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ORIGINAL ARTICLE

Potential for Behavioural Pressure Modulation at the Upper Oesophageal Sphincter in Healthy Swallowing

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Abstract

Supratentorial structures are known to be involved in the neural control of swallowing, thus the potential for volitional manipulation of pharyngeal swallowing is of rehabilitative interest. The extent of volitional control of the upper oesophageal sphincter (UOS) during swallowing remains unclear. Prior research has shown that the UOS opening duration can be volitionally prolonged during execution of the Mendelsohn manoeuvre, which does not change the UOS opening time in isolation but the swallowing response in its entirety. This study explored the capacity of healthy adults to increase the period of pressure drop in the region of the UOS (UOS-Pdrop) during swallowing, through volitional UOS pressure modulation in the absence of altered pharyngeal pressure. The period of UOS-Pdrop was used as a proxy of UOS opening duration that is associated with a pressure decrease at the region of the UOS. Six healthy adults were seen 45 min daily for 2 weeks and for one follow-up session. During training, high-resolution manometry contour plots were provided for visual biofeedback. Participants were asked to maximally prolong the blue period on the monitor (period of UOS-Pdrop) without altering swallowing biomechanics. Performance was assessed prior to training start and following training. There was evidence within the first session for task-specific volitional prolongation of the period of UOS-Pdrop during swallowing with biofeedback; however, performance was not enhanced with further training. This may suggest that the amount to which the period of UOS-Pdrop may be prolonged is restricted in healthy individuals. The findings of this study indicate a potential of healthy adults to volitionally prolong UOS opening duration as measured by the period of pressure drop at the region of the UOS. Further research is indicated to evaluate purposeful pressure modulation intra-swallow in patient populations with UOS dysfunction to clarify if the specificity of behavioural treatment may be increased.

Keywords Deglutition · Dysphagia · Upper oesophageal sphincter · Volition · High-resolution manometry

Introduction

Swallowing is a highly complex and dynamic function that is controlled not only by the brainstem but by diverse cortical and subcortical structures [1–3]. As supratentorial structures are involved in neural control of swallowing, the potential for volitional manipulation of pharyngeal swallowing is of rehabilitative interest [4]. Research has shown that behavioural manipulation of the swallowing response can be achieved primarily by increasing duration through execution of the Mendelsohn manoeuvre [5–9] or by increasing effort [7, 10–15].

The Mendelsohn manoeuvre and effortful swallowing are commonly used techniques for treatment of impaired upper oesophageal sphincter (UOS) opening intra-swallow. However, there is newer research that questions the impact

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of the Mendelsohn manoeuvre on UOS opening duration in healthy subjects [7, 9]. For both swallowing techniques, alteration of swallowing biomechanics [11, 16] and altered pharyngeal pressure have been documented [7, 10, 13, 14]. While volitional alteration of the pharyngeal phase in its entirety has been the subject of numerous studies, there is little known whether individual aspects of the swallowing response can be volitionally modulated.

Understanding the potential for purposeful modulation of single aspects of the pharyngeal phase is important considering that a change of the entire swallowing response may negatively impact functional swallowing [17]. Findings from a study by Macrae and colleagues [18] suggest that healthy adults have the potential to volitionally prolong the intra-swallow closure of the laryngeal vestibule if provided with combined feedback on performance and outcome. Huckabee et al. [19] reported on the capacity for volitional manipulation of pharyngeal pressure generation in a cohort of patients with dysphagia. The patients included in this study presented with simultaneous pressure generation in the upper and lower pharynx. Following intensive rehabilitation using manometric visual biofeedback, the temporal separation between pressure generation in the upper and lower pharynx increased considerably. Based on this study, Lamvik and colleagues [20] investigated the capacity of healthy adults to volitionally reduce the latency of pressures generated in the upper and lower pharynx. The authors documented that a small cohort of participants could volitionally reduce latency of pharyngeal closure; however, the findings imply that in large part, participants modulated the pharyngeal response cumulatively by swallowing faster. More research is needed to evaluate the potential for volitional control of discrete components of swallowing.

This exploratory research investigated the capacity of healthy adults to behaviourally prolong the period of pressure drop in the region of the UOS (UOS-Pdrop) during swallowing as a proxy of intra-swallow UOS opening duration. A study in healthy subjects allows for edification of the capacity for behavioural manipulation without confounding effects of neural injury. We hypothesised that healthy subjects would be able to behaviourally prolong the period of UOS-Pdrop during swallowing following intensive visual biofeedback training; pressure modulation at the UOS would be achieved without significant alteration of swallowing-related pressure measured in the pharynx.

Materials and Methods

Participants

Six participants were recruited from the community via a laboratory volunteer database and from the university via advertisement. The sample size and protocol were based on the study by Lamvik and colleagues [20] who evaluated purposeful alteration of pharyngeal swallowing and documented significant results. The criteria for exclusion included reported swallowing difficulties, neurological or muscular disease, gastrointestinal disease/reflux or drugs which might have an impact on swallowing. Ethical approval was obtained from the university ethics committee (HEC 2016/42). Prior to the start of data collection, participants provided informed consent.

Equipment

The high-resolution manometry (HRM) ManoScan 360™ system (A120, Medtronic, Minneapolis, MN) with a ManoScan™ ESO catheter (EPS0042) (2.75 mm diameter) was used for data collection and for visual biofeedback. The catheter housed 36 circumferential pressure sensors with 7.5 mm spacing between sensors.

Procedure

Participants attended daily training (approximately 45 min/day) for 2 weeks (10 days) and were seen for a follow-up session after a break of 2 weeks, to evaluate retention. Training took place in a clinical research laboratory. Participants were familiarised with major landmarks and areas of interest on HRM contour plots at the start of the first session. Calibration was then routinely performed as per standard operating instructions. As there is evidence to suggest that topical anaesthesia does not improve comfort during catheter placement [21, 22], no anaesthesia was applied to avoid potential altered swallowing function [21, 23, 24]. After application of lubricating gel on the catheter tip, the catheter was placed transnasally using a routine protocol [25]. Once sensor one was located just inside the naris and sensor 36 was in the cervical oesophagus, the catheter was secured with tape to the external nose. Participants were given 2 min to adjust to the catheter in situ. At the beginning of the first training session (session 1), baseline measures were collected. Outcome measures were taken after one and after 2 weeks of training (at the completion of session 5 and 10) and at the follow-up.

Training Task

Participants were seated upright in a chair facing the HRM contour plots on the monitor with their head in a neutral position. They were asked to self-explore how to prolong the duration of UOS opening by pressure manipulation of the UOS rather than by biomechanical alteration of the swallowing response. No specific method was directly trained or instructed by the researcher, beyond the following instructions that were provided at the beginning and in the middle of each session: 'While swallowing saliva, try to prolong the period of dark blue for as long as possible. Try to do this by specifically controlling the muscles at the entrance to the food tube rather than by changing head or neck position or moving other muscles' (Fig. 1). In total, 16 two-minute blocks or a total of 64 training swallows were performed per session. In each block, participants swallowed saliva four times, approximately once every 30 s, whenever they were ready. After each block, participants had a break of 45 s. Acknowledgement such as 'good try' was verbalised by the researcher during training breaks three times, evenly spread within each session. Additionally, verbal feedback about change in performance after 1 week of training compared to no training was provided at the beginning of the second training week. At the conclusion of each session, participants were invited to write down what they did to best achieve the task goal.

Collection of Baseline and Outcome Measures

First, baseline and outcome measures were collected during performance of five natural (non-manipulated) saliva swallows and five swallows of 10 mL water from a cup; no biofeedback was provided. The instruction included 'once I give the instruction, please swallow your saliva ('or water') as naturally as possible whenever you are ready'. Next, the participants were asked to increase the duration of intra-swallow pressure drop during five saliva and five water swallows with visual feedback provided (manipulated swallows). Identical instructions as during training were provided. For non-manipulated and manipulated swallows, saliva swallowing was evaluated first to avoid a potential impact of bolus swallowing on the trained condition (saliva swallowing). A period of at least 30 s between swallows was selected to allow participants time to accrue saliva and to allow UOS pressure to reach natural resting pressure post-swallow prior to the subsequent swallow.

Data Extraction

Interpolated thermal compensation was applied to the raw HRM spatiotemporal plots and the recordings were encoded. The researchers involved in data extraction were blinded to patient identity. The type of swallowing task (manipulation or non-manipulation condition) and bolus type (saliva or water swallowing) was not blinded as non-manipulated swallows were always assessed first to avoid potential influence of manipulation on natural swallowing. The main outcome measure, the trained task without bolus swallowing, was evaluated fist to avoid potential impact of bolus swallowing on the main outcome measure. Twenty percent of the data was randomly selected and extracted by the main researcher on a second occasion at least 1 week apart to evaluate intra-rater reliability. The main researcher provided verbal and written explanation to a second rater who extracted data of another randomly selected 20% of the data for assessment of inter-rater reliability. The principal investigator had approximately 1 year of experience in HRM data extraction; the second rater had about 2 years of practice.

For assessment of the period of UOS-Pdrop (s), UOS sensors during swallowing and at rest were visually identified in ManoView™ software. During swallowing, the most rostral sensor showing a pressure pattern similar to an 'M-wave' [26] was defined as the upper most UOS sensor. The most caudal UOS sensor was defined as the middle sensor of all sensors recording pressure at the UOS at rest.

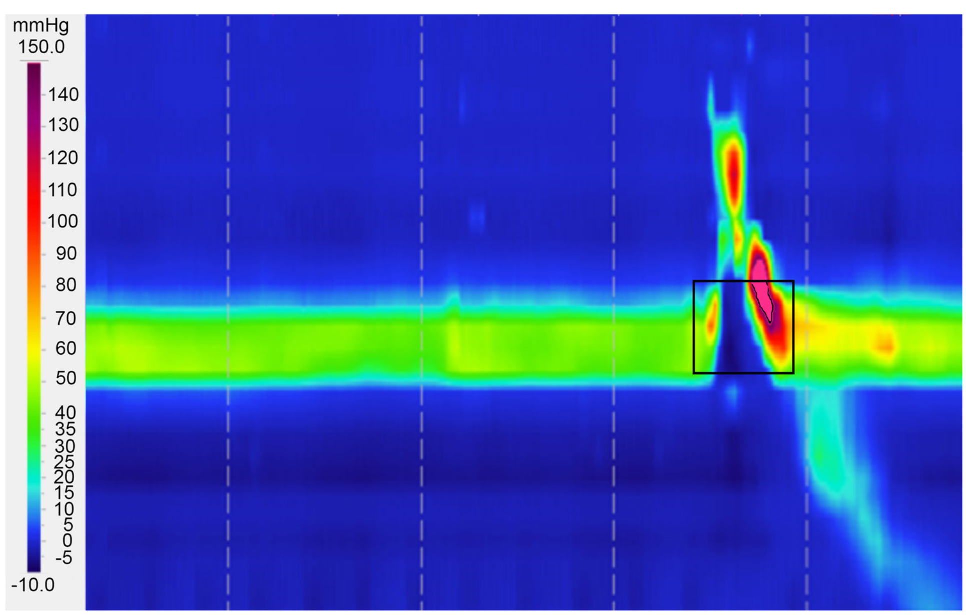

Fig. 1 High-resolution manometry (HRM) biofeedback of the period of pressure drop in the region of the upper oesophageal sphincter (UOS-Pdrop) during the manipulation task. The black square marks UOS-Pdrop

This sensor, rather than a more caudal sensor, was chosen to minimise the risk of including oesophageal pressure data into analysis. UOS sensors at rest were identified as sensors that recorded pressure ≥ 5 mmHg post-swallow. Following sensor identification, data were exported to custom-designed software (MATLAB R2014a, The MathWorks Inc., Natick, MA, 2014). The one UOS sensor which recorded the most negative pressure (nadir pressure) during swallowing was automatically selected in MATLAB. Based on this sensor, the period of UOS-Pdrop was measured. The starting point of the measurement period was defined by a pressure drop of 10% below the mean UOS resting pressure; the end was determined when the same pressure was reached again post-nadir [27]. For evaluation of UOS resting pressure, sensors were displayed, for each swallow, as line traces in a window. The window displayed 15 s of data, depicting the annotated swallow and the post-swallow period. The researcher determined the start- and end-point of the longest possible period of stable UOS resting pressure post-swallow by two manual clicks on the line traces. To avoid inclusion of elevated UOS resting pressure post-swallow [28], the start of the measurement period was set at 10 s after the swallow or later. The average UOS resting pressure across all displayed sensors within the tagged period was automatically calculated.

To capture potential concurrent pressure changes in the pharynx during pressure modulation at the UOS, pharyngeal maximum pressure (mmHg) and inverse velocity (ms/cm) as an amplitude and timing measure, respectively, were assessed. Table 1 provides definitions and measurement descriptions of the pharyngeal measures.

Data Analysis

Descriptive statistics included median and interquartile range for the period of UOS-Pdrop and the pharyngeal measures separated by task and session. The statistics are based on mean values of the five swallows per subject and task. Using R software [29], reliability was assessed using the intraclass correlation coefficient (ICC) for agreement of single measures. Intra-rater reliability was calculated based on a two-way mixed effects model [ICC(3,1)], inter-rater reliability on a two-way random effects model [ICC(2,1)] [30]. We additionally evaluated measurement reliability to understand the influence of sensor selection in ManoView™ on reliability. For calculation of measurement reliability, only data extraction using MATLAB was included. Interpretation of the results was based on published criteria [31]: poor reliability (ICC < 0.50), moderate reliability (ICC 0.50–0.75), good reliability (ICC > 0.75).

Performance Prior to Training Start

To evaluate whether participants achieved modulation of the period of UOS-Pdrop without daily training, baseline measures acquired during no manipulation and during

Table 1 Pharyngeal metrics

Measure	Metric type	Definition	Measurement	Justification
Pharyngeal maximum pressure (mmHg)	Amplitude measure	The maximum pressure was calculated across a selected area that was defined vertically by the most rostral and most caudal pharyngeal sensor and horizontally by the start and end of the pressure recordings of these two sensors	The most rostral pharyngeal sensor was defined as the one next to the most caudal sensor located in the velopharynx The most caudal pharyngeal sensor was defined as the one adjacent to the most rostral UOS sensor. Sensors at the border of pharynx and UOS tend to move vertically during swallowing; the most caudal pharyngeal sensor was the one located in the pharynx at all time-points during swallowing	The maximum, rather than the mean, pressure was extracted to detect any pressure alterations, including brief pressure peaks that may support participants in achieving the task goal
Inverse velocity (ms/cm)	Temporal measure	The time between the peak pressure of the most rostral pharyngeal sensor and the peak pressure of the most caudal pharyngeal sensor was divided by the distance of these two sensors (7.5 mm)	The most rostral and most caudal pharyngeal sensor were defined as stated for the pharyngeal maximum pressure	The inverse velocity rather than velocity (cm/ms) was extracted as simultaneous pressure peaks in the pharynx would result in infinite velocity

manipulation at session 1 were compared using the Wilcoxon signed-rank test.

Performance Following Daily Training

To determine the effect of a 1- and 2-week training protocol on performance, outcome measures of session 5 and 10 and the follow-up were compared to baseline measures of session 1. Separate analyses were completed for saliva and water swallows as the presence of a bolus may influence the period of UOS-Pdrop. As the assumptions for linear mixed model analysis were not met, Friedman's non-parametric tests were performed. Analyses were based on average values of the five swallows per participant and per outcome task. Wilcoxon signed-rank tests were conducted for post-hoc comparisons if results of a Friedman's test were significant.

Pharyngeal Pressure Alterations

To detect potential pharyngeal pressure alterations, pharyngeal measures acquired during manipulation of the outcome sessions were compared to baseline measures of session 1 using a Friedman's non-parametric test.

Qualitative Analysis

Qualitative content analysis was used to analyse the participants' descriptions of their strategies to best achieve the task goal. Codes which were inductively derived from the data were systematically applied for categorisation of the data [32, 33].

Table 2 Period of swallowing-related pressure drop at the region of the UOS (UOS-Pdrop) (s): median (interquartile range) across participants

Session	Non-manipulation task	Manipulation task
1	*Saliva*: 0.51 (0.13) *Water*: 0.74 (0.09)	*Saliva*: 0.67 (0.43) *Water*: 0.87 (0.08)
5	*Saliva*: 0.44 (0.07) *Water*: 0.54 (0.09)	*Saliva*: 0.47 (0.06) *Water*: 0.69 (0.18)
10	*Saliva*: 0.44 (0.15) *Water*: 0.59 (0.12)	*Saliva*: 0.43 (0.26) *Water*: 0.74 (0.13)
Follow-up	*Saliva*: 0.48 (0.14) *Water*: 0.62 (0.09)	*Saliva*: 0.64 (0.14) *Water*: 0.78 (0.14)

UOS upper oesophageal sphincter

Table 3 Pharyngeal maximum pressure (mmHg): median (interquartile range) across participants

Session	Non-manipulation task	Manipulation task
1	*Saliva:* 113.09 (24.26) *Water:* 109.82 (25.07)	*Saliva:* 109.50 (22.11) *Water:* 116.92 (5.03)
5	*Saliva:* 97.55 (18.75) *Water:* 104.56 (18.48)	*Saliva:* 115.71 (10.70) *Water:* 109.17 (29.43)
10	*Saliva:* 114.34 (9.55) *Water:* 114.87 (8.04)	*Saliva:* 124.67 (18.23) *Water:* 114.29 (25.69)
Follow-up	*Saliva:* 111.98 (19.34) *Water:* 97.04 (13.50)	*Saliva:* 115.32 (9.64) *Water:* 94.25 (20.03)

Results

Six healthy females with an age range of 23 to 68 years (mean age of 36 years) completed the training protocol without adverse events. One participant was ill at the tenth session, hence, the session had to be postponed by 3 days. For another participant, the follow-up was preponed by 3 days due to participant availability. Good intra-rater reliability of 0.84 (95% CI [0.78, 0.88]) and moderate inter-rater reliability of 0.68 (95% CI [0.59, 0.76]) were found for the period of UOS-Pdrop. Findings for pharyngeal maximum pressure indicated moderate intra-rater reliability with 0.57 (95% CI [0.43, 0.68]) and good inter-rater reliability with 0.98 (95% CI [0.98, 0.99]). Intra-rater reliability for inverse velocity was moderate with 0.70 (95% CI [0.59, 0.79]); inter-rater reliability was good with 0.87 (95% CI [0.76, 0.93]). For data extraction excluding sensor selection intra-rater and inter-rater reliability for UOS-Pdrop were good with 0.87 (95% CI [0.83, 0.91]) and 0.81 (95% CI [0.75, 0.86]), respectively. For inverse velocity intra-rater reliability was moderate with 0.69 (95% CI [0.60, 0.77]) and good for inter-rater reliability with 0.96 (95% CI [0.93, 0.97]). No reliability was assessed for pharyngeal maximum pressure, as no manual measurements were required in MATLAB. Descriptive statistics of the period of UOS-Pdrop across subjects per session are reported in Table 2, for pharyngeal maximum

Table 4 Inverse velocity (ms/cm): median (interquartile range) across participants

Session	Non-manipulation task	Manipulation task
1	*Saliva:* 30.18 (24.48) *Water:* 61.67 (19.57)	*Saliva:* 32.09 (32.49) *Water:* 57.56 (26.38)
5	*Saliva:* 31.73 (55.43) *Water:* 39.40 (39.53)	*Saliva:* 32.67 (47.83) *Water:* 41.56 (37.94)
10	*Saliva:* 22.00 (18.00) *Water:* 20.00 (16.67)	*Saliva:* 28.82 (16.36) *Water:* 27.2 (17.43)
Follow-up	*Saliva:* 11.33 (14.50) *Water:* 23.67 (11.00)	*Saliva:* 19.44 (21.28) *Water:* 19.00 (6.67)

pressure in Table 3, and for inverse velocity in Table 4. For three participants, one to at most two sensors in the pharynx were masked due to equipment malfunction; averaged data from adjacent sensors were used for pharyngeal outcome measures.

Performance Prior to Training Start

The period of UOS-Pdrop of saliva ($p=0.04$*) and of water swallows ($p=0.03$*) was longer during manipulation than during no manipulation at session 1. For saliva swallows, the median period of UOS-Pdrop across participants was 0.67 s during manipulation, and 0.51 s during no manipulation. For water swallows, the median period of UOS-Pdrop during manipulation was 0.87 s, and 0.74 s during no manipulation. Figure 2a, b depicts UOS-Pdrop during manipulation and during no manipulation prior to training start.

Performance Following Daily Training

The period of UOS-Pdrop of saliva swallows during manipulation changed across time ($\chi^2(3)=8.6$, $p=0.04$*). Post-hoc analysis revealed that there was no significant difference in manipulated period of UOS-Pdrop at any of the analysed time-points if compared to session 1 ($p=0.09$, $p=0.22$, $p=1$ for session 5, 10, and the follow-up, respectively). For water swallows, there was no significant change in manipulated period of UOS-Pdrop across time ($\chi^2(3)=6.8$, $p=0.08$). Figure 3a, b depicts the period of UOS-Pdrop during the manipulation task across time.

Pharyngeal Pressure Alterations

At session 1, there was no significant difference in the pharyngeal maximum pressure during manipulation compared to no manipulation for saliva swallows ($p=1$) with a median pharyngeal maximum pressure during manipulation of 109.50 mmHg and of 113.09 mmHg during no manipulation. There was no significant difference for water swallows ($p=0.69$) with a median pharyngeal maximum pressure of 116.92 mmHg during manipulation and 109.82 mmHg during no manipulation. During the UOS pressure manipulation task, the pharyngeal maximum pressure did not significantly change across time for saliva swallows ($\chi^2(3)=1.8$, $p=0.61$), and for water swallows ($\chi^2(3)=1.8$, $p=0.61$).

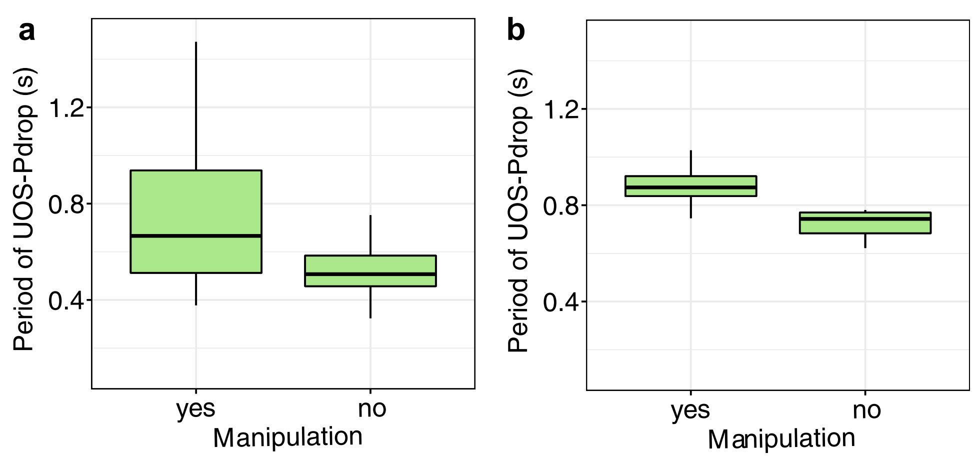

Fig. 2 **a, b** Performance without training (at session 1) during manipulation and no manipulation. Boxplots displaying the interquartile range (IQR) for the period of pressure drop in the region of the upper oesophageal sphincter (UOS-Pdrop) (across participants for saliva (**a**) and water (**b**) swallows. The whiskers represent 1.5 * the IQR

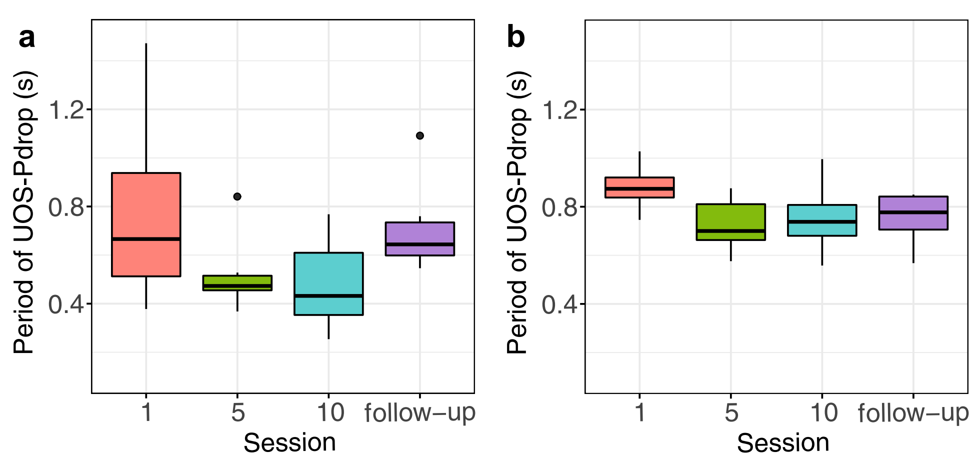

Fig. 3 **a, b** Performance following daily training. Boxplots displaying the interquartile range (IQR) for the period of pressure drop at the region of the upper oesophageal sphincter (UOS-Pdrop) during the manipulation task across participants for saliva (**a**) and water (**b**) swallows. The whiskers represent 1.5 * the IQR**.** Outliers are indicated by a dot

At session 1, no significant difference was found for the inverse velocity of saliva swallows ($p = 0.31$) with a median inverse velocity of 32.09 ms/cm during manipulation and 30.18 ms/cm during no manipulation. There was no significant difference for water swallows ($p = 0.56$) with a median inverse velocity of 57.56 ms/cm during manipulation and of 61.67 ms/cm during no manipulation. The inverse velocity did not significantly change across time during the UOS pressure manipulation task for saliva swallows ($\chi^2(3) = 1$, $p = 0.80$), and for water swallows ($\chi^2(3) = 6.6$, $p = 0.09$).

Qualitative Analysis

The following categories summarise the techniques applied by the participants to prolong the period of UOS-Pdrop: change of pressure amplitude (e.g. to swallow gently or effortful), change of timing of pressure generation (e.g. to swallow slower or faster), manipulation of other muscles (e.g. to stabilise the abdominals), visualisation (e.g. to visualise a relaxed UOS), imagination (e.g. to swallow a big marshmallow), relaxation (e.g. to relax the UOS at the end of a swallow), focus on biofeedback, other techniques (e.g. negative practice), or no strategy found. No technique was mentioned as 'most helpful' by more than one participant.

Discussion

This study evaluated pressure modulation at the UOS in healthy participants during swallowing. The finding that participants were able to behaviourally prolong the period of UOS-Pdrop for saliva and water swallows almost immediately may suggest that participants may have an inherent capacity to increase UOS opening duration as measured by the period of UOS-Pdrop; thus, training is not necessary for maximal performance. The ceiling effect on performance may be explained by the fact that UOS opening is one aspect of pharyngeal swallowing that is partly controlled by the central pattern generator in the brainstem [1, 2, 34]. The finding of a restricted capacity is consistent with newer research reporting no effect of the Mendelsohn manoeuvre on UOS opening duration in healthy adults [7, 9].

Potential mechanisms for the measured pressure changes at the UOS may include direct pressure modulation, altered cricopharyngeal muscle activity, and altered traction forces of the hyolaryngeal complex on the UOS. While the result of a prolonged period of UOS-Pdrop in the absence of altered pharyngeal pressure patterns suggests that healthy individuals are able to specifically target swallowing pressure at the UOS, some techniques described in the questionnaires imply biomechanical or pressure manipulation of the swallow in its entirety, rather than direct pressure modulation. Such strategies involve altered effort during swallowing or involvement of muscles other than the UOS sphincter muscles. Further research is needed to clarify whether UOS pressure modulation during swallowing can be achieved without associated change of other swallowing biomechanics not measured in this study. The use of imaging modalities, such as videofluoroscopy, would allow evaluation of potential biomechanical changes, while the use of EMG could provide information about altered cricopharyngeal muscle activity during volitional pressure modulation. Adjunctive impedance analysis may clarify the effects of pressure modulation on bolus flow, a critical aspect for efficient and safe swallowing. Further, combined pressure and impedance recordings may offer intensified visual feedback. Future studies are indicated to evaluate purposeful pressure modulation intra-swallow in patient populations with UOS dysfunction. This is specifically important for patients with impaired duration of pressure drop in the absence of impaired hyolaryngeal excursion and pharyngeal pressure generation. If pressure at the UOS can be purposefully modulated during swallowing, the specificity in behavioural treatment options may be increased.

Limitations of this research are acknowledged. Due to the small sample size, the research findings need to be interpreted in the context of exploratory research. A larger sample is required in future research. The majority of participants recruited for this project were under the age of 35 years and all participants were female. Thus, the findings may apply only for this specific sex and age group. Further research will benefit from a more diverse sample. Exclusion criteria including attention difficulties or colour vision deficiency may be considered in future research using HRM as a biofeedback modality in patients with dysphagia. Findings need to be interpreted in the context of non-parametric analyses which entail the risk of not detecting a potential true effect [35]. Future studies may benefit from automated or semi-automated analysis methods, such as Swallow Gateway™. The pharyngeal maximum pressure may be susceptible to catheter artefacts; the use of a general measure of pharyngeal contractility, such as the pharyngeal contractile integral, may be of value in future studies to gain complementary information about contractility force over space and time [36, 37]. Limitations of the technology, specifically malfunctioning sensors, are acknowledged.

Ongoing research is key to investigate whether further components of a partially brainstem driven swallowing response can be purposefully modulated in healthy individuals. Increased understanding of the role that cortical and subcortical structures may play in control of swallowing will be essential in the development of rehabilitation approaches of impaired swallowing [2]. However, it is acknowledged that healthy participants may be less able to modulate pharyngeal swallowing than patients with dysphagia. While in the study by Lamvik and colleagues [20] healthy participants could modulate timing of pharyngeal pressure generation only by swallowing faster, in the study by Huckabee and colleagues [19] patients with dysphagia increased the temporal separation between pressure generation in the upper and lower pharynx. This mirrors that healthy swallowing is a maximally functional behaviour; thus, volitional modulation may imply a potential functional compromise. Patients with dysphagia present an impaired functional behaviour; hence, increased functionality may be achieved with purposeful modulation. Thus, research investigating the potential for volitional manipulation of single components of pharyngeal swallowing in patients with dysphagia is warranted.

Conclusions

This research offers novel data regarding the ability of healthy adults to volitionally modulate UOS opening duration as measured by the period of pressure drop during swallowing. The findings of this study indicate that subjects are able to volitionally prolong the period of UOS-Pdrop with visual biofeedback, and that the capacity for change does not increase with further training. This may suggest that the amount to which the period of UOS-Pdrop can be prolonged is restricted in healthy subjects.

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Declarations

Conflict of interest The authors declare they have no conflict of interest.

References

1. Ertekin C, Aydogdu I. Neurophysiology of swallowing. Clin Neurophysiol. 2003;114(12):2226–44. https://doi.org/10.1016/S1388-2457(03)00237-2.
2. Humbert IA, German RZ. New directions for understanding neural control in swallowing: the potential and promise of motor learning. Dysphagia. 2013;28(1):1–10. https://doi.org/10.1007/s00455-012-9432-y.
3. Miller AJ. Overview of deglutition and digestion. In: Shaker R, Belafsky P, Postma G, Easterling C, editors. Principles of deglutition. A multidisciplinary text for swallowing and its disorders. New York: Springer; 2013. p. 3–17.
4. Robbins J, Butler SG, Daniels SK, Diez Gross R, Langmore S, Lazarus CL, Martin Harris B, McCabe D, Musson N, Rosenbek JC. Swallowing and dysphagia rehabilitation: translating principles of neural plasticity into clinically oriented evidence. J Speech Lang Hear Res. 2008;51(1):276–300. https://doi.org/10.1044/1092-4388.
5. Kahrilas PJ, Logemann JA, Krugler C, Flanagan E. Volitional augmentation of upper esophageal sphincter opening during swallowing. Am J Physiol. 1991;260(3 Pt 1):G450–6. https://doi.org/10.1152/ajpgi.1991.260.3.G450.
6. Logemann JA, Kahrilas PJ. Relearning to swallow after stroke-application of maneuvers and indirect biofeedback: a case study. Neurology. 1990;40(7):1136–8.
7. Doeltgen SH, Ong E, Scholten I, Cock C, Omari T. Biomechanical quantification of Mendelsohn maneuver and effortful swallowing on pharyngoesophageal function. Otolaryngol Head Neck Surg. 2017. https://doi.org/10.1177/0194599817708173.
8. Bodén K, Hallgren Å, Hedström HW. Effects of three different swallow maneuvers analyzed by videomanometry. Acta Radiol. 2006;47(7):628–33. https://doi.org/10.1080/02841850600774043.
9. Inamoto Y, Saitoh E, Ito Y, Kagaya H, Aoyagi Y, Shibata S, Ota K, Fujii N, Palmer JB. The Mendelsohn maneuver and its effects on swallowing: kinematic analysis in three dimensions using dynamic area detector CT. Dysphagia. 2018;33(4):419–30. https://doi.org/10.1007/s00455-017-9870-7.
10. Witte U, Huckabee ML, Doeltgen SH, Gumbley F, Robb M. The effect of effortful swallow on pharyngeal manometric measurements during saliva and water swallowing in healthy participants. Arch Phys Med Rehabil. 2008;89(5):822–8. https://doi.org/10.1016/j.apmr.2007.08.167.
11. Bülow M, Olsson R, Ekberg O. Videomanometric analysis of supraglottic swallow, effortful swallow, and chin tuck in healthy volunteers. Dysphagia. 1999;14(2):67–72. https://doi.org/10.1007/pl00009589.
12. Hind JA, Nicosia MA, Roecker EB, Carnes ML, Robbins J. Comparison of effortful and noneffortful swallows in healthy middle-aged and older adults. Arch Phys Med Rehabil. 2001;82(12):1661–5. https://doi.org/10.1053/apmr.2001.28006.
13. Hoffman MR, Mielens JD, Ciucci MR, Jones CA, Jiang JJ, McCulloch TM. High-resolution manometry of pharyngeal swallow pressure events associated with effortful swallow and the Mendelsohn Maneuver. Dysphagia. 2012;27(3):418–26. https://doi.org/10.1007/s00455-011-9385-6.
14. Huckabee ML, Butler SG, Barclay M, Jit S. Submental surface electromyographic measurement and pharyngeal pressures during normal and effortful swallowing. Arch Phys Med Rehabil. 2005;86(11):2144–9. https://doi.org/10.1016/j.apmr.2005.05.005.
15. Hiss SG, Huckabee ML. Timing of pharyngeal and upper esophageal sphincter pressures as a function of normal and effortful swallowing in young healthy adults. Dysphagia. 2005;20(2):149–56. https://doi.org/10.1007/s00455-005-0008-y.
16. McCullough GH, Kim Y. Effects of the Mendelsohn maneuver on extent of hyoid movement and UES opening post-stroke. Dysphagia. 2013;28(4):511–9. https://doi.org/10.1007/s00455-013-9461-1.
17. Garcia JM, Hakel M, Lazarus C. Unexpected consequence of effortful swallowing: case study report. J Med Speech Lang Pathol. 2004;12(2):59–66.
18. Macrae PR, Anderson C, Taylor-Kamara I, Humbert I. The effects of feedback on volitional manipulation of airway protection during swallowing. J Mot Behav. 2014;46(2):133–9. https://doi.org/10.1080/00222895.2013.878303.
19. Huckabee ML, Lamvik K, Jones R. Pharyngeal mis-sequencing in dysphagia: characteristics, rehabilitative response, and etiological speculation. J Neurol Sci. 2014;343(1):153–8. https://doi.org/10.1016/j.jns.2014.05.064.
20. Lamvik K, Jones R, Sauer S, Erfmann K, Huckabee ML. The capacity for volitional control of pharyngeal swallowing in healthy adults. Physiol Behav. 2015;152(Pt A):257–63. https://doi.org/10.1016/j.physbeh.2015.09.026.
21. Guiu Hernandez E, Gozdzikowska K, Apperley O, Huckabee M-L. Effect of topical nasal anesthetic on swallowing in healthy adults: a double-blind, high-resolution manometry study. Laryngoscope. 2017. https://doi.org/10.1002/lary.26996.

22. Kwong SL (2018) The upper esophageal sphincter: influence of associated pressure dynamics and capacity for behavioural modulation. Canterbury, Christchurch
23. Lamvik K. Modulation of spontaneous and volitional swallowing: methodological and behavioural analyses. Christchurch: University of Canterbury; 2016.
24. Lester S, Langmore SE, Lintzenich CR, Wright SC, Grace-Martin K, Fife T, Butler SG. The effects of topical anesthetic on swallowing during nasoendoscopy. Laryngoscope. 2013;123(7):1704–8. https://doi.org/10.1002/lary.23899.
25. Knigge MA, Thibeault S, McCulloch TM. Implementation of high-resolution manometry in the clinical practice of speech language pathology. Dysphagia. 2014;29(1):2–16. https://doi.org/10.1007/s00455-013-9494-5.
26. Castell JA, Castell DO. Modern solid state computerized manometry of the pharyngoesophageal segment. Dysphagia. 1993;8(3):270–5. https://doi.org/10.1007/bf01354550.
27. Meyer S, Jungheim M, Ptok M. High-resolution manometry of the upper esophageal sphincter (high-resolution manometry of the upper esophageal sphincter). HNO. 2012;60(4):318–26. https://doi.org/10.1007/s00106-011-2418-5.
28. Jungheim M, Busche A, Miller S, Schilling N, Schmidt-Thieme L, Ptok M. Calculation of upper esophageal sphincter restitution time from high resolution manometry data using machine learning. Physiol Behav. 2016;165:413–24. https://doi.org/10.1016/j.physbeh.2016.08.005.
29. R Core Team (2016) R: a language and environment for statistical computing
30. Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. Psychol Bull. 1979;86(2):420–8. https://doi.org/10.1037/0033-2909.86.2.420.
31. Portney LG, Watkins MP. Foundations of clinical research. Applications to practice. 3rd ed. London: Pearson Education; 2009.
32. Pope C, Ziebland S, Mays N. Qualitative research in health care: analysing qualitative data. Br Med J. 2000;320(7227):114–6. https://doi.org/10.1136/bmj.320.7227.114.
33. Sandelowski M. Whatever happened to qualitative description? Res Nurs Health. 2000;23(4):334–40. https://doi.org/10.1002/1098-240X(200008)23:4%3c334::AID-NUR9%3e3.0.CO;2-G.
34. Vasant DH, Hamdy S. Cerebral cortical control of deglutition. In: Shaker R, Belafsky P, Postma G, Easterling C, editors. Principles of deglutition. A multidisciplinary text for swallowing and its disorder. New York: Springer; 2013. p. 55–65.
35. Field A, Miles J, Field Z. Discovering statistics using R. London: SAGE; 2012.
36. Omari T, Ciucci M, Gozdzikowska K, Hernandez E, Hutcheson K, Jones C, Maclean J, Nativ-Zeltzer N, Plowman E, Rogus-Pulia N, Rommel N, O'Rourke A. High-resolution pharyngeal manometry and impedance: protocols and metrics - recommendations of a high-resolution pharyngeal manometry international working group. Dysphagia. 2020;35:281–95. https://doi.org/10.1007/s00455-019-10023-y.
37. O'Rourke A. The pharyngeal contractile integral is a useful indicator of pharyngeal swallowing impairment. Neurogastroenterol Motil. 2017. https://doi.org/10.1111/nmo.13144.

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