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Functional Electrical Stimulation for Facial Pacing: Effects of Waveforms on Movement Intensity and Ratings of Discomfort

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Abstract

Facial pacing systems aim to reanimate paralyzed facial muscles with electrical stimulation. To aid the development of such systems, the *frontalis* muscle responsible for eyebrow raising was transcutaneously stimulated in 12 healthy participants using four waveforms: square wave, square wavelet, sine wave, and sinusoidal wavelet. The aim was to investigate the effects of the waveform on muscle activation magnitude, perceived discomfort, and the relationship between the stimulus signal amplitude and the magnitude of evoked movement. The magnitude of movement was measured offline using video recordings and compared to the magnitude of maximum voluntary movement (MVM) of eyebrows. Results showed that stimulations evoked forehead movement at a magnitude comparable to the MVM in 67% of the participants and close to comparable (80% of the MVM) in 92%. All the waveforms were equally successful in evoking movements. Perceived discomfort did not differ between the waveforms in relation to the movement magnitude, but some individual preferences did exist. Further, regression analysis showed a statistically significant linear relation between stimulation amplitudes and the evoked movement in 98% of the cases. As the waveforms performed equally well in evoking muscle activity, the waveform in pacing systems could be selected by emphasizing technical aspects such as the possibility to suppress stimulation artifacts from simultaneous electromyography measurement.

Keywords: comfort; electrical stimulation; facial muscle; frontalis; unilateral facial paresis; waveform

1. Introduction

Functional electrical stimulation (FES) is a technique that uses electrical stimulation to supplement or replace the function of paralyzed muscles [1]. So far, the research has mainly concentrated on utilizing FES for the activation of limb muscles to enable movement in patients with upper motor neuron lesions such as spinal cord injury or stroke. Another important but far less investigated area of utilization for FES is the human face. Facial paresis is a condition that diminishes the quality of life in many dimensions. It often impairs the ability to blink and may hamper speaking, eating, and drinking. In addition, in unilateral paresis, the face looks asymmetrical, especially during facial expressions, and the altered appearance can cause significant psychological distress [2], [3].

Facial pacing refers to technology that has been proposed to foster regaining of the symmetry of facial movement that has been lost due to unilateral facial nerve paresis [4]. The idea of facial pacing is that muscle activations from the intact side of the face can be measured, for example, with electromyography (EMG), and simultaneously, the corresponding muscles of the paralyzed side can be activated with FES. It has been studied since 1970's in several experimental animal models [5], [6], [7], [8], [9], [10], [11]. The principle of facial pacing has also been demonstrated in humans so that the *frontalis* muscle was temporarily paralyzed with local anesthetics [12]. However, this is the only demonstration of the system with human models according to our knowledge. While partially or fully implanted systems would be more suitable for long-term use, noninvasive transcutaneous systems may offer temporary assistance, especially for patients recovering from acute facial paresis. Transcutaneous FES could potentially also provide an alternative for chronic patients who do not want to undergo surgery. Importantly, a recent study by Mäkelä *et al.* [13] showed that the activation of chronically paralyzed facial muscles by transcutaneous electrical stimulation was possible even in some cases where the muscles were clinically completely paretic if a subclinical innervation exists. Transcutaneous FES techniques are also needed to study the potential and possibilities of long-term use of facial FES systems.

To be functional, facial pacing technology needs to activate muscles predictably, and the stimulations should be tolerable in terms of discomfort experienced by the patient. With respect to predictability, the technical implementation of a pacing system is easier if the relationship between the amplitude of the stimulation waveform and the intensity of the introduced movement are known and preferably linear. Transcutaneous electrical stimulation also unavoidably stimulates sensory fibers and receptors. Thus, in addition to muscle movement, the electrical stimulation causes cutaneous sensations that range from a slight tingling to strong discomfort or even pain. The factors that affect the extent of sensory fiber and receptor stimulation and, in turn, the comfort of the sensation include electrode location, electrode size, and stimulation parameters such as stimulus waveform, pulse duration, and the frequency of stimulation pulse repetition.

Few studies focusing on the stimulation of limb muscles have investigated the level of experienced discomfort caused by the different pulse durations and pulse waveforms. Bowman and Baker [14] stimulated the quadriceps muscle and found that participants preferred longer (0.3 ms) symmetrical biphasic waveform over the shorter (0.05 ms) asymmetrical biphasic square pulse. In a study by Baker *et al*. [15], participants rated the biphasic waveform more comfortable than monophasic waveforms when the wrist flexor or extensor and quadriceps muscles were stimulated. A few other studies have investigated the effects of different waveforms on comfort when stimulating muscles located in the legs or arms. Bennie *et al*. [16] stimulated the quadriceps muscle with four waveforms (Russian, interferential, sine, and square) to investigate their effects on the mean stimulation current required to achieve 10% contraction of the maximal voluntary contraction, in addition to subjective comfort and physiological responses. They found that sine wave stimulation produced the desired muscle tension with the smallest mean stimulation current. Further, the sine waveform was also judged to be the most comfortable waveform. These findings were supported by a study by Petrofsky *et al*. [17], who compared the same four waveforms using the same current level for each. They found that sine waveform stimulation produced greater muscle strength with less pain than the other waveforms. On the other hand, Delitto and Rose [18] found no differences between the comfort ratings when the quadriceps muscle was stimulated by sine, sawtooth, and square waveforms. Similarly, sine and square waveforms produced no differences in effect on discomfort in a study by Szecsi and Fornusek [19].

As these studies show, the existing knowledge about the effect of waveforms on the comfort of stimulation is controversial. More importantly, previous research has focused on limb muscles. To the best of our knowledge, no prior studies have investigated the effects of the different waveforms on the magnitude of movement or perceived discomfort when stimulating facial muscles. There are a couple of reasons of why findings focusing on the stimulation of limb muscles cannot be applied to facial FES. First, the functionality of FES is affected by thickness of fat and depth of nerves, which vary between body parts [20]. Second, the morphology of human facial muscles is also different than limb muscles [21], [22]. In addition, the sensitivity to touch differs in different body parts [23]. The facial area is much more sensitive than the thighs or upper arms, for example. Thus, the earlier findings are not directly applicable for the electrical stimulation of facial muscles, which therefore requires separate research.

There are additional requirements for FES when it is implemented as part of a facial pacing system. Ideally, the simultaneous EMG measurement should be free of artifacts caused by the stimulation signal. Multiple methods have been applied to suppress these artifacts, including discarding the signal measured during stimulation or by using digital filtering to remove the remaining artifacts

[24]. Another method used is adaptive-matched filtering [25]. Simple low-order filters are also an option if the stimulation waveform is properly chosen. For example, wavelets that have high-frequency components can be used [26]. However, the waveform should not have a negative impact on the intensity of the evoked muscle movement compared to more conventional FES waveforms that are simple biphasic square wave pulses with more power at low frequencies.

The aim of the present study was to electrically stimulate the *frontalis* muscle with four different waveforms to investigate their effects on muscle activation and levels of experienced comfort or discomfort. Additionally, we studied the relationship between the amplitude of the stimulus signal and the magnitude of the resulting facial movement. The amount of tissue between skin and muscles varies throughout the face, and in the forehead, it is relatively low. For this reason, the *frontalis* muscle was chosen as the target facial muscle for this study.

2. Methods

2.1. Participants

Twelve healthy voluntary participants (nine males, three females) with an age range of 25–65 years (M = 42.5, SD = 11.9) took part in the experiment. The study was approved by the Ethics Committee of Pirkanmaa Hospital District (R15067), and each participant signed an informed consent form prior to their participation. All participants had some previous experience with the electrical stimulation of muscles.

2.2. Equipment

A detailed description of the device used to produce the electrical stimuli is published in Rantanen *et al.* [27]. The device produces arbitrary current waveforms. In the current study, the evaluated stimulation pulse waveforms were a square wave, a square wave pulse train with eight cycles and a sinusoidal envelope (square wavelet), a sine wave, and a sine wave pulse train with eight cycles and a sinusoidal envelope (sinusoidal wavelet). The waveforms are illustrated in Fig. 1. The positive and negative phases of the current pulses had equal amplitudes and durations. The duration of a single stimulus pulse (the positive and negative phases combined for sine and square waves or the duration of the envelope pulse for the wavelets) was 0.8 ms, which was repeated at 250 Hz to produce a 1000 ms long stimulus pulse train. These parameters were selected based on previous research [28], [29], [30] and explorative pilot testing.

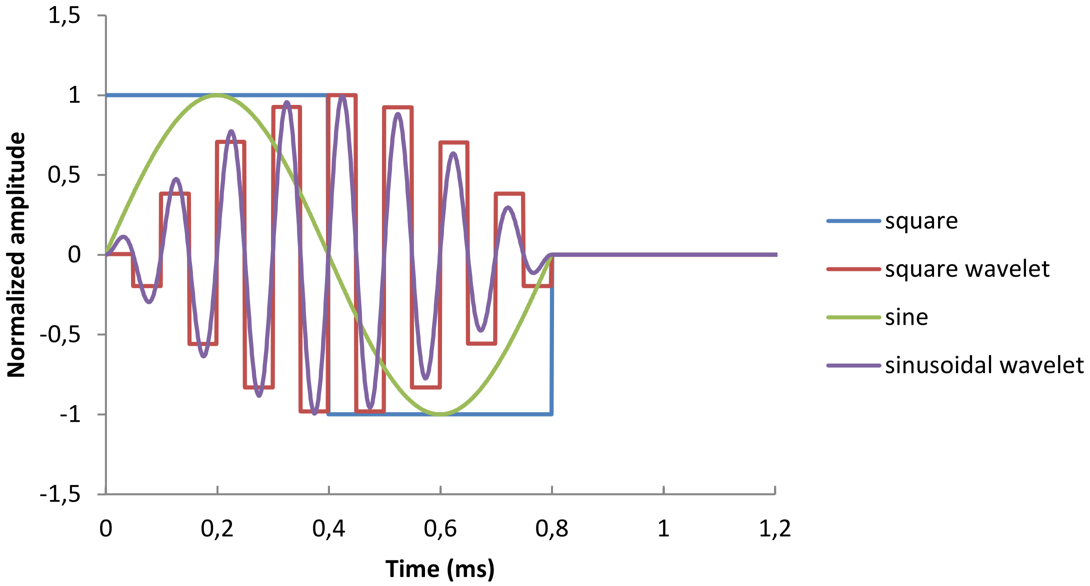


Fig. 1. Visualization of the four stimulation pulse waveforms.

The stimulation electrodes used were commercial adhesive pre-gelled electrodes (Quirumed®, GMDASZ Manufacturing Co., Ltd., Shenzhen, China) trimmed to a size of approximately 1.5 cm^2. The electrodes were attached to the skin above the *frontalis* muscle according to the guidelines for

EMG recording [31]. Videos of facial behavior used for offline visual analysis were recorded at 50 frames per second by a digital video camera placed in front of the participant.

2.3. Procedure

The stimulation electrodes were attached above the *frontalis* muscle, to the left side of the face (Fig. 2). The experimenter marked two dots 7 cm apart on the participant's face with a skin marker pen, one on the forehead, and one on the cheek below the left eye. These marks were used as reference points in the offline video analysis. Before muscle stimulation, the participant performed five maximum eyebrow raises, which were used as reference movements to investigate how well the stimulations performed in comparison to voluntary movements.

Following this, the *frontalis* muscle was stimulated with all the four previously described waveforms. The order of the stimulation waveforms was counterbalanced between the participants as follows:

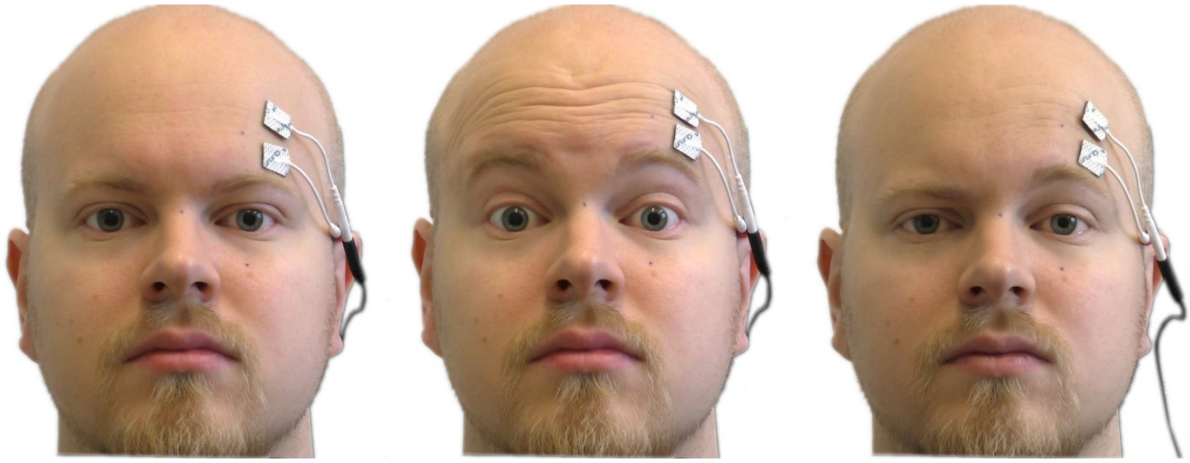
- square wave, square wavelet, sine wave, and sinusoidal wavelet ($n = 3$),
- square wavelet, sine wave, sinusoidal wavelet, and square wave ($n = 3$),
- sine wave, sinusoidal wavelet, square wave, and square wavelet ($n = 3$)
- sinusoidal wavelet, square wave, square wavelet, and sine wave ($n = 3$)

The stimulation was repeated three times at each amplitude level, with approximately 1-second interstimulus intervals. Based on a pilot test, steps for amplitude increases were chosen so that enough amplitude values could be obtained to characterize the movement response curve for each waveform. To achieve this, the step sizes for increasing the stimulus current in the wavelet stimulations were larger than in the non-wavelet waveforms (Table 1). The amplitude was increased until the participant wanted to discontinue the stimulation or the maximum stimulation amplitude (48 mA) was achieved.

Table 1. Amplitude Steps.

Step	Square wave	Square wavelet	Sine wave	Sinusoidal wavelet
1	0.5	1.4	0.7	2.0 mA
2	1.0	2.8	1.4	4.0 mA
3	1.5	4.2	2.1	6.0 mA
n	…	…	…	…

The stimulation began at a low level and continued until the participant reported feeling the stimulus for the first time (i.e., the sensory threshold was reached). From that point on, the experimenter asked the participant to evaluate the discomfort experienced by each stimulation amplitude level. The discomfort rating scale was a one-dimensional nine-point scale ranging from 1 (not at all uncomfortable) to 9 (very uncomfortable). The duration of the experimental session for each participant was approximately 43 minutes (range 31-60 minutes).



(a) (b) (c)

Fig. 2. Example images of different phases of the test: (a) neutral expression; (b) maximum voluntary eyebrow raise; and (c) forehead activation by electrical stimulation.

2.4. Data Analysis

The magnitude of forehead movement was taken from the video recordings and measured offline using a digital ruler. The magnitude of maximum voluntary movement (MVM) with eyebrow raises (Fig. 2b) and the second stimulus from each series of three stimulations at each amplitude level were measured (Fig. 2c). We measured the movement during the second stimulus, because the face was the most relaxed then. This was because during the first stimulation, the participant could startle, for example, and during the last the participant could already give the discomfort rating. The stimulated movement magnitude was then compared to the average of the five MVMs. The MVM of the forehead varies among individuals, and thus, the movement used for the analysis was the percentage proportion of the stimulated movement compared to the MVM.

Data were analyzed using SPSS® statistical software, version 22.0 (SPSS Inc., Chicago, IL, USA). Statistical analyses were performed using the Friedman test and the Wilcoxon signed-rank test. The Bonferroni correction was used for multiple pairwise comparisons.

Movement in response to stimulation was characterized by determining the linearity of the relationship between the stimulation waveform amplitude and the range of movement it introduced. The linear range was extracted for each participant and each waveform separately by only including the data points between 10% and 90% of the maximum movement range achieved by stimulation. Linear regression was used to fit a line to the data points, and the R^2 statistic and p-value of the regression were computed.

3. Results

The forehead MVM range was 4.2–11.5 mm (M = 7.1, SD = 2.2). Fig. 3 shows the number of participants in which the stimulation evoked certain proportions (50, 60, …, 100%) of the magnitude of the MVM of the forehead. The stimulation evoked at least 50% of MVM movement in all participants. At least 100% of MVM movement was achieved in 67% of the participants. The Friedman test showed no statistically significant differences between the waveforms for the maximal stimulated movements.

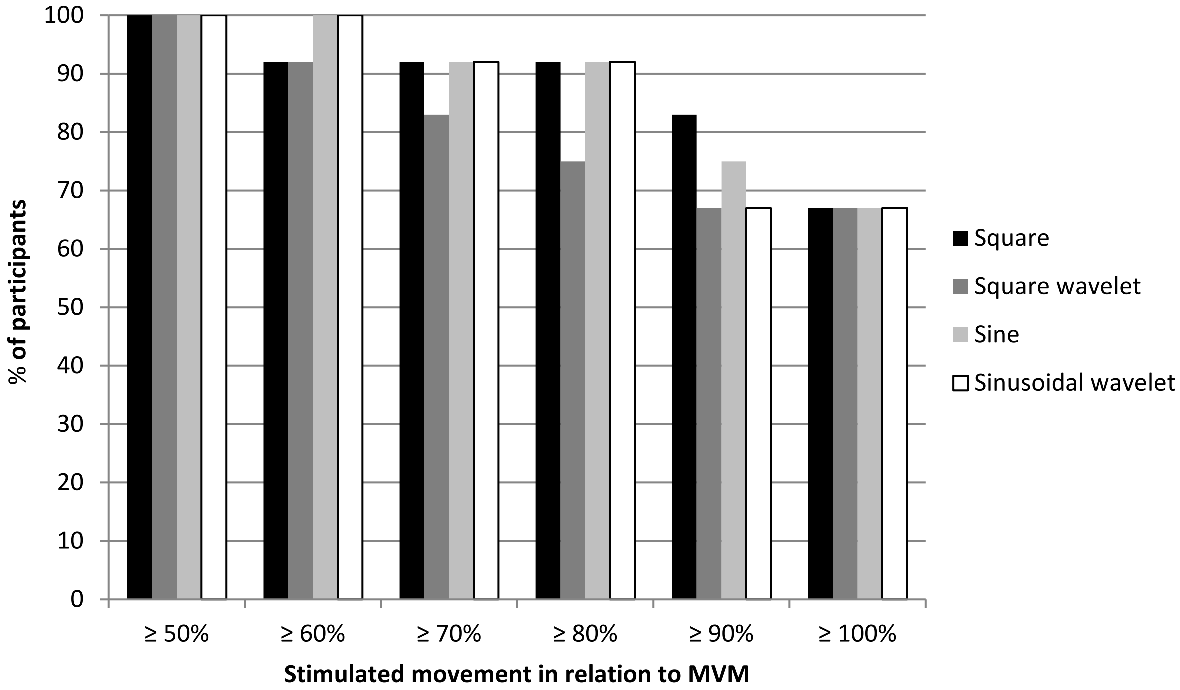


Fig. 3. The percentage of participants in which the stimulation evoked 50% to ≥ 100% of MVM forehead movement.

Fig. 4 shows the average discomfort evaluations when the stimulation evoked 50% to ≥ 100% of MVM forehead movement. The Friedman tests showed that the discomfort evaluations did not significantly differ between the waveforms.

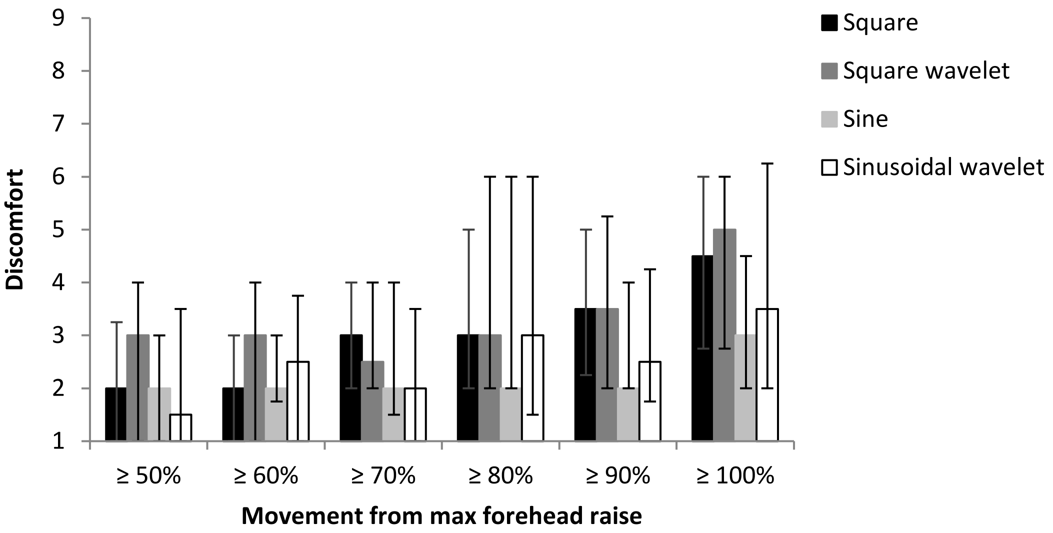


Fig. 4. The median discomfort evaluations, with interquartile ranges, at the different levels of movement.

To assess possible individual preferences between the waveforms and their discomfort ratings, the ratings of each participant were classified into four groups in ascending order as least uncomfortable, moderate-low discomfort, moderate-high discomfort, and most uncomfortable (i.e., the lowest rating of the four waveforms was placed in the category “least uncomfortable”, the next lowest in “moderate-low discomfort”, and so on). The classified discomfort ratings are listed in Table 2. To represent individual preferences, we chose discomfort ratings from the level when at least 100% of MVM movement was achieved (eight participants). If 100% of MVM movement was not achieved (participants 1, 4, 9, and 11), the maximum movement level that was achieved with all four waveforms was used. The Friedman test showed that the classification had a statistically significant effect on discomfort ratings ($\chi = 29.7$, $p < 0.001$). Pairwise post hoc comparisons showed that the ratings given to the most uncomfortable waveform differed significantly from the ratings given to the least uncomfortable ($Z = 3.1$, $p < 0.05$), moderate-low discomfort causing ($Z = 3.0$, $p < 0.05$), and moderate-high discomfort causing waveforms ($Z = 3.0$, $p < 0.05$).

Table 2. Discomfort ratings, ranging from 1 (not at all uncomfortable) to 9 (very uncomfortable), ordered by discomfort level classification

	Discomfort level				
Participant	Least	Moderate-low discomfort	Moderate-high discomfort	Most	Movement level (% of MVM)
1	1	2	2	2	70 %
2	1	4	5	6	100 %
3	1	2	3	4	100 %
4	5	5	6	7	60 %
5	4	5	6	6	100 %
6	2	2	2	3	100 %
7	2	2	2	3	100 %
8	7	7	7	8	100 %
9	3	4	5	6	50 %
10	6	6	6	8	100 %
11	5	6	6	7	80 %
12	2	2	3	6	100 %
Md	2.5	4.0	5.0	6.0	
IQR	3.8	3.8	3.8	3.8	

To rule out the possibility that the presentation order of the waveforms had an effect on the discomfort ratings, discomfort scores were categorized according to the order the waveforms were presented. The Friedman test showed that the presentation order had no significant effect on the discomfort ratings.

Fig. 5 shows one example of typical response curve, taken from participant 9, for the square wavelet ($R^2 = 0.94$) between the stimulation waveform amplitude and the range of introduced movement, with a linear response line fitted with linear regression. The R^2 values of the regression are presented in Table 3. The linear regression was statistically significant, with $p < 0.05$ in 98% of the cases, $p < 0.01$ in 73% of the cases, and $p < 0.001$ in 50% of the cases.

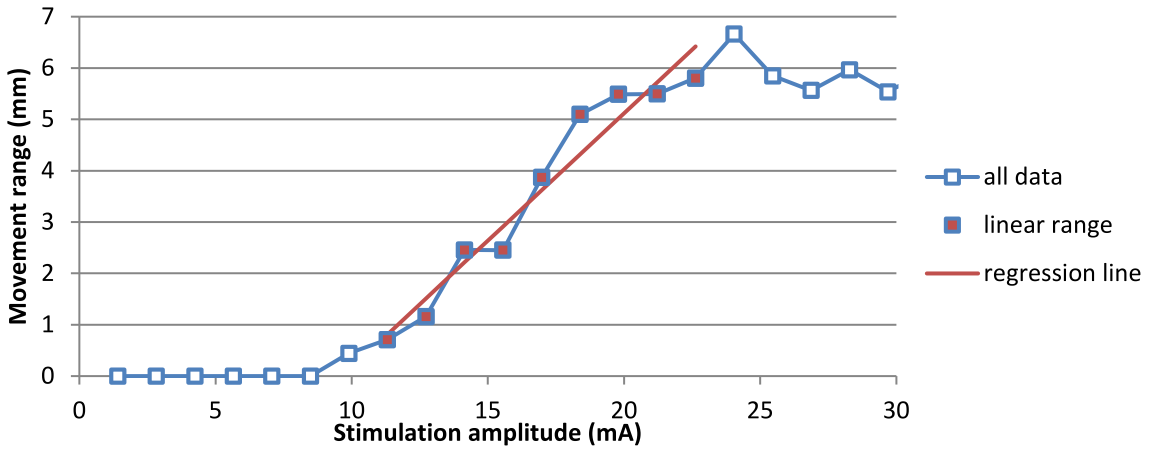


Fig. 5. An example of the linear regression of the movement response to a stimulation waveform consisting of pulses of a square wave with eight periods and a sinusoidal envelope.

Table 3. Linear Regression R^2 Statistics for the Pulse Waveforms.

participant	square	square wavelet	sine	sinusoidal wavelet
1	0.91**	0.98***	0.85**	0.93**
2	0.84**	0.89***	0.95*	0.89***
3	0.90**	0.92***	0.93***	0.93***
4	0.94*	1.00*	0.92	1.00*
5	0.93***	0.94***	0.89***	0.96***
6	0.94*	0.89*	0.93*	0.90*
7	0.79*	0.97***	0.92**	0.96*
8	0.96***	1.00***	0.85**	0.99***
9	0.97***	0.94***	0.98***	0.78***
10	0.93***	0.92***	0.94**	0.95***
11	0.97***	0.98***	0.94**	0.97***
12	0.94*	0.90**	0.83*	0.90**
$\bar{x}$	0.92	0.94	0.91	0.93
SD	0.05	0.04	0.05	0.06

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

4. Discussion

The results showed that the electrical stimulation of the *frontalis* muscle was successful with all participants. In respect to success of stimulation as such this is in line with an earlier study in which four facial muscles, including *frontalis* muscle, of healthy participants were stimulated by square waveform [30]. In contrast to [30], the present study compared the magnitude of the movement evoked by the electrical stimulations to the participants' own voluntary forehead raise. The results showed that the magnitudes of the evoked forehead activations were comparable to participants' MVM in 67% of the participants. At least 80% of MVM movement was achieved in 92% of the participants. All tested waveforms produced movement equally well.

Further, the results showed that the levels of experienced discomfort in respect to all waveforms did not differ at the same contraction levels. This result is in line with the earlier study by Delitto and Rose [18], who found that the waveform had no effect on comfort during quadriceps femoris muscle stimulation. However, it is noteworthy that the findings of the present study are novel because no other study has investigated the effects of different waveforms on perceived comfort in facial FES. On average, the stimulations of our study were rated as well tolerated. For example, at the 100% movement level, the average discomfort rating on a scale ranging from 1, not at all uncomfortable, to 9, very uncomfortable, was 4. Even though none of the waveforms were unanimously evaluated as the most or least comfortable, the results indicated that there are some individual preferences. For a real-life application, it might therefore be beneficial to have the possibility to select a preferred waveform.

The results on the linearity of the movement response to the amplitudes of different pulse waveforms are very promising. All studied waveforms produced a highly linear response in the extracted linear range, based on the R^2 values. With the exception of one waveform with one participant, the results were statistically significant. While the overall shape of response curves resembled a sigmoid curve starting below muscle activation threshold and the curve ending at the maximum muscle contraction, the deviations from a straight line in the linear range were small enough to consider the relationship linear. The use of the linear model simplifies the implementation and use of a facial pacing system because there is no need to determine the exact mapping between the stimulus amplitude and the resulting movement amplitude. Additionally, it was found that the wavelet waveforms also produced a linear response despite having different frequency content (i.e., higher-frequency components) than the simple biphasic square and sine wave pulses. This is an important finding because due to their narrow-band high-frequency energy content wavelet-type waveforms are better for suppressing the stimulation artifacts introduced to simultaneous EMG measurements, as required in fully functional facial pacing [e.g., 26].

Our study is the first one investigating the effect of different waveforms in the transcutaneous stimulation of the facial muscles on the movement intensity and the discomfort ratings, and the results are encouraging. However, our results show that activations that are fully comparable in magnitude (i.e., identical) to natural activations were not always achieved. This raises the question of a sufficient level of activation. The question and answer are manifold. We consider that achieving a fully symmetrical facial movement is not necessary for natural looking expression. It may, in fact, even be impossible. To start with, it is known that faces are generally asymmetrical [e.g., 32]. It is also known that the two sides of the face differ in muscle size, for example, and further, facial expressions are typically asymmetrical as well. Indeed, there is evidence that during emotional expressions, the left hemi-face is more expressive than the right hemi-face [33]. Previous research has shown that observers are most sensitive to asymmetries in eye closure, but in other parts of the face, small asymmetries go unnoticed or do not substantially affect the perceived naturalness of the expression [34], [35], [36]. In light of these considerations, we can conclude that our results are promising. We note, however, that the stimulated eyebrow raise was sometimes different from a self-activated voluntary expression in terms of wrinkling of the skin above the eyebrow, as is evident from Fig. 2. This may be an innate property of muscle activation caused by transcutaneous electrical stimulation. On the other hand, the electrodes were placed according to the

EMG recording guidelines [31], which may be not the optimal placement for stimulation. As a result, the perceived naturalness of stimulated expressions requires research on its own.

The aim of the present study was not to investigate muscle fatigue, but it is possible that fatigue occurred in the *frontalis* muscle during the experiment. Muscle fatigue refers to decrease in the ability to produce force resulting from recent activation [37], [38]. In the present study, we used 250 Hz stimulation frequency. Regarding the limb muscles it has been shown that higher pulse frequencies result faster muscle fatigue than lower pulse frequencies [39], [40]. We decided to choose relatively high frequency stimulation based on literature [28], [29] and explorative pilot testing, where the high frequency stimulation was experienced as more comfortable than lower frequencies, which caused tapping-like sensation. All in all, as discussed in the introduction, human face and facial muscles are in many ways different from other body parts. Thus, techniques and parameters used for limb muscles are likely not directly applicable for facial stimulation, but the effect of stimulation frequency on the fatigue of the facial muscles should be studied in the future. Further, even if the muscle fatigue has taken place, it should have not affected the results, because we used counter balancing for the order of the stimulation waveforms.

It is also likely that the activation of paralyzed muscles requires higher amplitudes as compared to healthy muscles. Thus, in addition to waveforms it is important to study how other stimulation pulse parameters and properties are associated to the experiences of pain or discomfort. Regarding the limb muscles, it has been suggested that shortening pulse width [41] or adding an interphase interval between the positive and negative phase of biphasic pulse [42], [43] can cause stronger contractions with smaller amplitudes and thus, can help to achieve more comfortable muscle contraction. These as well as the effect of stimulation frequency would be interesting to study further in future research.

5. Conclusion

This is the first study that has investigated the effects of different waveforms in the transcutaneous stimulation of the facial muscles on the movement magnitude and the discomfort ratings. Also, the relationship between stimulation amplitude and magnitude of evoked movement was studied. The study compared four different pulse waveforms for FES of the *frontalis* muscle. All the waveforms were equally successful in producing movement, but in some cases, the achieved movement range was limited in comparison to that produced through voluntary activation. The waveforms did not differ in comfort-level evaluations, but the participants had personal preferences regarding which one of the waveforms was rated as the most uncomfortable. All waveforms were successful at creating a linear response between the stimulation waveform amplitude and the evoked movement. Based on these finding, a stimulus signal with sinusoidal wavelet waveform would be the preferred choice in facial pacing applications as it enables efficient cross-talk cancellation from the EMG measurement by filtering.

The main limitations of the study are that only one facial muscle was studied, and the movements of facial skin caused by this muscle are only in a specific direction, as compared to other muscles that produce more complex facial behavior. Future research on the topic should focus on collecting more information about the movement responses of other facial muscles, evaluating the perceived naturalness of the evoked expressions, and evaluating how well muscle contraction intensities can be produced with a facial pacing system that relies on the findings of this study. In this study, we investigated facially intact participants, but additionally, we are currently working with patients suffering from unilateral facial paralysis. Even though the functionality of somatosensory nerves is preserved in the individuals with facial paralysis and thus, they likely experience electrical stimulation quite similarly as healthy participants, there may still be some differences, especially in the facial muscle movement, because of the differences in muscle functionality. Due to the normal facial muscle function it may be difficult for healthy participants to be completely passive in the presence of FES, for example. One limitation is also that the magnitude of forehead movement was measured offline using a digital ruler by a human observer. In the future, even more objective method (i.e., automated software) could be used. All in all, the findings are valuable considering the requirements of creating facial pacing technology.

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