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Transcutaneous electrical stimulation on the anterior neck region: The impact of pulse duration and frequency on maximum amplitude tolerance and perceived discomfort

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Summary

Maximum amplitude tolerance (MAT) has been known as a primary factor determining the depth of electrical current penetration. However, the effect of varying transcutaneous electrical stimulation (TES) parameters on MAT and discomfort level is poorly understood. Furthermore, limited information exists regarding the biopsychological factors that may impact MAT and discomfort. The primary aims of this study were to compare the effects TES protocol with varying levels of pulse duration (300 μ s vs 700 μ s) and frequency (30 Hz vs 80 Hz) on the MAT and discomfort in healthy older adults. The exploratory aim of this study was to examine relationships between submental adipose tissue thickness, pain sensitivity and gender with MAT and discomfort. Twenty-four healthy older adults participated in this study. Transcutaneous electrical stimulation was delivered to the submental region. Maximum amplitude tolerance and discomfort were measured for each condition. Furthermore, submental adipose tissue thickness and pain sensitivity were measured for each subject. Maximum amplitude tolerance was significantly increased for the TES protocols with short-pulse duration [$F(3, 69) = 38.695, P < .0001$]. Discomfort was similar across different TES protocols. Submental adipose tissue thickness ($r = .30, P < .003$) and pain sensitivity ($r = -.43, P < .0001$) were related to MAT. Pain sensitivity rating was also related to discomfort ($r = .45, P < .0001$). In conclusion, using TES protocols with short-pulse duration may increase the MAT. Higher amplitude stimulation may increase the impact on deep swallowing muscles. In addition, submental adipose tissue thickness and pain sensitivity are potential biopsychological factors that may affect MAT and discomfort.

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CONFLICT OF INTEREST

Electrodes used in this study were provided by DJO Global, Vista, CA, USA. DJO Global had no role in study design, data collection, data analysis, data interpretation or writing of the manuscript. The authors have stated explicitly that there is no conflict of interests in connection with this article.

Keywords

ageing; deglutition; deglutition disorders; electric stimulation therapy; neck muscles; rehabilitation

1. | BACKGROUND

Transcutaneous electrical stimulation (TES) to the anterior neck region is a treatment option in swallowing therapy that purports to strengthen weak swallowing muscles in patients with dysphagia.¹ Several studies have investigated the clinical efficacy of existing TES protocol with conflicted outcomes.² One potential reason for the conflicted outcomes might be a lack of knowledge regarding the optimal TES protocol for stimulating the swallowing muscles. In fact, key swallowing muscles are small and overlap each other such that many lie in deep layers or behind cartilaginous and adipose tissues. As a result of this anatomy, an effective TES protocol should penetrate through deep layers of tissue in the neck to stimulate key swallowing muscles. However, previous TES-based kinematic swallowing studies reported a descending pattern for hyoid and laryngeal movement in healthy adults and patients with dysphagia.^{3–5} This descending pattern might occur because the existing TES protocol potentially stimulates large, close to the surface infrahyoid muscles (ie, omohyoid, sternohyoid and sternothyroid) and may not penetrate sufficiently to reach deeper muscles associated with swallowing function.

A potential explanation for the lack of TES impact on deep swallowing muscles may relate to an insufficient level of TES amplitude to stimulate deep swallowing muscles. Transcutaneous electrical stimulation amplitude is the primary parameter that determines the depth of electrical current penetration.⁶ Prior work on limb muscles has shown that increasing the TES amplitude produces a stronger depolarising drive that penetrates through deeper tissue layers and recruits more motor axons beneath the stimulating electrodes.^{7,8} However, increasing the TES amplitude is limited by the subject's maximum amplitude tolerance (MAT) level.⁹ Given the primary impact of amplitude level on the depth of electrical current penetration, a potential way to increase the depth of electrical current penetration is to raise the subject's MAT.

A commonly used TES protocol known as VitalStim (VitalStim, DJO Global, Vista, CA, USA) uses a long-pulse duration (700 μ s) and high frequency (80 Hz) for swallowing rehabilitation. However, no rationale has been provided for these TES parameters. Transcutaneous electrical stimulation studies on limb muscles have consistently reported that TES protocols with long-pulse duration demonstrate reduced MAT compared with the TES protocols with short-pulse duration.^{10,11} Conversely, studies of stimulation frequency reveal highly variable outcomes in relation to MAT ranging from no relation¹² to an inverse relation.¹¹ Moreover, studies on limb muscles reported that low-frequency TES may increase perceived discomfort level compared with high-frequency TES.¹³ Collectively, increased MAT may result in greater electrical stimulation to deeper swallowing muscles, but little knowledge exists regarding the effects of varying TES pulse duration and frequency on MAT and perceived discomfort level.

In addition to TES parameters, some biopsychological characteristics of subjects may relate to MAT and reported discomfort level. This relationship may influence the depth of electrical current penetration by reducing the utilised amplitude of TES and indirectly affect the effectiveness of TES-based rehabilitation. While the mechanism of effect is not immediately clear, studies on limb muscles have consistently reported that male participants usually demonstrate higher MAT with lower perceived discomfort compared with their female counterparts.^{14,15} Furthermore, previous studies on limb muscles indicate that adipose tissue potentially functions as an insulator, and due to its high electrical resistance, it may reduce the impact of electrical current on deeper muscle tissues.^{16,17} Therefore, people with greater thickness of adipose tissue may need to tolerate higher current amplitude and greater discomfort to reach muscle contraction. In addition to these biological factors, an individual's pain sensitivity may also influence MAT and perceived discomfort level. Previous pain studies reported that people with higher pain sensitivity may demonstrate lower pain tolerance (lower MAT) and greater discomfort.^{18,19} In summary, based on the results of limb studies, being male with thinner adipose tissue thickness and less pain sensitivity is related to higher MAT and lower perceived discomfort level and may enhance the benefit of TES-based rehabilitation. However, no clear information exists regarding the effects of these biopsychological factors on MAT and perceived discomfort level during electrical stimulation in the region of swallowing musculature.

The primary aim of this study was to compare the effects of varying pulse duration and frequency during TES applied to the submental swallowing region on MAT and perceived discomfort level in healthy older adults. The focus on healthy older adults was based on reports indicating that the prevalence of dysphagia increases with age.²⁰ Furthermore, recent studies of the impact of TES on swallowing indicate that older adults may respond differently than younger adults on the same TES protocol.^{21,22} The exploratory aim of this study was to examine potential relationships between submental subcutaneous adipose tissue thickness, pain sensitivity and gender with MAT and perceived discomfort level.

2 | METHODS

2.1 | Participants

Twenty-four (N = 24) healthy, community-dwelling participants (12 men and 12 women) with a mean age of 63.42 years (SD = 2.63 years) were participated in this study. Before participating in the study, all participants were screened by phone to ascertain they met the criteria for participating in this study. Subjects were included if they were between 60 and 70 years of age with no diet restrictions due to diagnosed dysphagia. Subjects were excluded if they had any history of health conditions or medications that might affect swallowing or are noted as contraindications for TES. The local institutional review board (IRB) approved this study (IRB approval number: IRB201500476), and all subjects signed an informed consent form.

2.2 | TES protocols

Electrical stimulation was applied using the VitalStim Experia Electrotherapy System (VitalStim, DJO Global, Vista, CA, USA). This device permits modification of electrical

stimulation parameters including pulse duration and frequency. Transcutaneous electrical stimulation was delivered through four stimulating electrodes that were placed on the submental region of the neck. For each participant, the skin on the neck was cleaned with an alcohol wipe included in the VitalStim electrode package. Both electrode channels were aligned obliquely above the hyoid bone to target the suprahyoid region. For each channel, the proximal electrode was attached at the midpoint between the chin and the lesser cornu of the hyoid bone, and then, the lateral electrode was attached at the midpoint between the chin and mandibular angle (Figure 1). Four different TES protocols were tested for each participant: (i) long-pulse duration, high frequency (700 μ s, 80 Hz); (ii) long-pulse duration, low frequency (700 μ s, 30 Hz); (iii) short-pulse duration, high frequency (300 μ s, 80 Hz); and (iv) short-pulse duration, low frequency (300 μ s, 30 Hz). Each TES protocol was presented twice to consider the possible effect of adaptation to different TES protocols. A one-minute rest interval was included between each TES condition. The presentation order of all 8 TES conditions (4 TES protocols x 2 trials) was randomised by a computer-generated random order schedule.

2.3 | MAT measurement

Maximum amplitude tolerance was defined as the highest level of TES amplitude that a participant could tolerate for each TES protocol. To measure MAT, the stimulation amplitude was increased gradually by one mA in 5-second intervals. The stimulation amplitude was increased until the participant notified the investigator (by raising his/her hand) that a further increase in stimulation amplitude could not be tolerated for any reason. At that point, all stimulation was immediately stopped. This amplitude level was defined as the MAT for that TES protocol. The same procedure was followed for each of the eight conditions.

2.4 | TES discomfort measurement

After reaching the MAT for each TES protocol in each trial, participants were asked to rate any perceived discomfort level in the submental area. The primary measure of discomfort was a visual analogue scale (VAS). The VAS provides a continuous scale for magnitude estimation and comparisons of perceived discomfort level. The scale consisted of a 10-cm straight line ranging from “No Discomfort” to “Worst Discomfort Ever.”

2.5 | Submental adipose tissue thickness measurement

Submental adipose tissue thickness was measured for each participant with a digital body fat calliper (Ningbo Sunshine International Co, Zhejiang, Ningbo, China). The researcher pinched and pulled down a longitudinal fold of submental skin. The contact surface of the calliper was placed at a 90° angle to the skinfold approximately 1 cm above the fingers to measure the thickness of the skinfold. To control the measurement variability, three measurements were taken. This measure was used to determine the possible relation of adipose tissue thickness with MAT and discomfort level.

2.6 | Pain sensitivity assessment

The Pain Sensitivity Questionnaire (PSQ) measured participants' pain sensitivity.²³ The PSQ is a validated self-rating instrument for the assessment of pain sensitivity. It is composed of 17 items. Each item describes a daily life situation and asks the subject to rate how painful that event would be on a numeric scale ranging from 0 (not painful at all) to 10 (worst pain imaginable). Fourteen of 17 items are simulated situations that are rated as painful by a majority of healthy subjects. The painful items cover a range of pain intensities and include a variety of different types of pain, such as hot, cold, sharp and blunt pain, and they refer to various body sites including the head and upper and lower extremities. However, three other items (Items 5, 9 and 13) describe situations that are normally not rated as painful by healthy subjects. According to the PSQ scoring guideline, these items should not be included in the final score. Thus, the total PSQ score was based on the average of the remaining 14 items. This measure was used to examine the possible relationship between pain sensitivity with MAT and perceived discomfort level.

2.7 | Statistical analysis

Distributions of the primary outcome variables were reviewed and parametric assumptions confirmed for analysis of variance (ANOVA). To identify any possible impact of adaptation on MAT and discomfort variables, primary repeated measure ANOVAs were conducted across the first, second, seventh and eighth randomly presented TES protocols. "Adaptation" was defined as any significant pairwise difference in MAT or discomfort level between the first two and the last two presented TES protocols. Maximum adaption effect to TES amplitude is expected to be found between the two ends of the presented TES trials.¹⁵ Subsequently, separate repeated measure ANOVAs were conducted to compare MAT and discomfort level across four different TES protocols (long-pulse duration, high frequency; long-pulse duration, low frequency; short-pulse duration, high frequency; short-pulse duration, low frequency). When ANOVAs were significant at $P < .05$, post hoc Bonferroni tests were used to explore pairwise significant differences. Measures of effect size were reported as partial eta squared (η_p^2), which is a common effect size metric in the behavioural science studies.²⁴ Effect size measures have been classified as small ($\eta_p^2 = .01$), medium ($\eta_p^2 = .06$) or large ($\eta_p^2 = .14$).²⁵ In addition, bivariate correlational analyses were performed using Pearson's correlation coefficient to examine the relationship between submental adipose tissue thickness and pain sensitivity, with MAT and discomfort level. Furthermore, MannWhitney U test (nonparametric t test) was conducted to determine the association of gender with MAT and perceived discomfort level. All analyses were performed using IBM SPSS 21 (IBM Corp, Armonk, NY, USA).

3 | RESULTS

3.1 | Adaptation effect

No significant effects of adaptation to TES amplitude were identified for MAT [$F(2.1, 48.5) = 3.03, P < .054$] or discomfort level [$F(1.6, 37.9) = 1.50, P < .235$].

3.2 | The effect of TES parameters on MAT

Participants demonstrated great variation in MAT (ranging from 2 to 25 mA) across the different TES protocols (Table 1). Maximum amplitude tolerance differed significantly across TES protocols [$F(3, 69) = 38.695, P < .0001, \eta_p^2 = .627$]. Post hoc Bonferroni tests demonstrated that MAT levels were higher in TES protocols with short-pulse duration, low frequency ($M = 13.62 \text{ mA} \pm SD = 6.01 \text{ mA}$), and short-pulse duration, high frequency ($14.35 \text{ mA} \pm 6.36 \text{ mA}$), compared with TES protocols with long-pulse duration, low frequency ($8.85 \text{ mA} \pm 5.99 \text{ mA}$), and long-pulse duration, high frequency ($8.31 \text{ mA} \pm 4.91 \text{ mA}$) (Figure 2).

3.3 | The effect of TES parameters on discomfort

Participants demonstrated great variation in perceived discomfort level (ranging from .6 to 10) across the different TES protocols (Table 1). No significant main effect of TES protocol was identified for discomfort level [$F(3, 69) = 1.432, P < .241$].

3.4 | The relation of biopsychological factors with MAT

Submental adipose tissue thickness was significantly related to MAT ($r = .30, P < .003$). Subjects with greater submental adipose tissue thickness tolerated higher MAT. In addition, pain sensitivity was significantly, inversely related to MAT ($r = -.43, P < .0001$). Subjects with higher pain sensitivity tended to tolerate lower MAT for each TES protocol. Gender was not significantly associated with MAT ($U = 1119.500, P < .812$).

3.5 | The relation of biopsychological factors with perceived discomfort level

The relation of submental adipose tissue thickness and perceived discomfort level approached significance ($r = .18, P < .069$). However, pain sensitivity was significantly related to discomfort level ($r = .45, P < .0001$). Subjects with higher pain sensitivity tended to report greater discomfort following each TES protocol. Gender was not significantly associated with perceived discomfort ($U = 1049.000, P < .450$).

4 | DISCUSSIONS

This study compared the effect of TES protocols with varying levels of pulse duration (300 μs vs 700 μs) and frequency (30 Hz vs 80 Hz) on MAT and perceived discomfort level in healthy older adults. Pulse duration demonstrated a significant impact on MAT. Specifically, both TES protocols with short-pulse duration (300 μs) increased MAT compared with the TES protocols with long-pulse duration regardless of frequency. Conversely, perceived discomfort level was comparable across the different TES protocols. Furthermore, subjects with greater submental adipose tissue thickness tolerated higher MAT. In addition, subjects with higher pain sensitivity tolerated significantly lower MAT but reported higher discomfort level. Gender revealed no significant association with MAT and discomfort level.

Both TES protocols with short-pulse durations increased MAT. This result is consistent with the strength-duration curve model depicting neural excitation following electrical stimulation.^{11,26} According to this model, pulse duration has a hyperbolic relationship with

the amplitude of current stimulating pain nerve fibres. As pulse duration increases, a lower amplitude level is required to stimulate the pain nerve fibres (ie, pain threshold).¹¹ This inverse relationship might be explained by the activation principle of nerve fibres, which relies on the charge movement across the fibre membranes.²⁷ Given this principle, increasing pulse duration may provide a longer-time window for the electrical current charges to pass through the fibre membrane and to stimulate a larger number of pain fibres which can decrease the pain threshold level. Decreasing the pain threshold is directly associated with maximum pain tolerance.¹⁰ As a result, compared with short-pulse duration, long-pulse duration may decrease the pain threshold level leading to lower MAT.

Unlike pulse duration, frequency had no significant impact on MAT. These results are contrary to Howson et al's study,¹¹ indicating an inverse linear relation between frequency and MAT. A potential reason for the disparity of results could be related to differences in frequency employed in these studies (1–16 Hz vs 30–80 Hz in current study). It seems plausible that frequency may have more influence on MAT when it is under the threshold of tetanic muscle contraction (ie, <30 Hz).²⁸ Future studies should compare the effect of TES protocols with varying frequencies below and above the tetanic muscle contractions on MAT.

Discomfort level was comparable across the different TES protocols. Although using short-pulse duration significantly increased MAT, subjects reported similar discomfort regardless of pulse duration. In other words, pulse duration may affect the MAT, but not the intensity of perceived discomfort once MAT is reached. However, prior studies have reported that low-frequency TES protocols induce more discomfort compared to those with high frequency.¹³ One possible explanation for this discrepancy may originate from differences in the definition of low frequency in the current study (30 Hz) vs other studies (ie, 5 Hz and 10 Hz). Future studies with a wider range of pulse frequencies are required to clarify the effect of frequency on discomfort level applied to the submental muscles.

Submental adipose tissue thickness was significantly related to both MAT and perceived discomfort level. This finding was consistent with previous findings in limb muscles indicating a positive relationship between increasing subcutaneous adipose tissue and increasing MAT and perceived discomfort during stimulation.²⁹ A potential explanation for this effect might be related to the high resistivity of adipose tissue to electrical current penetration.¹⁷ In simple terms, increased adipose tissue functions like an insulator. Thus, subjects with greater adipose tissue thickness not only require higher current amplitude to evoke muscle contraction, but also perceive more discomfort to reach MAT.¹⁷

Pain sensitivity was significantly related to both MAT and perceived discomfort level. Specifically, adults with higher pain sensitivity ratings demonstrated lower MAT but reported higher perceived discomfort in the submental area. These findings are consistent with previous pain studies suggesting inverse relations of pain sensitivity to pain tolerance and the direct relation of pain sensitivity to perceived pain discomfort.^{18,19} Future TES studies should take into account the effect of pain sensitivity on MAT and any resulting physiological or kinematic aspects of swallowing.

Gender was not associated with either MAT or perceived discomfort level. Conversely, prior studies on limb muscles suggested that MAT is higher in males than females.^{14,15} One obvious difference between the current study and prior studies is the location of TES. Transcutaneous electrical stimulation to the anterior neck (submental region) may result in different subject reactions than TES to limb muscles. However, this speculation will require further investigation as other factors may contribute to this result. For example, Riley et al³⁰ suggested that more than 40 subjects per group are required to achieve adequate power to demonstrate gender effect on MAT, assuming a large to moderate effect size. In addition to larger samples, future studies might consider anatomical site and other potential variables that may impact MAT and perceived discomfort level across genders.

The present study was limited to evaluation of varying TES pulse duration and frequency on MAT and perceived discomfort level. Specific to swallowing functions, future studies should consider kinematic and physiological measures to evaluate the impact of various TES parameters on different aspects of swallowing physiology. A focus on deep swallowing musculature would help to clarify if the higher MAT associated with short-pulse durations had a valuable impact on swallow functions. Future studies with a larger sample size should further investigate additional biopsychological factors that might be related to subjects' differences in MAT and perceived discomfort level during various TES protocols. This line of research may lead to enhanced TES protocols for swallowing rehabilitation.

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FIGURE 1.
Two channel stimulating electrode placement on submental region

FIGURE 2.
Mean maximum amplitude tolerance across different Transcutaneous electrical stimulation protocols

Table 1

Means and standard deviations (SD) for maximum amplitude tolerance (MAT), perceived discomfort level, submental adipose tissue thicknesses and pain sensitivity across gender and in total

Variables	Male Mean (SD)	Female Mean	Total Mean
MAT (mA)			
Long PD, High F	9.25 (6.54)	7.38 (2.40)	8.31 (4.91)
Long PD, Low F	9.71 (8.07)	8.00 (2.88)	8.85 (5.99)
Short PD, High F	15.63 (8.08)	13.08 (3.97)	14.35 (6.36)
Short PD, Low F	13.75 (7.62)	13.50 (4.46)	13.63 (6.10)
Discomfort (out of 10)			
Long PD, High F	6.48 (2.76)	6.37 (1.81)	6.43 (2.28)
Long PD, Low F	6.88 (2.37)	6.36 (1.80)	6.62 (2.07)
Short PD, High F	6.45 (2.77)	6.33 (1.41)	6.39 (2.15)
Short PD, Low F	5.91 (2.87)	6.41 (1.45)	6.16 (2.23)
SM adipose tissue thickness (millimetre)	10.30 (4.51)	14.32 (4.77)	12.31 (4.98)
Pain sensitivity (out of 10)	4.66 (1.68)	3.87 (1.88)	4.26 (1.80)

Frequency (F) is defined as pulses per second, stated in hertz (Hz). The time span of a single pulse is recognised as the pulse duration (PD) stated in microseconds (μ s).