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ORIGINAL ARTICLE

Effect of Volitional Effort on Submental Surface Electromyographic Activity During Healthy Swallowing

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Abstract

The effortful swallowing technique aims to compensate for or rehabilitate impaired swallowing by using maximal volitional effort to behaviorally modify aspects of swallowing physiology. Given that swallowing is a submaximal task, swallowing at submaximal levels has recently been suggested as a more task-specific therapeutic technique. The aim of this study was to investigate differences in muscle activity during minimum, regular, and maximum effort swallowing of different boluses and across different ages, with the goal of characterizing the task specificity of minimum effort and maximum effort swallowing. Forty-three healthy adults (22 female) representing four age groups (20–39, 40–59, 60–79, and 80 + years) participated in the study. They were verbally cued to swallow saliva and 5 mL water boluses using participant-determined minimum, regular, and maximum levels of effort, in randomized order. sEMG peak amplitude and duration of each swallow were measured. Linear mixed effects analyses demonstrated that compared to regular effort swallowing, maximum effort swallowing resulted in increased sEMG amplitude ($p < .001$) and prolonged duration ($p < .001$), while minimum effort swallowing resulted in decreased amplitude ($p < .001$) but no significant difference in duration ($p = .06$). These effects occurred regardless of age or bolus type. Differences in sEMG activity were smaller between regular and minimum effort swallowing than regular and maximum effort swallowing. Both increasing and decreasing volitional efforts during swallowing translate to significant modulation of muscle activity. However, regular swallowing is more similar to minimal effort swallowing. Results reinforce the concept of swallowing as a submaximal task, and provide insight into the development of sEMG biofeedback techniques for rehabilitation.

Keywords Deglutition · Deglutition disorders · Swallowing · Dysphagia · Electromyography · Rehabilitation

Introduction

Swallowing is a complex sensorimotor behavior, primarily mediated by brainstem mechanisms but also substantially modulated by higher cortical processes [1]. The amplitude and duration of the swallowing response can be increased or decreased depending on sensory and cortical inputs, so that boluses of different sizes, consistencies, and temperatures can be safely ingested. This ability to behaviorally modify aspects of swallowing physiology allows the use of voluntary maneuvers to consciously affect change in the swallowing system [2, 3]. Altering volitional effort has a substantial modulatory effect on swallowing behavior [4]. Increasing volitional effort, such as during effortful swallowing, is one technique recommended by speech-language pathologists to compensate for and rehabilitate impaired swallowing function [3, 5, 6]. The effortful swallowing maneuver

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aims to improve base of tongue to posterior pharyngeal wall contact by swallowing with increased effort, with consequent improved bolus passage and reduced residuals [6, 7]. However, some studies have reported maladaptive swallowing patterns associated with effortful swallowing [8–10]. Minimal effort or "effortless" swallowing was anecdotally reported as a compensatory strategy used by patients with dysphagia to mitigate these negative consequences [8, 9]. Given that swallowing is a submaximal strength task [11, 12], it is possible that not all patients benefit from maximal strengthening techniques such as effortful swallowing. Previous research has suggested that incorporating a range of submaximal targets during swallowing rehabilitation to improve accuracy of motor execution may be a more task-specific technique of addressing dysphagia [13–15]. While the effects of effortful swallowing have been studied extensively, very little research has been undertaken to identify the extent to which manipulating effort in the opposite direction, i.e., swallowing with minimal effort, can affect the amplitude and temporal aspects of swallowing. In order to fully understand the effect of volitional effort in swallowing rehabilitation, it is important to investigate the entire range of effort, from minimum to maximum.

A single study has directly compared the relative effects of maximum and minimum effort swallowing. Pouderoux & Kahrilas [4] found that swallowing with minimum effort resulted in reduced force and pressure of lingual movement, while swallowing with maximum effort resulted in augmentation of lingual force and pressure. As a percentage of maximum effort swallowing, oral tongue force during regular effort swallowing was executed with an amplitude of 40–50%, while minimum effort swallowing was approximately 20–30% [4]. Despite the small sample size ($n=8$), findings from their study support the concept of swallowing as a distinctly submaximal task, at least in the domain of volitionally controlled oral lingual pressure, with normal swallowing producing only slightly greater lingual pressure than minimal effort swallowing.

Surface electromyography (sEMG) has previously been used by clinicians and researchers to measure relative amplitude and timing of submental muscle activity during swallowing [3, 16]. sEMG biofeedback can be used as an effective and non-invasive adjunct tool to dysphagia rehabilitation exercises such as effortful swallowing, by allowing patients to monitor and modify their patterns of movement using external visual information displayed on a screen in real-time [17–19]. Skill-based training protocols have emerged where the goal of treatment is to improve precision and accuracy of muscle activity during swallowing [13, 20]. One specific protocol uses sEMG of submental muscles to control timing and magnitude of swallowing behavior [13]. In this protocol, visual targets are placed on the screen below the patient's maximal amplitude but higher than their presumed minimum amplitude during swallowing, such as 20–70% of maximum swallowing sEMG activity [21]. However, there has been no research to quantify the minimum amplitude of volitional swallowing, which in turn makes it difficult to determine placement of biofeedback targets that are within the patient's physiologic range of sEMG activity. Regular swallowing uses approximately 45% of the muscle activity required during effortful swallowing [3, 16]. It is unknown if individuals are able to reduce muscle activity below the level used in regular swallowing, and whether the lowermost range of 20% of maximal muscle activity is physiologically achievable, as there may be a minimum magnitude of muscle activity needed for functional swallowing. Thus, at a very pragmatic level, determining the normal range of muscle activity generated during minimum, regular, and maximum effort swallowing in normal populations will be clinically useful for developing biofeedback exercise protocols for patients with dysphagia.

The difference between the maximum and submaximal capacity of a muscle needed during functional swallowing has been termed functional reserve [22]. Although it may depend on the measurement approach [23], there is some evidence for declining functional reserve in the healthy elderly, where older individuals have reduced maximum isometric lingual pressure compared to younger adults, but lingual pressure during swallowing is preserved [11, 24]. These healthy age-related changes in *functional* reserve (that is, the difference in muscle capacity between maximum voluntary contraction and regular swallowing) suggest that there may be similar age effects on *swallowing* reserve, defined as the difference between muscle contraction during maximum effort swallowing and regular effort swallowing [25]. Both younger and older adults have increased sEMG amplitude during effortful swallowing, with a similar magnitude of swallowing reserve [25]. However, another study found that the difference between regular and effortful swallowing was greater in younger than older adults, with older adults less able to modulate oral pressures by using volitional effort during swallowing [26]. Therefore, the influence of age on swallowing reserve is still unclear. Additionally, bolus type may also affect swallowing reserve. Effortful swallows performed with saliva had a significantly greater effect on lowering nadir pressures at the upper esophageal sphincter (UES) than effortful swallows performed with a water bolus [27]. These differences demonstrate the need to take age and bolus type into account when investigating sEMG activity and volitional effort. If there is a reserve between regular and maximum effort swallowing, there may be a similar difference between regular and minimum effort swallowing, which is also influenced by age and bolus.

A prior study by Pouderoux and Kahrilas [4] evaluated the full range of swallowing behavior in reference to lingual pressure, which is a component of more volitional oral phase. The primary objective of the current study was to evaluate the effect of volitional effort on modulation of submental sEMG activity during the pharyngeal response. The submental muscles (mylohyoid, geniohyoid, and anterior belly of the digastric muscles) in combination with the posterior digastric and stylohyoid muscles contribute to elevation of the hyolaryngeal complex during pharyngeal swallowing [28]. It was hypothesized that compared to regular effort swallowing, minimum effort would result in reduced muscle activity and maximum effort would increase muscle activity. This would determine whether there might be a difference between regular and minimum effort swallowing, similar to the reserve between regular and maximum effort swallowing. Evidence of this difference is important because it would suggest that a minimum threshold needs to be surpassed to generate a physiological, patterned swallowing response in healthy individuals. A secondary goal was to examine the influence of age and bolus type (water and saliva swallows) on muscle activity during conscious modulation of effort. We hypothesized an interaction between effort and age, and effort and bolus type, where younger adults would demonstrate a larger effect of effort compared to older adults, and saliva swallows would have a larger effect on effort compared to water swallows. These findings would hold significance for future research and clinical work using sEMG biofeedback in dysphagia rehabilitation with patients across the lifespan.

Methods

Participants

Adult participants were recruited in four age groups: 20–39, 40–59, 60–79, and 80 + years old. Sample size calculations based on pilot data revealed that approximately 10 participants should be included in each age group. Participants were recruited via written and verbal advertisement. Forty-three healthy adults (22 female, 21 male) participated in the study, with 10 participants in the 20–39-year-old age group, 11 in the 40–59 year group, 12 in the 60–79 year group, and 10 participants in the 80 + year group. Male/female gender balance was approximately matched within and across age groups. All participants reported a negative history for neurological or swallowing impairments. Written informed consent was obtained prior to data collection, and the study was approved by the appropriate regional Human Ethics Committee (Approval Number 2015_149).

Experimental Procedure

Participants were seated comfortably during the study. sEMG data were collected using the KayPentax Digital Swallowing Workstation (KayPentax, Lincoln Park, NJ, USA) and self-adhesive Triode™ patch electrodes (Thought Technology, Montreal, Canada). Skin preparation included shaving the skin if there was hair and "peeling" of the skin surface under the chin using adhesive tape, followed by cleaning of the skin surface using an alcohol wipe [29]. The submental muscle group (anterior belly of the digastric, geniohyoid, and mylohyoid muscles) was identified via palpation between the mental symphysis anteriorly and the superior palpable border of the thyroid posteriorly. The two recording electrodes were placed at midline over the submental muscle group in the anterior–posterior plane, with the ground electrode oriented laterally (Fig. 1) [30, 31]. Raw sEMG signals were rectified and integrated (50 ms time constant). The sEMG signal was used to plot a real-time waveform on a computer screen, with time in seconds on the x-axis and amplitude in µV on the y-axis. A significant change in the activity of the submental muscle group (e.g., when swallowing) was typically depicted on the screen as a peak in the waveform (Fig. 2).

Participants completed six different swallowing conditions: (1) maximum effort saliva swallow, (2) maximum effort water swallow, (3) regular effort saliva swallow, (4) regular effort water swallow, (5) minimum effort saliva swallow, and (6) minimum effort water swallow. Instructions for a regular effort swallow were: "Swallow like you normally would." Instructions for a maximum effort swallow were: "As you swallow, swallow hard with all the muscles in your mouth and throat." For a minimum effort swallow, instructions were: "Swallow as lightly as you can, with as little effort as possible." Water boluses were self-presented using a Provale™ cup (Reliant Medical Products, Birmingham, AL, USA), which dispensed a fixed amount (5 mL) of water for every trial. Saliva and 5 mL water boluses were chosen

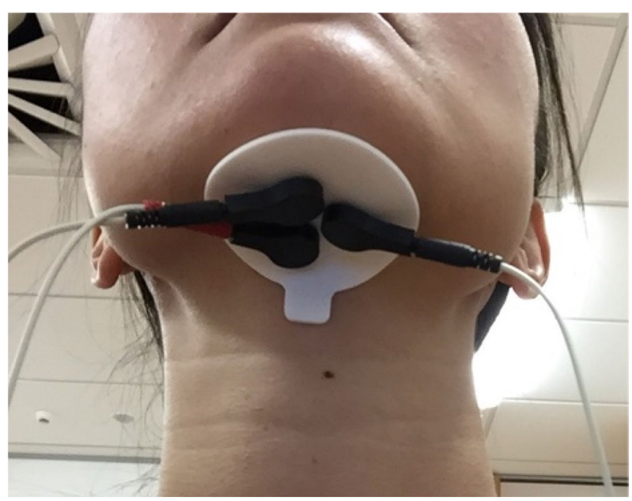
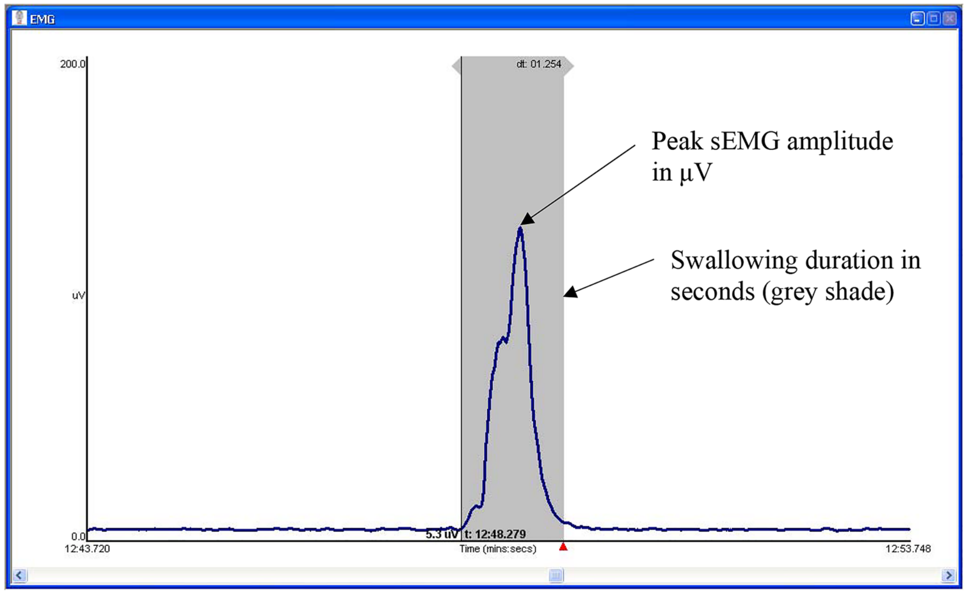


Fig. 1 Placement of the adhesive electrode patch on the surface of the skin under the chin for submental surface electromyography (sEMG)

Fig. 2 Annotated example of surface electromyographic (sEMG) signal during a swallowing response



as swallowing a thicker or larger bolus with minimal effort may cause an increased risk of aspiration.

Participants were trained on the execution of the tasks prior to data collection. During training only, participants were able to view the sEMG signal in real time on the computer screen for visual biofeedback, to aid their comprehension of the task. They were encouraged to maximize the signal peak amplitude during effortful swallowing and minimize the amplitude during minimum effort swallowing. Each of the swallowing tasks was practiced at least three times or until adequate comprehension and execution of the task could be demonstrated.

During data collection, each of the six conditions were repeated five times for a total of 30 trials. The 30 trials were completed in randomized order at a rate of approximately one swallow every 30 s. Prior to each trial, participants were told which of the six swallowing conditions to perform, and then given a verbal command to swallow 2–3 s later. For water swallows, participants were instructed to sip the fixed amount of water from the cup, bring their head and neck back to neutral position, and hold the water in the oral cavity for a few seconds. A stable sEMG baseline was ensured before giving the participant the verbal command to swallow now. Participants were instructed to ingest the 5 mL bolus in a single swallow. Since verbal or visual biofeedback of performance might influence swallowing behavior, no biofeedback was provided during data collection.

Outcome Measures

Each swallow was marked during data collection by the researcher, using the tagging function of the Digital Swallowing Workstation. Recording of a swallowing response was based on the researcher's careful visual observation of thyroid movement during swallowing, paired with participant confirmation. The outcome measures extracted from each swallowing waveform were peak sEMG amplitude (µV) and swallowing duration (s). Amplitude was extracted by manually selecting and zooming in on the waveform segment associated with the swallowing event; the software then extracted the maximum amplitude within the selected segment. There can be large variability in raw sEMG amplitudes between participants due to inter- and intra-individual differences (e.g., skinfold thickness, muscle activity, and electrode contact; [29]). To account for this, prior to analysis, raw amplitude data were normalized to each participant's own maximum amplitude obtained during effortful swallowing. This was calculated by dividing each data value by the participant's single maximum peak amplitude value, and multiplying by 100%.

Swallowing duration was defined as the onset of a dramatic or sharp increase of the sEMG signal from a baseline resulting in the peak amplitude, to the point where the waveform returns to a similar baseline amplitude level [32–35]. In order to further quantify this measure, the onset of a dramatic increases in the sEMG signal from baseline was defined as a greater than 45-degree rise in the waveform in a 10-s time window (Fig. 2).

Statistical Analyses

Statistical analyses of the data were completed using RStudio software (version 1.1.442). Inter-rater reliability between the primary rater and a secondary rater with expertise in sEMG measurement of swallowing was calculated on a random 20% of the dataset for swallowing duration, using intraclass correlation coefficients. Linear mixed effect analyses were completed to investigate the relationship between swallowing task, age, and bolus type on outcome measures. Fixed effects entered in the model were swallowing task (maximum, regular, minimum effort swallowing), age group (20–39, 40–59, 60–79, 80 + years), and bolus type (water, saliva). Random intercepts for participant and by-participant random slopes for the effect of task were included to control for individual differences, while random intercepts for the five replications of each swallowing condition were included to allow for the variability between trials to be estimated. Interactions of task by age group and task by bolus were investigated. If no significant interactions were found, the main effect of task was analyzed. If a main effect was found, post hoc analysis was completed using pairwise comparisons to determine significant differences between levels of effort, using Tukey adjustments to correct for multiple comparisons. All analyses were completed separately for the two outcome measures of amplitude and duration. Statistical significance was assessed by comparing the full model against a model without the effect in question, using likelihood ratio tests with an alpha level of 0.05.

Visual inspection of residual plots for duration data revealed no obvious deviations from homoscedasticity or normality. Duration data reported as means ± SD. However, peak amplitude data deviated from homoscedasticity and normality, and were natural log transformed for analysis to meet these assumptions, and are reported as median (IQR) due to these deviations.

Results

A total of 1290 swallows (30 swallows from each of 43 participants) were measured. Five percent (65/1290) of the total measured swallows were discarded from data analysis as there was no steep increase in the waveform greater than 45 degrees, or if it was impossible to distinguish the swallowing peak from extraneous muscle activity. Seventeen percent (11/65) of the discarded swallows were maximum effort swallows, 34% (22/65) were regular effort, and 49% (32/65) were minimum effort swallows. High inter-rater reliability was found for measuring swallowing duration, ICC (2, 1) = 0.82, 95% CI [0.73, 0.87]. Table 1 displays descriptive

Table 1 Normalized peak amplitude and swallowing duration, by task, bolus, and age group

Task	Bolus	Age group (years)	Peak amplitude (%) Median (IQR)	Duration (s) Mean ± SD
Maximum effort	Saliva	20–39	81.4 (24.4)	1.34 ± 0.40
		40–59	74.0 (26.7)	1.21 ± 0.31
		60–79	84.9 (27.0)	1.36 ± 0.49
		80 +	83.7 (27.0)	1.33 ± 0.42
	Water	20–39	76.5 (26.8)	1.32 ± 0.36
		40–59	83.7 (19.7)	1.18 ± 0.27
		60–79	87.8 (25.2)	1.18 ± 0.34
		80 +	88.4 (27.6)	1.23 ± 0.33
Regular effort	Saliva	20–39	29.4 (19.3)	0.92 ± 0.24
		40–59	27.0 (16.6)	0.98 ± 0.25
		60–79	37.3 (28.3)	1.03 ± 0.29
		80 +	53.3 (33.6)	1.12 ± 0.41
	Water	20–39	34.0 (26.0)	0.95 ± 0.33
		40–59	30.7 (25.7)	0.94 ± 0.22
		60–79	39.3 (21.5)	0.91 ± 0.28
		80 +	47.0 (37.3)	0.96 ± 0.29
Minimum effort	Saliva	20–39	22.3 (14.2)	0.87 ± 0.27
		40–59	21.1 (13.0)	0.88 ± 0.22
		60–79	27.5 (15.9)	0.99 ± 0.34
		80 +	43.9 (35.9)	0.99 ± 0.35
	Water	20–39	28.4 (21.9)	0.94 ± 0.35
		40–59	24.0 (30.8)	0.93 ± 0.30
		60–79	31.0 (20.2)	0.90 ± 0.31
		80 +	36.5 (33.4)	0.88 ± 0.27

Peak amplitude expressed as a percentage of the single maximum value acquired during maximum effort swallows. *IQR* interquartile range statistics for sEMG amplitude and duration, displayed by task, bolus type, and age group.

There was no significant interaction of task and bolus type for sEMG amplitude [χ^2 (2) = 5.84, p = 0.054], nor a significant interaction between task and age group [χ^2 (6) = 6.67, p = 0.35], indicating task-related changes in sEMG amplitude occurred consistently across different boluses and different age groups. There was a main effect of task on peak amplitude [χ^2 (2) = 1267.8, $p < 0.001$]. The estimated mean peak amplitude for maximum effort swallows (79.4%, 95% CI [71.5, 88.2]) was higher than for regular effort swallows (36.0%, 95% CI [32.5, 39.6]; $p < 0.001$). Estimated mean peak amplitude for minimum effort swallows (M = 26.7%, 95% CI [24.0, 29.7]) was lower than regular effort swallows ($p < 0.001$). Regular swallowing amplitude was more similar to minimum than maximum effort swallowing. Boxplots of observed peak amplitude during maximum, regular, and minimum effort swallowing are displayed in Fig. 3.

There was no significant interaction of task and bolus type noted for swallowing duration [χ^2 (2) = 5.41, p = 0.07], nor a significant interaction between task and age group [χ^2 (6) = 8.32, p = 0.22], indicating task-related changes in duration occurred consistently across different boluses and different age groups. For swallowing duration, there was a main effect of task [χ^2 (2) = 23.60, $p < 0.01$]. Estimated mean duration of maximum effort swallows (1.27 s, 95% CI [1.18, 1.35]) was longer than duration of regular swallows (0.97 s, 95% CI [0.91, 1.04]; $p < 0.001$). Estimated duration of minimum effort swallows (0.92 s, 95% CI [0.86, 0.98]) was not significantly different from regular effort swallows (p = 0.09). Figure 4 shows boxplots of observed duration during maximum, regular, and minimum effort swallowing.

Discussion

The main goal of this study was to evaluate the extent to which volitional effort affects muscle activity during swallowing in healthy adults. Identifying the minimum-to-maximum range may enhance our understanding of therapeutic swallowing techniques, particularly the relevance and task specificity of effortful swallowing. These data may also aid the understanding of the relative degree of muscle contraction needed for functional swallowing. The finding that maximum effort swallowing produced greater amplitude and duration of muscle activity than regular swallowing provides support for the concept of a swallowing reserve, reported in previous research [25]. The relatively small proportion of submental sEMG amplitude required for regular swallowing compared to effortful swallowing was found to be consistent with other reports in the literature [3, 16, 25, 30]. This is the first study to find a significant difference in sEMG amplitude between regular and minimum effort swallowing. This difference was smaller than that between regular and maximum effort swallowing, similar to the findings of Pouderoux and Kahrilas [4] for lingual pressure. This suggests that floor of mouth muscle contraction during regular swallowing is more physiologically similar to minimum effort swallowing,

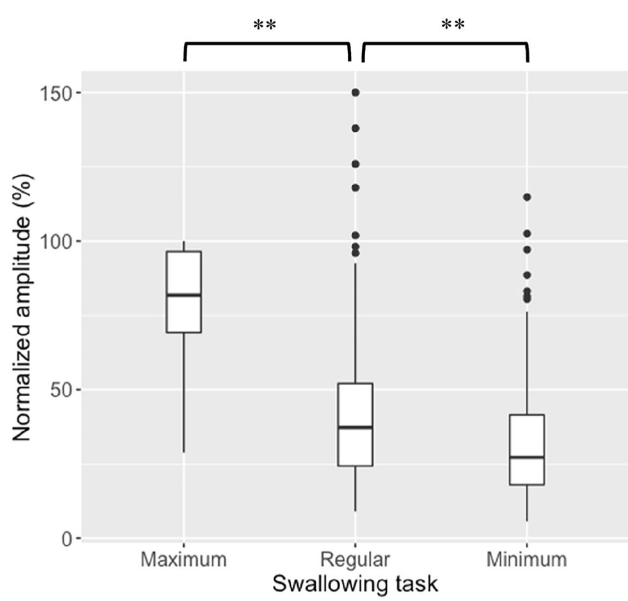


Fig. 3 Boxplots of normalized peak amplitude by swallowing task. Horizontal lines indicate lower and upper quartiles of the data, center line denotes the median, and vertical whiskers represent 1.5 times the interquartile range. **$p < .01$

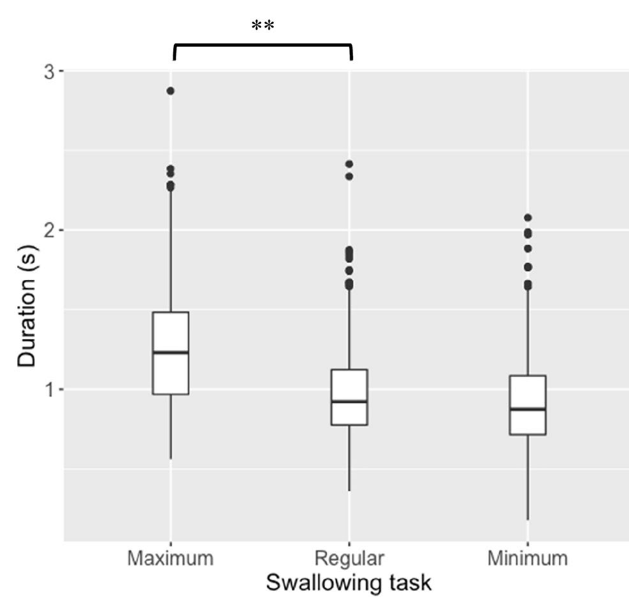


Fig. 4 Boxplots of swallowing duration by task. Horizontal lines indicate lower and upper quartiles of the data, center line denotes the median, and vertical whiskers represent 1.5 times the interquartile range. **$p < .01$

reinforcing the concept that swallowing is a submaximal task [11].

These findings conceptually challenge the emphasis on maximum-effort muscle strengthening as a rehabilitation approach, as only a proportionally small amount of available muscle activity is needed for regular, functional swallowing. Rehabilitation techniques that emphasize progressive strengthening at high power levels may not be appropriate for patients that do not demonstrate significantly reduced muscle contraction during regular swallowing attempts. Given these results, training the precision and accuracy of submental muscle activation at a submaximal level (i.e., a level similar to regular swallowing) may be more logical than increasing maximum strength. Careful assessment of the underlying swallowing impairment is important to determine the most appropriate treatment approach for each patient, for example using sEMG biofeedback and dynamometry to assess swallowing-related skill and strength [36].

Rehabilitation approaches using submaximal swallowing tap into the principle of task specificity, which states that neuroplastic and behavioral improvement is maximized when the treatment exercise is similar to the desired behavior. Skill-based exercises that focus on swallowing at a range of submaximal targets, instead of supra-maximal targets, may more closely mirror the muscle activity levels used in functional, ingestive swallowing [13, 20, 21]. In one protocol, the flexibility and fine motor control of swallowing behavior was promoted by encouraging patients to control timing and amplitude of swallowing activity in order to accurately "hit" a target placed on the screen using the sEMG waveform. Targets were placed at a submaximal level, between 20 and 70% of maximum swallowing sEMG activity [21]. It was found that patients with Parkinson's disease who underwent daily skill-training for two weeks had significantly faster swallowing rate on a timed water swallow test and shorter sEMG premotor and pre-swallow times.

Our study demonstrated that healthy adults are able to volitionally decrease swallowing amplitude in order to acquire submaximal targets, but the 95% confidence interval for the minimum peak sEMG activity needed to generate functional swallowing was 24–30%. Although previous studies have set the lower bound of targets as low as 20% [21], our data suggest that skill-training targets should not be set lower than approximately 30% of the patient's maximum muscle activity during effortful swallowing. By incorporating this lowermost limit, individuals should have improved participation in skill-training protocols because the task is physiologically achievable.

Although the sEMG amplitude of minimum effort swallowing was significantly different from regular effort swallowing, swallowing duration was not. The rapid sequencing of certain swallowing events is necessary for airway protection, and the short duration of swallowing may already be optimized for efficiency and safety. Even though there is variability in temporal measures of swallowing within and between healthy individuals, the range of values is still under 1 s. A systematic review of 46 studies found that mean UES opening duration ranged from 0.21 to 0.67 s, and mean laryngeal closure-to-UES opening interval ranged from -0.16 to 0.02 s [37]. This may explain why swallowing duration could not be significantly shortened with minimal effort swallowing.

A secondary goal of this study was to investigate the influence of age and bolus on the ability to modulate sEMG amplitude and duration using volitional effort. It was hypothesized that age would affect the extent to which submental sEMG activity could be increased and decreased. Results of this study did not support this hypothesis. Older participants were able to maintain the same magnitude and duration of muscle activity during regular swallowing as younger participants, and were able to amplify and reduce muscle activity during maximum and minimum effort swallowing, respectively, to the same extent as younger people. This suggests that, despite any age-related reductions in muscle strength [38], both swallowing reserve [25] and the flexibility to modulate the swallowing response may be maintained with age.

It was hypothesized that differences seen in sEMG muscle activity due to volitional effort would be smaller when swallowing water compared to saliva. This hypothesis was not supported, as the effect of volitional effort on sEMG muscle activity remained constant regardless of water or saliva swallowing. Results from previous research using different outcome measures have been inconclusive on this matter, with effortful and non-effortful swallowing demonstrating the same effect on oropharyngeal and midpharyngeal pressure in both water and saliva swallows, but different effects on UES pressure [27]. While dysphagia exercises are usually completed with saliva swallowing, incorporating bolus swallows into therapy may increase the specificity of the task [39]. Results from this study suggest that volitional modulation of muscle activity is still possible when swallowing with a bolus.

Research reports documenting the biomechanics of minimal effort swallowing are scarce. Two of these reports differed from the current study in that they involved patients with dysphagia, and used different outcome measures: timing and displacement of structural movement using videofluoroscopy [8] and pharyngeal pressures using manometry [9]. In a case study on a patient with dysphagia after removal of a brainstem tumor, it was hypothesized that maladaptive behavior had developed after using effortful swallowing as a compensatory technique for 5 months [8]. The patient demonstrated improved swallowing by using a more relaxed, "effortless" swallow. In another study using pharyngeal manometry as visual biofeedback, effortful swallowing was associated with increased mis-sequencing of pharyngeal pressure generation. These patients reported improved ability to generate optimal sequencing of pharyngeal pressure generation when swallowing using minimal effort [9]. Perhaps the reduced muscle contraction generated during minimal effort swallowing improved swallowing by "normalizing" maladaptive behaviors caused by the use of effortful swallowing. Interestingly, both the above studies demonstrated that minimal effort swallowing resulted in a prolongation or later onset of swallowing events, while this study found a non-significant reduction in swallowing duration. This could be explained by the different populations, assessment techniques, and outcome measures studied.

The effect of volitional swallowing maneuvers may be very different when applied to healthy adults with optimized swallowing behaviors, compared to patients with dysphagia [40]. The idea that there is a lower limit of muscle activity needed for swallowing suggests that patients with a subthreshold level of activity might have insufficient motor unit recruitment for safe and functional swallowing. Further research investigating the effect of minimal effort swallowing on muscle activity in the dysphagic population will provide more insight into the clinical relevance of this maneuver.

Study Limitations

Limitations of this study include the lack of instructions given to participants on tongue strategy during effortful swallowing. Previous research has found that using different methods of effortful swallowing execution (emphasizing tongue-to-palate contact during the maneuver rather than minimizing contact) resulted in increased submental sEMG amplitude and oropharyngeal pressure [31]. This study did not specifically instruct participants on whether to emphasize or de-emphasize tongue-to-palate pressure, which may explain why a small number of participants had regular and minimum effort swallows with a higher amplitude than their maximum effort swallows.

Another limitation was the subjective determination of sEMG onset and offset to calculate swallowing duration. Trials with a water bolus demonstrated a higher baseline amplitude prior to swallowing due to oral holding of the bolus, compared to saliva swallows with no pre-swallow hold. This higher pre-swallow baseline may have affected accurate identification of swallowing onset and thus calculation of the swallowing duration measure. Identification of swallowing onset in minimum effort trials was also challenging because the swallowing peak was not as obvious, and the sEMG onset slope resulting in the peak was less steep than those seen in regular and maximum effort swallows. This resulted in almost half of the discarded swallows being minimum effort trials. Since the discarded minimum effort swallows were not easily identified as swallowing peaks and thus likely to be swallows with lower amplitude, the data in this study may be biased towards being slightly higher than the actual average. While there was high inter-rater reliability of the swallowing duration measure in this study, using computer software to mark onset and offset in an objective manner may improve the validity of measurement. In addition, a swallowing response was determined by visual observation paired with participant confirmation, however, accuracy of this method has not been established. Using thyroid palpation or videofluoroscopy could more accurately confirm the presence of a swallowing response.

Finally, we only used cued swallows in the study, which required the participants to hold the bolus in their mouth for a few seconds before swallowing. Cued swallows may have resulted in shorter swallowing durations than if non-cued swallows had been used [41]. However, a bolus hold was necessary to ensure a stable baseline sEMG signal before swallowing, so that we could clearly discriminate the onset of swallowing behavior in the sEMG signal. Since all six conditions used cued swallows, comparing between conditions is still considered valid.

Conclusion

In conclusion, the range of muscle activity used in saliva and bolus swallowing was investigated by measuring submental sEMG swallowing peak amplitude and duration during participant-determined minimum, regular, and maximum effort swallowing. Results demonstrate that healthy adults have the ability to modulate muscle activity using volitional effort, and this skill is retained regardless of age or bolus type. Regular swallowing is more similar to minimal effort than maximal effort swallowing, reinforcing the idea of swallowing as a submaximal behavior and challenging the approach of maximal effort swallowing in dysphagia rehabilitation. Results from this study suggest that sEMG biofeedback targets for skill-based assessment and training protocols should not be set lower than 30% of maximum swallowing amplitude, although further research is needed in people with dysphagia to clarify the clinical translation of this data.

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Author Contributions All authors contributed to study conception and design. Data collection was performed by Karen Ng. Formal analysis performed by Karen Ng and Esther Guiu Hernandez. The first draft of the manuscript was written by Karen Ng, and all authors reviewed and edited subsequent drafts. All authors read and approved the final manuscript.

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Compliance with Ethical Standards

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

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