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Facial muscle activations by functional electrical stimulation

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ABSTRACT

The present aim was to investigate transcutaneous facial muscle stimulation in order to take further steps in developing facial pacing technology, which can offer a new treatment option for patients with unilateral facial paralysis. This technology ultimately measures muscle activations from one side of the face and simultaneously activates the corresponding muscles of the other side with electrical stimulation. Four facial muscle locations—*frontalis*, *orbicularis oculi*, *zygomaticus major*, and *orbicularis oris*—of the healthy participants (N = 24) were stimulated to produce an eyebrow raise, eye blink, smile, and lip pucker, respectively. The results showed that a visually observable movement of the forehead and the lower lip was achieved in all participants. On average, the stimulations at the movement threshold were rated as tolerable in terms of pain ratings and neutral in terms of pleasantness ratings. Complete eye blink was achieved in 22 participants, and most did not experience painful sensations. The stimulation of the cheek evoked observable movement in 23 participants, but the stimulation also often resulted in concurrent activation of the eye, mouth, and nose area. The results suggest that transcutaneous stimulation seems to be a promising method for developing further facial pacing technology.

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1. Introduction

Unilateral facial paralysis is a condition in which one side of the face functions normally while functions on the other side are impaired and in which the face may look asymmetrical at rest. The most common form of unilateral facial paralysis is Bell's palsy [1]. It is also termed as idiopathic facial paralysis, which means the cause of paralysis is unknown. The annual prevalence for Bell's palsy is 20–30 cases per 100,000, thus affecting about one in 60–70 people in their lifetime [1–3]. About 70% of patients have full recovery within three months, but the other 30% are left with facial dysfunctionalities of varying degrees [4]. In addition to Bell's palsy, other causes of facial paralysis that more frequently lead to long lasting or permanent facial dysfunctionalities include trauma, infections (e.g., borreliosis and herpes zoster), tumor diseases, surgical interventions, and congenital paralysis.

A person suffering from facial paralysis may have functional deficits like problems with speaking, eating, drinking, and eye blinking. In addition, the face has a key role in social communication in conveying important information about one's identity, personality, and emotions. Facial paralysis reduces one's ability to express facial emotions, and a person suffering from it often experiences psychological distress because of the altered appearance [5,6]. Thus, the condition dramatically diminishes the quality of one's life in many dimensions. Current treatment of facial paralysis consists mainly of surgical reanimation and behavioral rehabilitation, both of which have been shown to be somewhat functional [7,8]. A third option that this study is especially focused on is to develop technology that could stimulate facial muscles in a way that would at least allow critical symmetrical functioning to be regained.

Facial pacing refers to technology that measures electric muscle activations with facial electromyography (EMG) from muscles of the intact side of the face and simultaneously activates the corresponding muscles of the other (paralyzed) side with functional electrical stimulation (FES). Reanimating the facial functions of the paralyzed side by utilizing the activity of the non-paralyzed one could result in regaining the symmetry of facial behavior [9].

Although the idea of facial pacing was presented several decades ago, the majority of studies have focused on investigat-

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ing the feasibility of electrical stimulation in animal models with implantable electrodes that would involve highly intrusive surgery to install [10–12]. However, facial pacing can also be implemented noninvasively by measuring and stimulating muscle activities transcutaneously using an external facial prosthetic device which could be developed as small and wearable in the future [13]. It is noteworthy that in most cases, irrespective of the cause of the paresis, the facial musculature system remains functional, although muscle atrophy starts to proceed early from the onset of paralysis. Patients specifically recovering from acute facial palsy and patients whose recovery process has been incomplete but whose facial nerve has not fully degenerated could benefit from such a device. Patients could avoid surgeries, which always have risks of complications. In addition, transcutaneous electrical stimulation could possibly be utilized in facial exercise therapy. For example, such therapy could be utilized to prevent muscle atrophy or to restore the volume and function of the muscles in chronic denervation [14–16].

Earlier human studies have focused on studying the detection and production of an eye blink [17–21]. Frigerio and Cavallari [18] demonstrated a natural-like eye blink with healthy human participants using the transcutaneous stimulation of the facial nerve branch to activate the *orbicularis oculi* muscle. Further, in a preliminary study with three facial paralysis participants, transcutaneous electrical stimulation caused a complete blink below the maximal discomfort threshold in two out of three patients [21]. In addition, in the study of Frigerio et al. [20], a complete eye closure was achieved with transcutaneous facial nerve stimulation in 55% of participants with acute unilateral facial paralysis.

The inability to blink is the most eminent functional deficit caused by facial paralysis. This is due to the dysfunctional eye protection and lack of moisture over the eye, which can lead to severe corneal damage [22,23]. However, other facial functions also have a significant role in daily behaviors and in emotional and social life especially. The most frequent consequences of incomplete recovery after facial paralysis are weaknesses in frontal wrinkling, opening the mouth, smiling, or lip puckering [24]. The only human study regarding the stimulation of areas other than the *orbicularis oculi* muscle is the study of Kurita et al. [25]. They used local anesthetics to induce a transient paralysis of the *frontalis* muscle for healthy volunteers. Needle-type electrodes were inserted into both the non-paralyzed side to detect muscle activity and into the paralyzed side to stimulate the muscle. The results showed functional and aesthetically acceptable facial movement created by the activation of the paralyzed *frontalis* muscle using EMG measurements from the un-anesthetized side to create corresponding muscle activity with FES. To summarize, studies investigating more widely the transcutaneous stimulation of facial muscles seem to be infrequent. Thus, there is a clear need and motivation to study both the stimulation of other facial muscles, as well as related subjective sensations and feelings caused by electrical stimulation.

To further investigate the potential of transcutaneous facial pacing, we have established a multidisciplinary project that first develops technology [13], then tests it with intact participants, and finally runs tests with patients with facial paralysis. The aim of the present study was to study the electrical stimulation of facial muscles with healthy human participants in order to gain further knowledge of the potential of facial pacing. At this point, we were especially interested in the possibility of evoking intended muscle activations, what kind of stimulation amplitudes would be required to evoke them, and what kind of subjective experiences the stimulations would evoke. More specifically, we aimed to study three current levels: (a) a minimum current participants can sense, (b) a minimum current required to evoke a visually observable movement, and (c) a maximum current still tolerable for the stimulation. Stimulation waveform parameters other than the current amplitude were kept constant. Further, we collected ratings of experienced pleasantness, naturalness, and painfulness of the stimulations. Four facial muscle locations were chosen for the stimulation: the *orbicularis oculi* to produce an eye blink, the *frontalis* to produce an eyebrow raise, the *zygomaticus major* to produce a smile, and the *orbicularis oris* to produce a lip pucker.

2. Methods

2.1. Participants

Twenty-four healthy voluntary participants (15 males, 9 females) with an age range of 21–63 (M = 37.1, SD = 12.0) took part in the study. The study was accepted by the ethical committee of Pirkanmaa Hospital Disctrict (R15067), and each participant signed an informed consent form prior to their participation. Ten participants had previous experience with electrical stimulation of muscles (e.g., transcutaneous electrical nerve stimulation), one was uncertain, and the rest had no such experience. The participants' average body mass index (BMI) was 25.2 (SD = 3.1). BMI was computed because adipose tissue has higher electrical resistivity compared to most other tissues. Electrical current flows through the path of least resistance, and a subcutaneous adipose tissue may work as an insulator layer directing the current flow away from it and the underlying muscle.

2.2. Equipment and stimulated muscles

The facial pacing device is developed and manufactured by our academic consortium. In the current study, the FES functionality of the pacing apparatus was used. A separate PC is used to adjust the stimulation parameters and to store the measurement data. The device and the PC communicate wirelessly through Wi-Fi connection. Generation of the stimulation signals allows varying stimulus waveform parameters, such as stimulus phase (positive and negative) duration and pulse repetition frequency (for a detailed description of the device, see [13]. The selected current waveform used in this study was a biphasic square wave with symmetric positive and negative phases (equal width, equal amplitude). The following parameters of the stimulation were used: positive and negative phase duration 0.4 ms and pulse repetition frequency 250 Hz. Pulse train duration was 80 ms for the *orbicularis oculi* and 1000 ms for the *frontalis* (in the forehead), the *zygomaticus major* (in the cheek), and the *orbicularis oris* (around the mouth), as seen in Fig. 1. The stimulation parameters were based on literature [18,20,26,27] and explorative pilot testing. Commercial stimulation electrodes made from carbonized rubber were attached to the skin above the stimulated muscles according to the guidelines for EMG recording [28]. Videos of facial behavior were recorded for offline visual analysis at 50 frames per second with a Panasonic V750 digital video camera that was placed in front of the participant.

2.3. Procedure

When a participant arrived, the experimenter introduced the electrically shielded, sound attenuated laboratory and asked the participant to fill out an informed consent form and a background questionnaire. Then, the participant was seated in front of the video camera. Before the actual experiment, a practice trial was run to get participants used to the stimulation and the procedure. For this purpose, stimulation electrodes were attached to the left hand over the muscles of the thenar eminence. During the practice phase, this area of the hand was stimulated and the experimental procedure was conducted.

After the practice phase, the stimulation electrodes were attached to the left side of the participants' face for stimulating

Fig. 1. Placement of the electrodes: *orbicularis oculi* (upper left), *frontalis* (upper right), *zygomaticus major* (lower left), and *orbicularis oris* (lower right). Photographs published with permission from the subject.

one muscle at a time. The order of the stimulation sites was counterbalanced as follows:

- *Frontalis*, *orbicularis oculi*, *zygomaticus major*, and *orbicularis oris* (n = 8),
- *Zygomaticus major*, *orbicularis oris*, *frontalis*, and *orbicularis oculi* (n = 8),
- *Orbicularis oris*, *frontalis*, *orbicularis oculi*, and *zygomaticus major* (n = 8).

The stimulation was repeated five times at each amplitude level starting from level 0.5 mA. Following this, the amplitude of the stimulation was increased in 0.5 mA intervals until one of the following occurred:

1 The stimulation caused a cutaneous sensation reported by the participant (i.e., perception threshold).
2 The facial muscle movement was observed by two experimenters (i.e., movement threshold). In the case of the *orbicularis oculi*, the amplitude was increased until an eyelid movement (i.e., eye twitch) was evoked.
3 The participant wanted to stop the stimulation (i.e., tolerability threshold) or the maximum stimulation amplitude (10 mA) was achieved. In the case of the *orbicularis oculi*, the amplitude was increased until an eye closure (i.e., blink) was evoked or until the participant reported the tolerability threshold being reached.

After each amplitude level, the experimenter asked the participant's confirmation to continue by asking "Will you continue?" The participant evaluated the pleasantness and painfulness of the stimulation after each of the three stimulation phases (i.e., perception threshold, movement threshold, tolerability/eye closure threshold). At the movement and tolerability/eye closure threshold, the participant also rated the felt naturalness of the movement (i.e., how natural the movement felt). Following the point where the movement threshold was achieved, the participant gave ratings of painfulness of the stimulation at each stimulation amplitude level. The pleasantness and naturalness scales were nine-point bipolar rating scales varying from 1 (unpleasant/unnatural) to 9 (pleasant/natural), with 5 representing the center (neither unpleasant/unnatural nor pleasant/natural) of the scale. The pain rating scale was a one dimensional nine-point scale ranging from not at all painful to very painful. At the end of the experiment, the participant was asked to choose the most pleasant or natural stimulus location(s). They were also encouraged to give additional comments.

2.4. Data analysis

In respect to eye blink stimulation, data from two participants was discarded. One participant wanted to stop the stimulation because of feeling discomfort already before an eye twitch was elicited. The data of one participant was discarded because of excessive blinking irrespective of stimulation. Thus, the data analysis in respect to eye blink stimulation is based on n = 22. Amplitude threshold data was analyzed using one-way repeated measures analysis of variance (ANOVA). Greenhouse-Geisser adjusted degrees of freedom were used when violations of sphericity occurred. Bonferroni corrected pairwise t-tests were used for post-hoc comparisons. The subjective rating data was analyzed using Friedman tests. If a statistically significant effect was found, Wilcoxon signed-rank test was used for pairwise comparisons. The differences between the participants who had or did not

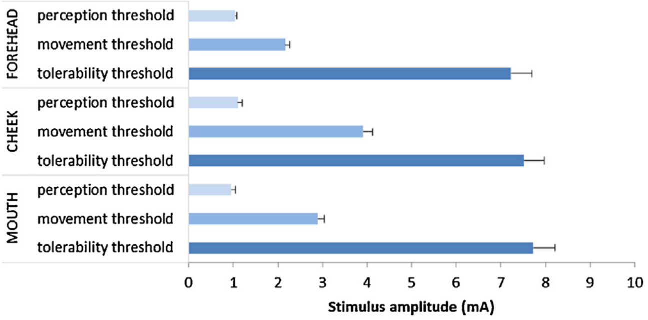

Fig. 2. The average amplitude levels (and SEMs) for each threshold.

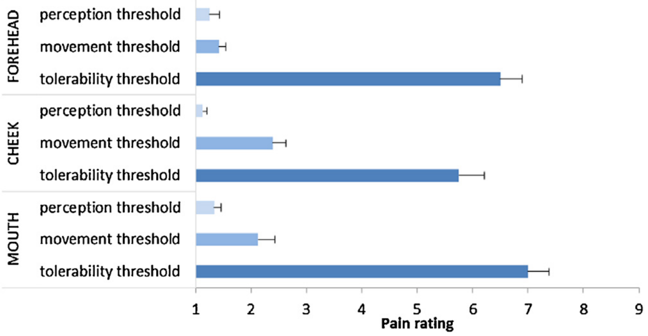

Fig. 3. The average pain ratings (and SEMs) for each threshold.

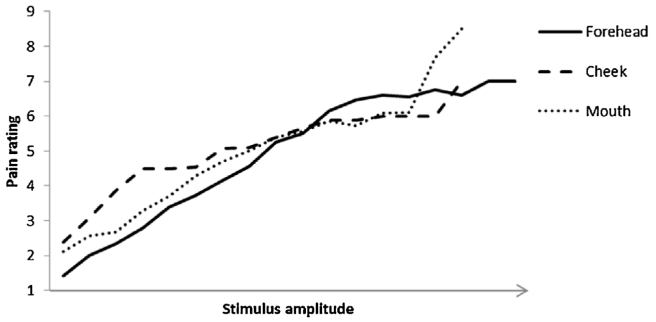

Fig. 4. The average pain ratings as a function of stimulus amplitude from the moment a visible movement was evoked.

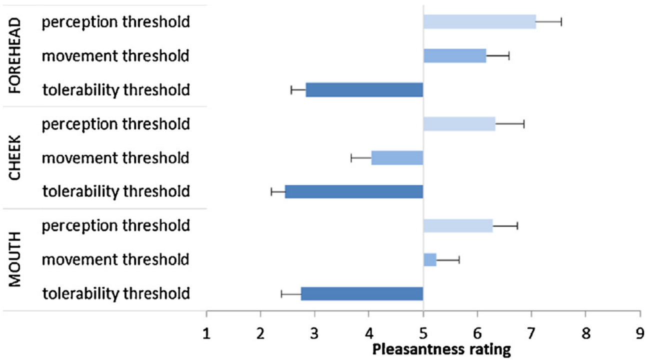

Fig. 5. The average pleasantness ratings (and SEMs) for each threshold.

have previous experience with electrical stimulation were tested with independent samples t-tests. The associations between BMI and current thresholds and between BMI and the ratings were tested using the Pearson product moment correlation coefficient.

The eye twitch and eye closure were determined offline from frame by frame analysis of the video recordings. To exclude naturally occurring eye blinks evoked by the sensation in the skin, the amount of eye closure were determined from situations when only the stimulated-side eyelid moved. Videos focusing on the forehead, cheek, and mouth stimulations were also visually analyzed in order to code which parts of the face moved at each stimulation level.

3. Results

3.1. Forehead, cheek, and mouth

Average amplitude levels and Standard Error of the Means (SEMs) for the perception, movement, and tolerability thresholds are shown in Fig. 2. A one-way ANOVA with stimulation location as a within subject factor was conducted separately for each threshold. The effect of the stimulus location was statistically significant only for the movement threshold, $F(1, 33) = 34.96$, $p < .001$, $\eta2 = 0.47$. Post-hoc pairwise comparisons showed that the amplitude level to elicit a movement was significantly lower for the forehead than for the cheek ($MD = 1.76$, $p < .001$, $d = 1.81$) and the mouth ($MD = 0.78$, $p < .001$, $d = 0.95$). The amplitude level to elicit a movement was also significantly lower for the mouth than for the cheek ($MD = 0.98$, $p < .01$, $d = 0.78$).

The averaged pain ratings are presented in Fig. 3. A Friedman test with stimulation location as a within subject factor was conducted separately for the perception, movement, and tolerability thresholds. The effect of the stimulus location was statistically significant for the pain rating at the movement threshold, $\chi = 16.10$, $p < .001$. Post-hoc pairwise comparisons showed that the stimulation of the forehead was rated as less painful than the stimulation of the cheek ($Z = 3.38$, $p < .001$) and mouth ($Z = 2.07$, $p < .05$). The effect of the stimulus location was also statistically significant for the tolerability threshold, $\chi = 9.94$, $p < .01$. Post-hoc pairwise comparisons showed that the stimulation of the mouth ($Z = 2.93$, $p < .01$) and forehead ($Z = 2.01$, $p < .05$) were rated as more painful than the stimulation of the cheek.

Pain ratings increased along the increase of stimulus amplitudes (see Fig. 4). We note that at the end of the experiment many of the participants explained that although they were asked to give pain ratings after stimulations, the stimulations were not actually painful. The feeling they experienced and evaluated was described more as a discomfort than as pain.

The mean ratings for pleasantness are presented in Fig. 5. A Friedman test with stimulation location as a within subject factor was statistically significant for the movement threshold, $\chi = 17.61$, $p < .001$. Post-hoc pairwise comparisons showed that the stimulation of the forehead was rated as more pleasant than the stimulation of the cheek ($Z = 3.50$, $p < .001$) and the mouth ($Z = 2.75$, $p < .01$). Further, the stimulation of the mouth was rated as more pleasant than the stimulation of the cheek ($Z = 2.91$, $p < .01$).

The mean ratings for the naturalness of movement are presented in Fig. 6. A Friedman test with stimulation location as a within subject factor was statistically significant for the movement threshold, $\chi = 6.43$, $p < .05$. Post-hoc pairwise comparisons showed that the stimulated movement of the forehead was rated as more natural than the stimulated movement of the cheek ($Z = 2.67$, $p < .01$). The other pairwise comparisons were not statistically significant.

3.2. Eye blink

Average amplitude levels for the perception, eye twitch, and eye closure thresholds are shown in Fig. 7. The stimulation of the *orbicularis oculi* muscle caused an eye twitch within the amplitude range of 1.5–2.5 mA (M = 2.2 mA) and a complete eye closure within the amplitude range of 2.5–5.0 mA (M = 3.6 mA).

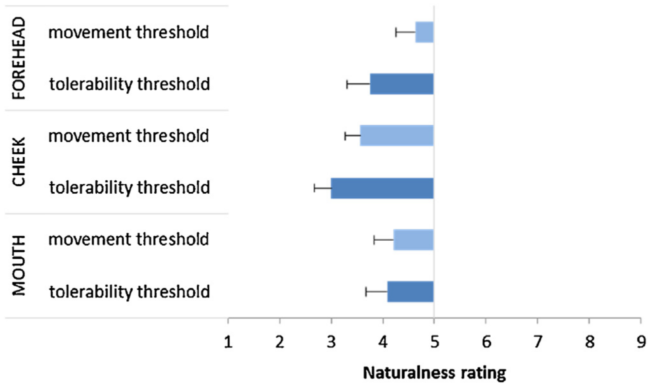

Fig. 6. The average ratings of naturalness (and SEMs) for each threshold.

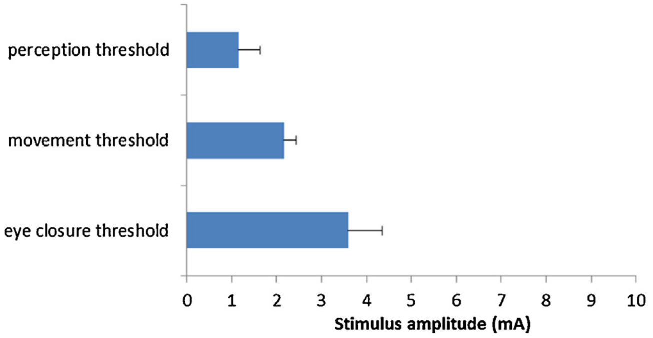

Fig. 7. The average amplitude levels (and SEMs) for blink stimulation at each threshold.

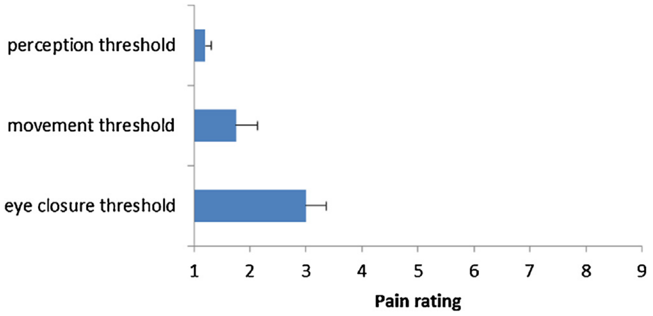

Fig. 8. The average pain ratings (and SEMs) for blink stimulation at each threshold.

The offline video analysis revealed that an eye twitch in 14 participants and an eye closure in 9 participants was achieved earlier than was observed in real time during the experiment. Thus, the ratings of pleasantness and naturalness in these cases were discarded. The pain rating data is more complete because they were collected after each stimulation amplitude level after the movement was noticed in real time. Average pain ratings for the perception, eye twitch, and eye closure thresholds are shown in Fig. 8. The reported average pain rating for the current threshold to elicit an eye twitch was 1.8 (SD = 1.5, n = 16) and 3.0 (SD = 1.7, n = 20) for the current threshold to elicit a blink.

3.3. Concurrent muscle activations

The video analysis revealed that the stimulation of the *frontalis* caused an eyebrow raise, the stimulation of the *orbicularis oculi* caused an eye blink, and the stimulation of the *orbicularis oris* caused a lip pucker, as was intended. This was accomplished by stimulating the locations conventionally used in EMG measurements of the given muscles [28]. Further, the visual analysis showed that the stronger the stimulation, the larger the movement. Quantifying the extent of the movements was beyond the scope of this study.

Table 1
The results of the video analysis at the movement threshold level regarding activations while stimulating the cheek.

The number of participants (%)	Movement location at the movement threshold
5 (22%)	Cheek area
7 (30%)	Mouth area
4 (17%)	Mouth area and nose
7 (30%)	Mouth area and side of the nose

Table 2
The number (and percentages) of participants who rated specific stimulus locations as the most pleasant or natural.

	The most pleasant	The most natural
Forehead	**9 (37.5%)**	5 (20.8%)
Eye blink	4 (16.7%)	**8 (33.3%)**
Cheek	3 (12.5%)	3 (12.5%)
Mouth	7 (29.2%)	4 (16.7%)

The stimulation of the *zygomaticus major* was more challenging. Video analysis at the movement threshold level revealed that stimulation of the cheek activated the cheek area in 22% of the participants. With the rest of the participants, stimulation of the cheek activated first either the muscles in the mouth area, both the mouth and nose area, or both the mouth and laterally the nose area (see Table 1). Further analysis showed that when the stimulation amplitude was increased, the activation in the cheek area was better (but not purely) achieved in 22 out of 24 participants (M = 5.1 mA, SD = 1.5 mA). In addition, with 19 participants, stimulation of the cheek also evoked movement in the eyelid before or after reaching the movement threshold.

3.4. The effects of background variables

Pairwise comparisons between the participants with and without previous experience on electrical stimulation did not show any statistically significant differences in the ratings of pain, pleasantness, or naturalness of the movement.

There was a statistically significant although small correlation between BMI and the amplitude level for forehead movement ($r(22) = 0.41$, $p < .05$) and between BMI and the amplitude level for cheek movement ($r(21) = 0.46$, $p < .05$). There were no statistically significant associations between BMI and the ratings of pain, pleasantness, or naturalness of the movement.

3.5. Preference evaluations

Table 2 presents how many participants rated different stimulus locations as the most pleasant or the most natural. The responses were spread evenly among the locations, but the forehead received the most “the most pleasant” mentions, and the eye blink received the most “the most natural” mentions.

4. Discussion

Previous animal studies and the first studies with human participants have shown that facial pacing can be used in generating facial muscle activations in unilateral facial paralysis. In addition to reliable and fast detection of muscle activations, successful stimulation of facial muscles is needed for dynamic, symmetrical, and cosmetically acceptable reanimation. Of course, the stimulation also needs to be tolerable. Thus, knowledge about the sensations and feelings evoked by electrical stimulation is needed considering the everyday use of facial pacing devices. The existing human studies have concentrated mainly on the production of eye blinks, and research about the electrical stimulation of other facial muscles is largely missing. In the present study, we stimulated not only the eye area to induce eye blinks, but also the forehead, cheek, and mouth to produce eyebrow raises, smiles, and lip puckers. Thus, the present research was the most comprehensive study investigating transcutaneous electrical stimulation of facial muscles to date.

Our findings are very promising, as they showed that a visually observable movement of the forehead and the lower lip was achieved in all participants. Further, the cheek stimulation resulted in observable activation in 23 out of 24 participants. Complete eye blink was achieved in all participants ($n = 22$) except the two who were discarded for obvious reasons.

In respect to forehead, cheek, and mouth, the stimulations were sensed already at around 1 mA. These facial movements were visually observable following 2–4 mA stimulations. It is noteworthy that stimulations were tolerated until up to 7–8 mA. Pain ratings showed that at both perception and observable movement levels the stimulations were not very painful, but cheek stimulations were experienced as more painful than the other stimulations. At the tolerability level, the pain ratings were quite high already but still not at the maximum end of the scale, however. Pleasantness ratings interestingly showed that at perception and movement thresholds the stimulations were felt in the forehead and mouth area as pleasant. The cheek stimulation at the movement level was rated as unpleasant. The ratings of naturalness for these facial areas showed that stimulations were rated as mildly unnatural, but for the cheek area they were the most unnatural. Ratings of pain, pleasantness, and naturalness in respect to cheek area probably reflect the fact that the amplitude level required to elicit the movement was significantly lower for the forehead and the mouth than for the cheek. However, the stimulation of the cheek was rated as less painful at the tolerability threshold than the stimulation of the mouth, even though the amplitude levels did not differ between stimulus locations. We note that at the end of the study many participants spontaneously indicated that even though they were asked to give pain ratings, the stimulations were not actually painful but merely uncomfortable. Thus, the results suggest that the stimulations causing more visible movement elicit unpleasant sensations but maybe not that much pain. This notion is valuable for the future development of facial pacing methods.

A complete eye closure was achieved with the average amplitude level of 3.6 mA, while in a previous study that included individuals with acute facial paralysis [20], the mean current required for eye blink generation was 7.2 mA. The difference in results can be explained by the approximately twice as high pulse repetition frequency (250 Hz) in the current study compared to the one (100–150 Hz) in Frigerio et al. [20]. The total charge delivered to the muscle within a time unit stays the same when the pulse repetition frequency is doubled, and the amplitude can be halved given that the duration of a single pulse is the same in both cases. Thus, the presented results and the ones by Frigerio et al. [20] suggest that the total charge within a time unit required for the stimulation stays the same despite the acute facial paralysis of the individuals in their study.

There was also a small positive correlation between BMI and the amplitude levels for cheek and forehead movements. However, BMI had no effect on the maximum tolerability of stimulation amplitude levels or the ratings of the stimulation. This is probably because people with higher BMI generally have more fat tissue in the facial area, thus resulting in a larger current required to activate the muscle; the operation of the sensory nervous system is not affected by the amount of fat tissue.

Our findings further showed that the stimulation of the cheek area was the most challenging. With some participants, the stimulation of the cheek evoked activation more in the mouth or nose area than in the cheek. This refers to the activation of the *orbicularis oris* and *levator labii superioris* muscles. In addition, the stimulation of the cheek area also resulted in concurrent eye lid twitches in many participants. These concurrent activations were probably due to the activation spreading through facial nerve branches or fat tissue. The lower eyelid of *orbicularis oculi* as well as *zygomaticus major* muscle, for example, receives innervation mainly from the *zygomatic* branch of the facial nerve. This shared innervation is likely to explain part of the concurrent activations. Another likely reason is that the *orbicularis oculi* and *zygomaticus major* muscles are closely connected by the plexus of the nerves called *zygo-orbicular* plexus which crosses over the *orbicularis oculi*, *zygomaticus major* and *zygomaticus minor* muscles [29]. The cheek area also contains more fat tissue than the forehead, eye, and mouth areas. Thus, one future challenge is to investigate how transcutaneous stimulation can be targeted more specifically to the *zygomaticus major* muscle.

The somatosensory nerves and their functionality in the individuals with facial paralysis is preserved. Thus, the sensations and feelings evoked by electrical stimulation are likely quite similar among the healthy participants and individuals with facial paralysis. In future studies with people having facial paralysis, we will investigate does the activation spread happen while stimulating their facial muscles.

One concern is related to the electrical stimulation of paralyzed facial muscles and synkinesis; does the electrical stimulation contribute the facial synkinesis. The term synkinesis means an abnormal synchronization of the involuntary movement of a single muscle or a group of muscles during the contraction of intended muscle [30]. The cause of the condition remains unclear, but it may relate, for example, to the misdirection of regenerating axons, or the changes in the synaptic connections between motoneurons induced by injury to their axons [31–33]. Some studies on rats have suggested that daily electrical stimulation of the facial nerve can facilitate the development of facial synkinesis [e.g., 34]. However, human studies have shown that the electrical stimulation of facial muscles or facial nerve trunk branches is safe during early phase of the facial palsy and there have not been significant differences in synkinesis between electrical stimulation and control groups [35,36,8].

The main limitation of this study was that it was conducted in healthy volunteers. However, to the best of our knowledge, there are no studies that have investigated comprehensively transcutaneous electrical stimulation of the human facial muscles or collected subjective ratings about the stimulations. Thus, the current study provided knowledge about the esthetics of the stimulated movements and the tolerability of the stimulations with different amplitude levels and different parts of the face. Our future studies will include finding out the required stimulation amplitudes to evoke movement in the muscles of people with facial paralysis and exploring more precisely sensations and feelings evoked by the stimulation. It is possible that higher amplitudes are needed to activate paralyzed muscles, thus, we are developing stimulation techniques to alleviate the experiences of pain or discomfort, as well as the unpleasantness the stimulation causes. Further, we are developing the actual pacing software for the prototype device to process EMG signals in real time, automatically determine stimulation waveform parameters, and trigger the stimulation. One important research line is related to the electrode development. In order to make transcutaneous electrodes more unnoticeable and usable in everyday use, the investigation of thin, transparent, and elastic materials is needed.

5. Conclusion

In conclusion, the present study investigated how electrical stimulation can evoke an eyebrow raise, a smile, a lip pucker, and an eye blink, as well as what the subjective experiences are in respect to the stimulations. The results showed visually observable movement of the forehead and the lower lip in all participants. Stimulations evoking small movements were rated as relatively pleasant and tolerable. The stronger the stimulation was the larger the movement and the higher the pain ratings were. Electrical stimulation evoked complete eye blinks in 22 participants, and the sensation was rated mainly as tolerable. Stimulation of a smile was more challenging, most likely due to the activation spreading to other parts of the face. In follow-up studies, we will investigate the means to alleviate the uncomfortable experiences caused by the stimulation, study how we could stimulate the *zygomaticus major* more accurately, and test the stimulation with patients with unilateral facial paralysis. Regarding a longer term perspective, noninvasive, transcutaneous solutions could be a new treatment option, especially for patients recovering from acute facial palsy and for patients whose facial nerve has not fully degenerated promoting the weak and incomplete movements of the paralyzed side.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.bspc.2018.10.015.

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