianlty prolonged during maneuvers swallows. In contrast, total UES open duration (UOD) did not vary across swallowing conditions ($F_{(2,22)} = 0.387$; p =0.684). Likewise, the upper esophageal sphincter contractile integral (UCI) ($F_{(1.2,13.25)} = 1.58$; p =0.228), UES basal pressure (UES-BP) ($F_{(2,22)} = 1.78$; p =0.191), UES maximum admittance (UESmaxAD) ($F_{(2,22)} = 2.07$; p =0.15), integrated relaxation pressure (IRP 0.25) ($F_{(2,22)} = 0.36$; p =0.705) and UES Peak pressure (UESPeakP) ($F_{(2,22)} = 1.67$; p =0.211) were all not changed during Mendelsohn maneuver and effortful swallows.

Effects on proximal esophageal pressure profile

The proximal esophageal contractile integral (PCI) was significantly reduced during Mendelsohn maneuver swallows, but not during effortful swallows, compared to non-effortful control swallows. The integral was also smaller during Mendelsohn swallows compared to effortful swallows.

Effects on Swallowing Risk Index

The swallowing risk index (SRI) did not differ across swallowing conditions ($F_{(2,20)} = 2.65$; p = 0.095).

Discussion

We employed a novel, integrated pressure flow analysis to investigate the effects of two common rehabilitation strategies in dysphagia management, the effortful swallow and Mendelsohn maneuver, on pharyngeal and proximal esophageal peristalsis. Our data are in line with previous research documenting increased effort during both maneuvers[5,12], as reflected in increased recruitment of the floor of mouth musculature, increased pharyngeal pressure generation and markedly reduced pressures in the proximal esophagus[17].

In contrast to expectations based on previous studies[2,24], UES admittance measurements did not demonstrate any significant increase in UES opening area during either maneuver, despite the marked increase in FOM sEMG, which would have exerted an increased anterior pull on the cricopharyngeus muscle. However, we did observe faster UES luminal opening during bolus presence, consistent with more vigorous anterior pull by FOM contraction during maneuver swallows.

Effects on floor of mouth sEMG

As both maneuvers are conceptually based on increased volitional effort during swallowing, it is not surprising that the peak contractile vigor of the FOM musculature was increased during both swallowing maneuvers. This finding is in line with previous studies[5] and supports the concept that both maneuvers exert a greater anterior pull on the CP muscle. This was evident in faster UES luminal opening during maneuver swallows, as indicated by a shorter opening latency and longer closure latency in the presence of unaltered overall UES opening duration. We acknowledge that due to the proximity and overlap of the tongue musculature with the FOM muscle group, it is possible that the increased sEMG amplitude during maneuver swallows may at least in part represent greater lingual propulsion.

Effects on pharyngeal pressure profile

The increased FOM activation was mirrored by increased peak pharyngeal pressure and velo-pharyngeal and pharyngeal contractile integrals during both swallowing maneuvers. This is in agreement with previous studies [8,10,11,12] and likely reflects the overall volitional modification of central pattern generator (CPG) output which alters peak contractile strength, but not the timing of the pharyngeal contraction sequence.

Effects on upper esophageal sphincter relaxation and opening

The lack of effects on most UES parameters was unexpected, given that published findings suggest that improvement of UES opening is a primary objective of these swallowing maneuvers[2,24]. It could be argued that the lack of effect was due to the fact we performed the study in young healthy volunteers. However, we note the marked increase in FOM activation and the fact that we intentionally used a medium sized test bolus that afforded sufficient capacity to detect UES opening effects. Interestingly, the pressure-only and admittance-only UES swallow function variables did not show any effects, whereas those measures representing bolus flow relative to signature pressure events, e.g. the latencies between peak hypo-pharyngeal admittance and UES opening and closing, were significantly modified. We infer from this observation that the swallowing maneuvers sped up the opening of the UES during bolus presence. It is likely that this occurred due to a more vigorous anterior pull of the FOM muscles during maneuver swallows, resulting in faster maximal UES opening. As the overall UES opening duration, which is governed by central pattern generators in the brainstem, was unaffected by maneuver swallows, UES closing duration was consequently longer.

It may be argued that faster UES opening would functionally translate to improved bolus admittance through the UES. This was not the case in the present study and is in agreement with a previous study documenting a lack of effect on nadir relaxation pressures[8] during effortful and Mendelsohn swallows. However, as bolus admittance is significantly influenced by other biomechanical contributors, such as bolus volume and viscosity, it is possible that at greater bolus volumes, faster UES opening would facilitate bolus admittance through the UES.

Effects on proximal esophageal contraction

Expanding on previous research[17], we show that Mendelsohn maneuver swallows reduced the proximal esophageal pressure integral. The neurophysiological mechanisms underlying this effect are not clear. Given that this effect did not occur during effortful swallowing, we hypothesise that modifying the duration of pharyngeal contraction during Mendelsohn maneuver swallowing is a main contributor to this effect. This is in keeping with the notion that volitional modification of the pharyngeal contraction pattern interacts with the esophageal swallowing pattern generated by swallowing CPGs in the brainstem. Whilst it is not yet fully understood how and at which level the pattern generators for the pharyngeal and esophageal phases of swallowing interact, there is some evidence from tract tracing studies that interconnections exist at the level of the nucleus tractus solitarius (NTS), in particular the interstitial and centralis subnuclei, where oropharyngeal and esophageal swallowing nuclei are located, respectively[25]. It has also been shown that esophageal motor neurons are inhibited during activation of pharyngeal motor neurons (deglutitive inhibition) as, for example, during sequential swallowing[26]. Because of this rostro-caudal inhibition, it is possible that during Mendelsohn Maneuver swallows proximal esophageal contraction is inhibited in a similar fashion until conclusion of the (volitionally prolonged) pharyngeal phase of swallowing. Previous research documenting no changes in the distal esophagus, including the distal contractile integral, contractile front velocity or transition zone defect during Mendelsohn maneuver swallows[17], support the hypothesis that the effects seen in the proximal esophagus are primarily driven by modification of brainstem CPG output and not the enteric nervous system.

Clinical relevance

The lack of patient specific data in relation to the effects of swallowing maneuvers is a major limitation in the literature. Our study is no exception in this regard, and therefore further investigations of the interaction of maneuver swallowing and bolus volumes in different age groups and individuals with dysphagia are planned. However, our finding that maneuver swallows facilitate faster opening of the UES is of clinical relevance, as it suggests potential benefits for those with a sensory miss-regulated system. For example, those presenting with delayed swallow trigger may benefit from faster UES opening to respond more quickly to the descending bolus.

As displayed in Appendix 2, we also note that in some of our healthy participants, hypoharyngeal pressure appeared to increase, although this was not reflected at the group level of the healthy participants studied. As increased hypo-pharyngeal pressure may be a sign of impeded transphincteric bolus flow, it is warranted to further evaluate this phenomenon in those with already impaired hypo-pharyngeal bolus flow.

Limitations and Future Directions

The participants recruited in this study were young healthy volunteers with no history of dysphagia. Considering the effects of aging on swallowing[27], it remains to be evaluated whether similar effects as reported here are observed in older individuals and those who present with pharyngeal and esophageal motility disorders. This is particularly pertinent as it has been demonstrated that the effortful swallowing maneuver affects UES pressures differently in older compared to young individuals[28]. Specifically, trans-sphincteric intrabolus pressure increased in the older cohort during effortful swallows[28], suggesting potential resistance to bolus flow across the UES. Our findings align with this study as no effects on trans-sphincteric bolus flow were observed in the young individuals tested, but further evaluation in the elderly using HRIM pressure flow analysis is warranted.

It is also critical to further investigate the interaction of maneuver swallowing and bolus volume and consistency across larger samples of different age groups. The sample size of the current study was limited and the results should be interpreted in this context.

Conclusion

We document in a group of young healthy participants that effortful and Mendelsohn maneuver swallowing significantly alter pharyngeal pressure generation, which is accompanied by greater activation of the FOM and prolonged inhibition of the cricopharyngeal muscle segment. In addition, reduced proximal esophageal contractility during Mendelsohn maneuver swallows may functionally impose resistance to bolus flow and hence further investigation into the effects of these maneuvers of swallowing in older individuals and those with dysphagia is warranted.

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Table 1. Outcome variables derived from pharyngeal high resolution impedance manometry.

Variable	Variable name, unit	Definition
Floor of mouth sEMG		
Peak sEMG amplitude	sEMGPeak, mV	maximum contraction during a swallow amplitude of FOM task
FOM sEMG integral	sEMG Int, mV.s	submental sEMG amplitude across the duration of the swallow task, i.e. area under the sEMG curve
Pharynx		
Velo-Meso pharyngeal contractile integral	VCI, mmHg.cm.s	sum of the pressure amplitudes >20mmHg from the velo-pharyngeal proximal margin to the superior pharyngeal constrictor margin over the period from UES opening to 0.5s after UES closure
Pharyngeal peak pressure	PeakP, mmHg	average maximal pressure (mmHg) from superior pharyngeal constrictor margin to UES proximal margin
Pharyngeal contractile integral	PhCI, mmHg.cm.s	sum of pharyngeal pressures >20mmHg from superior pharyngeal constrictor margin to UES proximal margin over the period from UES opening to 0.5s after UES closure
Hypo-pharyngeal Intrabolus pressure	IBP, mmHg	pressure at maximal hypo-pharyngeal admittance (maximum distension) at 1cm superior to the UES apogee position. Note that data from one participant was excluded for this outcome measure due to presence of a contact pressure artefact that clearly did not represent intrabolus pressure.
Hypo-pharyngeal bolus presence time	BPT, s	period of bolus presence in the hypo-pharynx, recorded at 1cm superior to the UES apogee position. Bolus presence was determined by means of reduced impedance in this regions during swallowing.

Distension-contraction latency	DCL, s	Latency between maximal distension and peak pressure in the pharynx
Upper esophageal sphincter		
UES pre-deglutitive basal pressure	UES-BP, mmHg	average UES profile pressure recorded over the period from 1-0.25s prior to UES opening.
UES integrated relaxation pressure	IRP 0.25	lowest 0.25s of UES profile pressure during relaxation.
UES maximum admittance	UESmaxAd, S	the maximum UES admittance profile value recorded during UES relaxation.
UES post-deglutitive peak pressure	UESPeakP, mmHg	maximum UES profile pressure recorded from 0-1sec after UES closure.
UES contractile integral	UCI, mmHg.cm.s	sum of UES pressures >20mmHg from UES proximal to distal margin over the period from 0-1sec after UES closure.
Latency between onset of the UES opening and maximal luminal opening	opening latency (OL), s	period between onset of UES opening and peak hypo-pharyngeal admittance
Latency between maximal luminal opening and UES closure	closure latency (CL), s	period between peak hypo-pharyngeal admittance and UES closure
UES opening duration	UOD, s	latency between UES opening and UES closure
Proximal esophagus		
Proximal Contractile Integral	PCI, mmHg.cm.s	sum of proximal esophageal pressures > 20 mmHg from UES distal margin to transition zone over the period of 3 s after UES closure[30].

Table 2. Means and SE/SD of all variables across swallowing conditions. Comparisons to control swallows highlighted in bold if $p<0.05$.

	Normal			Mendelsohn			Effortful		
	Mean	CI lower	CI upper	Mean	CI lower	CI upper	Mean	CI lower	CI upper
sEMG measurements									
sEMG peak (mV)	0.16	0.1136	0.1967	**0.40**	0.214	0.577	**0.35**	0.242	0.467
sEMG Int (mV.s)	0.02	0.0126	0.0248	**0.15**	0.066	0.234	**0.07**	0.036	0.1
Pharyngeal measurements									
VCI (mmHg.s.cm)	127	80.29	173.85	**425**	249.92	600.63	**277**	164.5	388.52
PeakP (mmHg)	157	125.34	190.4	**220**	157.1	282.02	**198**	151.21	245.69
PhCI (mmHg.s.cm)	70	45.92	94.73	**234**	171.08	296.76	**143**	100.44	185.62
IBP (mmHg)	13.5	7.645	19.437	12.8	6.01	19.59	12.2	3.49	20.87
BPT (sec)	0.37	0.31	0.43	0.33	0.26	0.39	0.34	0.26	0.42
DCL (sec)	0.26	0.192	0.31	0.37	0.297	0.448	0.34	0.283	0.387
UES measurements									
UES-BP (mmHg)	70	50.016	90.704	79	44.04	113.28	57	40.74	72.95
UCI (mmHg.s.cm)	221	160.79	282.18	**179**	113.13	245.01	**206**	144.8	267.79
UESmaxAd (mS)	3.28	3.128	3.605	3.23	3.018	3.55	3.43	3.14	3.72
IRP0.25 (mmHg)	4.4	0.186	8.66	5.6	0.874	10.365	4.9	-1.36	11.1
UESPeakP (mmHg)	234	167.5	302.2	195	121.48	268.5	245	145.67	343.73
Opening latency (s)	0.25	0.22	0.28	**0.19**	0.14	0.25	**0.2**	0.15	0.26
Closure latency (s)	0.27	0.19	0.34	0.31	0.25	0.38	**0.33**	0.25	0.4
UOD (s)	0.54	0.46	0.63	0.53	0.46	0.61	0.55	0.45	0.65

Proximal esophageal measurement								
PCI	204	135.73	272.07	**93**	51.47	133.82	167	121.33	212.64
Global swallow function score								
SRI	3.17	1.64	4.70	2.38	0.97	3.79	2.26	0.97	3.55

Table 3. Summary of statistically significant main effects and post-hoc comparisons. CI, confidence interval.

Main effect across all three swallowing conditions			Post-hoc comparisons					
			Control vs. Mendelsohn		Control vs. Effortful		Effortful vs. Mendelsohn	
Outcome variable	F$_{(2,22)}$	p-value	t$_{(11)}$	p-value (CI)	t$_{(11)}$	p-value (CI)	t$_{(11)}$	p-value (CI)
sEMG measurements								
sEMG peak	10.61	0.001	3.36	0.006 (0.08, 0.39)	4.98	<0.0001 (0.11, 0.29)	0.79	0.44 (-0.07, 0.15)
sEMG Int	10.31	0.001	3.59	0.004 (0.05, 0.21)	3.8	0.003 (0.02, 0.08)	2.5	0.029 (0.01, 0.15)
Pharyngeal measurements								
VCI	16.9	<0.0001	4.75	0.001 (160.05, 436.35)	3.22	0.008 (47.17, 250.34)	3.51	0.005 (55.75, 243.13)
PhCI	29.5	<0.0001	6.2	<0.0001 (105.32, 221.86)	4.05	0.002 (41.44, 140.34	5.8	<0.0001 (44.97, 100.43)
PeakP	4.56	0.022	2.42	0.034 (5.57, 117.8)	3.08	0.01 (11.58, 69.57)	0.97	0.35 (-26.63, 68.86)
UES measurements								
OL	6.76	0.005	3.15	0.009 (0.016, 0.091)	2.87	0.015 (0.01, 0.08)	0.61	0.55 (-0.04, 0.022)
CL	3.6	0.044	2.8	0.017 (0.03, 0.104)	1.68	0.12 (-0.11, 0.014)	0.62	0.55 (-0.056, 0.031)
Proximal esophageal measurement								
PCI	9.85	0.001	3.46	0.005 (40.55, 181.94)	1.46	0.163 (-17.41, 91.25	4.19	0.002 (113.3, -35.31)

Legends for Appendix

Appendix 1. A. High resolution color pressure topography plot of a 10ml viscous bolus swallow recorded in a healthy subject. Scale right shows the range of pressure (blue indicates lowest pressure, red indicates highest pressures). Pressure patterns allow the pharyngeal chamber to be separated into three regions; velo-/meso-pharynx complex, hypo-pharynx and upper esophageal sphincter (UES) within which pressure integrals were calculated (namely the velo-meso pharyngeal contractile integral, VCI; pharyngeal contractile integral, PhCI, the UES contractile integral, UCI and proximal esophageal contractile integral, PCI).

The dotted line within the UES region shows the axial location of maximum UES pressure during the swallow (Pmax position) tracking a ~3cm superior movement of UES high pressure zone from resting to apogee position (0cm). The dotted line within the hypo-pharynx indicates the positon 1cm proximal to the UES apogee (+1cm) which is the standard location we use to define hypo-pharyngeal pressure and admittance variables (see below).

B. The same pressure topography plot with color removed showing 50mmHg isobaric contour steps. The upper black line shows the pressure waveform recorded at the hypo-pharyngeal position during the swallow (apogee +1cm) and the lower black line shows UES pressure waveform constructed from pressures recorded at the Pmax positon over time. From these data, the mean pre-deglutitive UES basal pressure (UES-BP), UES integrated relaxation pressure (UES-IRP) and post-deglutitive UES peak pressure (UES-PeakP) can be determined.

C. The same pressure topography plot with color removed showing isobaric contours. The upper purple line shows the admittance waveform recorded at the hypo-pharyngeal position during the swallow (apogee +1cm) and the lower purple line shows UES admittance waveform constructed from impedance recorded at the Pmax positon over time. Note: Admittance (in Siemens, S) is the *inverse product* of Impedance ($S = 1/\Omega$) therefore the admittance *rises* with bolus distension of the hypo-pharynx and UES and the maximum admittance within the UES (Max UES Adm.) is indicative of maximum cross-sectional area of the lumen.

D. The same plot as in C, however now showing how the UES admittance and pressure waveforms can be used together to define the onset of UES opening (O), based on the admittance upstroke within the UES, and UES closure (C), based on the pressure upstroke within the UES. For estimation of hypo-pharyngeal bolus presence time (BPT), the UES threshold admittance level recorded at the determined UES closure time (*th* on lower admittance plot) is applied as a cut-off to the pharyngeal admittance recording (see th, on upper admittance plot). Hence the period that the pharyngeal admittance exceeds the cut-off threshold defines bolus presence time (period shaded on the hypo-pharyngeal admittance waveform).

E. The same pressure topography plot with color removed. However, in this figure the lines indicate the time of maximum admittance (Max Adm.) and peak pressure generation (Peak Press.) along the hypo-pharyngeal region, indicating the time of maximum bolus distension and maximum contraction of the hypo-pharynx during the swallow. Hypo-pharyngeal intra-bolus distension pressure (IBP) is defined by the pressure recorded at maximum distension, 1cm proximal of the UES apogee. Hypo-pharyngeal mean peak pressures (mean Peak P) define maximum contractility of the pharyngeal constrictors. The average latency from maximum distension to peak contraction (DCL) defines the timing of flow relative to contraction.

Appendix 2. Upper Panels. High resolution color pressure topography plots of 10ml viscous bolus swallows recorded in a healthy subject who demonstrated worsening swallowing biomechanics in relation to Maneuver swallows. Scale right shows the range of pressure (blue indicates lowest pressure, red indicates highest pressures). In each the upper grey line shows the pressure profile recorded at the hypo-pharyngeal position during the swallow (apogee

+1cm) and the lower lines show the UES pressure (grey) and admittance (purple) profiles constructed as in Appendix 1.

Lower Panels. Hypo-pharyngeal and UES pressure and admittance profiles for the three swallow conditions superimposed for comparison. Noticeable in this example sequence is an earlier rise in pressures during maneuver swallows, consistent with increased flow resistance in the hypo-pharynx and earlier closure of the UES. Furthermore, the admittance profiles at both levels show a lower maximum admittance during maneuver swallows which would be interpreted as a reduced luminal diameter during the maneuver swallows compared to normal.