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Facial muscle activation patterns in healthy male humans: A multi-channel surface EMG study

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ABSTRACT

In order to accurately characterize essential muscle activity during facial movements a new surface EMG (SEMG) technique was introduced and applied. Results represent reference data of healthy persons for future diagnostic purposes. In 30 healthy males monopolar electromyograms of the facial muscles were simultaneously recorded from 48 bilateral-symmetrically applied small surface electrodes while performing 29 facial movements of high clinical relevance. Mean SEMG amplitudes were quantified by power spectral analysis, normalized and presented as movement-related SEMG profiles. The mean SEMG amplitudes increased significantly in response to facial movements. Critical values of the movement-related SEMG amplitude increase were ascertained, valid for 90% of all examined subjects. The mean SEMG amplitudes differed between the performed facial movements, the examined muscles, and intramuscularly between lateral–medial and superior–inferior electrode positions, but not systematically between right and left side of face. The results show that the interplay between individual facial muscles and intramuscularly between their functional subunits is more differentiated than was previously estimated. With the presented facial SEMG technique the produced SEMG profiles are highly relevant for better planning of facial movement restoration. Based on the established reference data, this method can be used to objectively evaluate a facial paresis and to monitor changes during the course of disease and treatment. To easily apply the method, a reduction of electrode positions is intended after the clinical evaluation.

1. Introduction

The incidence of the peripheral facial nerve paresis estimated to be 20–35/100,000 inhabitants in Western Europe and the US (Guntinas-Lichius and Sittel, 2004). Peripheral facial paresis may be due to an idiopathic genesis, and may be caused by metabolic, inflammatory, and/or traumatic mechanisms. Besides the peripheral lesion of facial nerves, central facial nerve affections also exist. The most important reason for this central disturbance is stroke (incidence see Truelsen et al., 2006; Heuschmann et al., 2009). Cerebral inflammations, trauma, or tumors seldom provoke this kind of facial nerve paresis.

The diagnostics of facial nerve paresis include clinical examination of patients and establishing patient history as well as electrophysiological evaluation including electroneurography (Rosler et al., 1989), electromyography (Diener and Putzki, 2008) and the examination of the blink reflex (Ghonim and Gavilan, 1990; Lu and Tang, 1996). In addition magnetic stimulation is also used for etiologic differentiation (Rosler et al., 1995).

For diagnosis and monitoring, it is necessary to analyse the facial muscle function in as detailed a manner as possible. Current methods combining qualitative and semi-quantitative characterization by clinical examination and grading systems are not very precise. More detailed and accurate quantification of facial muscle functions would be especially helpful in evaluating long-term course after surgical intervention, to determine synkinesis (Stennert et al., 1977) or auto-paralytic syndromes of facial nerve innervated muscles (Stennert, 1982). Up to now, detailed knowledge of healthy facial muscle activation patterns evoked by defined motor tasks was missing. The only method, elucidating muscle activation processes, is electromyography (EMG). Only the EMG allows a characterization of the final common motor path. For the diagnosis of facial nerve paresis, the needle-EMG technique has been the gold standard (Diener and Putzki, 2008). But, it is an invasive technique, and obviously, extensive and differentiated needle-EMG examination of the facial muscles would be too uncomfortable. In contrast, surface-electromyography (SEMG) is

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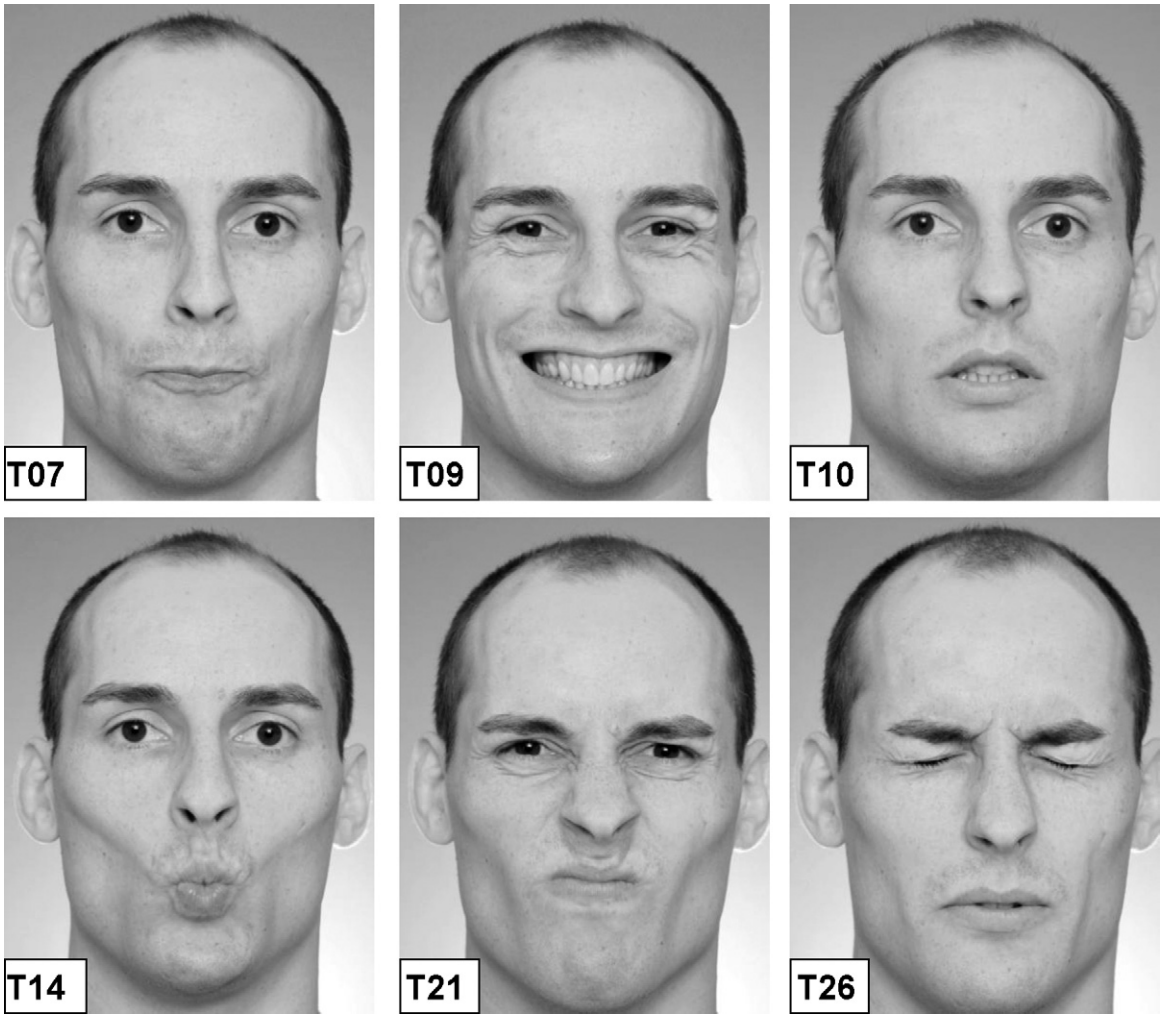

Fig. 1. Facial movements which resulted in a high level activation of recorded facial muscles (corresponding SEMG profiles in Fig. 3). Pressing the lips together (T7), voluntary smiling (T9), depressing the lower lip (T10), pursing lips (T14), wrinkling the nose (T21), closing the eyelids forcefully (T26).

a non-invasive technique, and is especially approved, if multi-channel EMG recordings are indicated to compare activation patterns between several muscles or muscle regions. Therefore, the functional deficits in facial muscle activation and coordination in patients suffering from facial nerve paresis may also be characterized by means of SEMG. For researching facial nerve paresis therapy and for the eventual development of therapeutic management systems, SEMG derived maps of facial muscle activation can greatly assist in ascertaining the course of the disease and the success of therapy.

Hence, a non-invasive multi-channel SEMG technique was developed, using 48 small surface electrodes, to characterize simultaneously typical coordination patterns of the facial muscles. Up to now, similar approaches using non-invasive multi-channel techniques, considered only the lower and middle facial nerve innervated facial muscles without the inclusion of the ocular region (Cacou et al., 1996; Lapatki et al., 2003), or used too few measuring points in both regions (Ohyama et al., 1988). A more detailed characterization, including the ocular and forehead regions, would be important from a clinical point of view. The aim of this contribution is to introduce a newly developed SEMG application and, additionally to present SEMG reference data of facial muscle activation patterns in healthy subjects, considering neurological examination guidelines for patients with facial nerve paresis.

2. Methods

2.1. Subjects

30 healthy male volunteers with no neurological diseases (29 right-handed, 1 left-handed, mean age: 26 years, SD ± 3.2) were examined by a newly created monopolar 48-channel-SEMG technique while they performed different facial movements. All subjects were thoroughly informed about the SEMG examination and gave consent to participate in the study. The study was approved by the local ethics committee (Medical Faculty of the Friedrich-Schiller-University Jena: 2129-10/07).

2.2. SEMG registration and motor tasks

The SEMG examination took place in the late morning between 10 a.m. and 1 p.m. to exclude circadian influences. Subjects sat in relaxed upright position, face to face with the examiner. The planned facial movement was named and demonstrated. The test person was allowed to try the facial movements. These were observed and corrected by the examiner. During the following multi-channel SEMG registration each task was performed three times with interposed breaks of 5 s. Videos were simultaneously recorded for later evaluation of the individual motor tasks performances. In the first motor tasks (T1–T6), volunteers had to

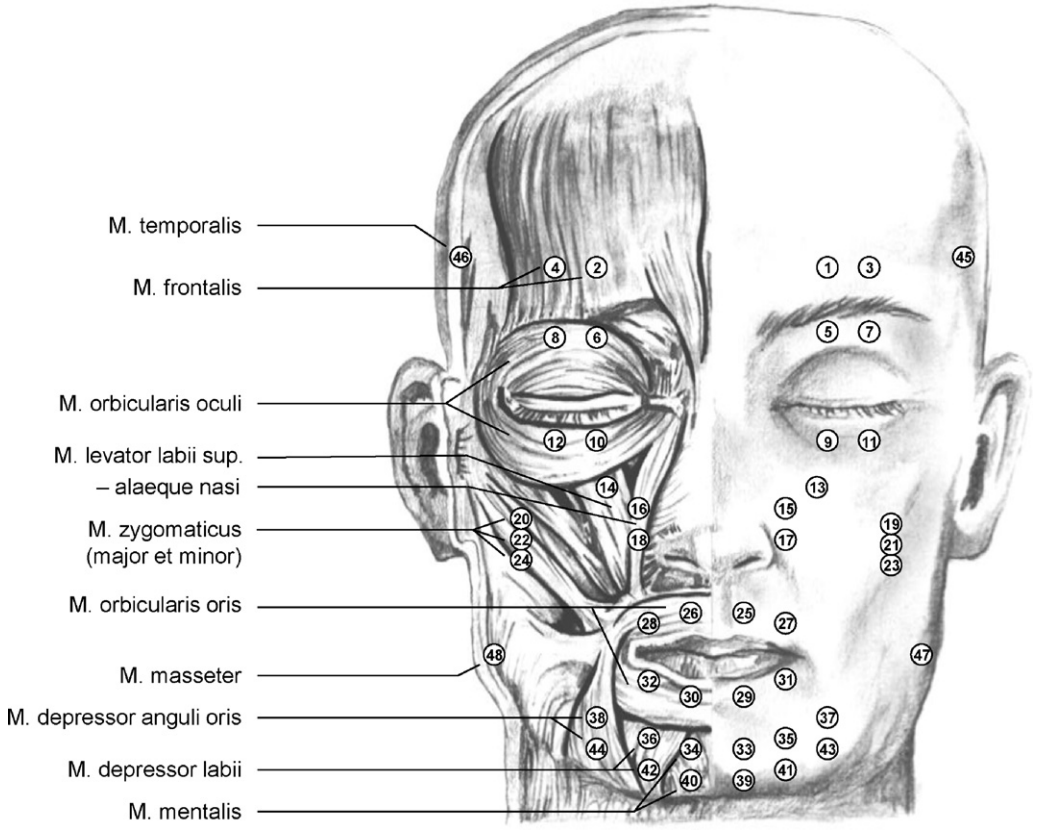

Fig. 2. Scheme of the electrode arrangement.

pronounce German vowels. They articulated A/a▼▲/, Ä/æ/, E/e▼▲/, I/i▼▲/, O/o▼▲/, U/u▼▲/ (/international phonetic alphabet/). Subsequently, the following facial movements were examined: (T7) pressing the lips together, (T8) pulling the corners of the mouth downwards, (T9) voluntary smiling: pulling the corners of the mouth upwards and backwards, (T10) depressing the lower lip, (T11) protruding the lower lip, (T12) pulling the upper lip upwards, (T13) pulling the upper lip upwards and depressing the lower lip simultaneously, (T14) pursing lips, (T15) blowing out the cheeks, (T16) sucking the cheeks inward, (T17) whistling with a similar tone pitch, (T18) opening the jaw with closed lips, (T19) exhaling forcefully with moderate closed lips (a more diffuse whistling), (T20) opening the lips as wide as possible while the jaw is closed, (T21) wrinkling the nose, (T22) voluntary smiling only on the right side of the face, (T23) voluntary smiling only on the left side of the face, (T24) raising the eyebrows up and wrinkling the forehead, (T25) contracting the eyebrows, (T26) closing the eyelids forcefully, (T27) squinting the eyes, (T28) closing the right eyelid, (29) closing the left eyelid (Fig. 1).

Monopolar electromyograms were bilaterally recorded from the following facial muscles: frontalis-, orbicularis oculi-, zygomatic-, levator labii superioris/levator labii superioris alaeque nasi-, orbicularis oris-, depressor anguli oris-, depressor labii-, mentalis muscle. Furthermore, SEMG activity was recorded from the masseter and temporal muscle, chewing muscles which are innervated by the trigeminal motor nerve, to exclude measurements that involved unintentional teeth clenching while performing facial movements (data not presented). Electrode positions (Fig. 2) were established by means of topographic-anatomical landmarks as well as origin and insertion of the muscles (Fig. 2). After skin preparation (EPICONT, Marquette Hellige GmbH, Freiburg, Germany) the surface electrodes (Ag–AgCl discs, diameter of 4 mm, Zentner, Freiburg, Germany), coated with electrode cream (GE Medical Systems Inform. Techn., Freiburg, Germany), were attached to the skin by squares of flexible adhesive tape (Fixomull stretch, BSN medical GmbH, Hamburg, Germany). The SEMG was recorded monopolarly by means of a multi-channel EMG system (Biovision, Wehrheim, Germany) with reference electrodes at the ear lobes and a ground electrode at the mastoid. The −3 dB level frequency range of the EMG amplifiers was 10–700 Hz, the sampling rate was 3000/s and the resolution was 2.44 μV/bit.

2.3. SEMG analysis and quantification

In the first step of analysis EMG curves were evaluated visually. At least 40 intervals of 170 ms (512 samples) were marked within the uniform section of the EMG curves of each task and then quantified by power spectral analysis (Fast Fourier transformation; ATISApro, GJB Datentechnik GmbH, Langewiesen, Germany) (Scholle et al., 1992; Schumann et al., 1994). Movement artefacts (e.g. singular fluctuations of the base line) and the QRS complexes of the electrocardiogram were omitted (Anders et al., 1991) and were not involved in the computation. To characterize the mean EMG amplitude the square root of the total EMG power (10–1500 Hz) was calculated from the non-smoothed EMG periodograms. In this process the spectral power at the 50, 100, 150, 200 and 250 Hz position was excluded to reduce the influence of potential 50 Hz interferences on the mean EMG amplitude. The mean EMG amplitude values of the 40 EMG intervals per task were pooled to form representative values $x_{s,t,e}$ for all combinations: individual subjects, motor task t, electrode position e. Then data were normalized by the individual mean EMG amplitude level. In other words, each EMG amplitude value $x_{s,t,e}$ for a particular subject was divided by the median of all motor tasks and electrode positions of this subject $\tilde{x}_s$. To create more illustrative values for the reference purpose of this study, this quotient was multiplied by the EMG amplitude level of the sample that means, by the over all EMG amplitude median $\tilde{x}$ of

Table 1
Facial muscle regions: statistical differences between facial movements and between electrode positions.

Frontalis muscle (electrodes 1–4)	
Between facial movements (T24–T27)	$p < 0.001$
Right side–left side	n.s.
In medial–lateral orientation	$p < 0.001$
Orbicularis oculi muscle (electrodes 5–12)	
Between facial movements (T24–T27)	$p < 0.001$
Right side–left side	n.s.
In medial–lateral orientation	$p < 0.001$
Upper and lower eyelid (T24–T27)	n.s.
T24, T25 and T24, T27	$p < 0.05$
Levator labii superioris muscles (electrodes 13–18)	
Between facial movements (T1–T21)	$p < 0.001$
Right side–left side	n.s.
In superior–inferior orientation	$p < 0.001$
Zygomatic muscles (electrodes 19–24)	
Between facial movements (T1–T21)	$p < 0.001$
Right side–left side	n.s.
In superior - inferior orientation	$p < 0.001$
Orbicularis oris muscle (electrodes 25–32)	
Between facial movements (T1–T21)	$p < 0.001$
Right side–left side	n.s.
In medial–lateral orientation	$p < 0.05$
Pars superior and inferior	$p < 0.001$
Depressor anguli oris, depressor labii, mentalis (electrodes 33–44)	
Facial movements (T1–T21)	$p < 0.001$
Right side–left side	n.s.
In medial–lateral orientation	$p < 0.001$
In superior–inferior orientation	$p < 0.01$

Multivariate analysis of variance (ANOVA, repeated measures) to demonstrate differences of the mean EMG amplitude between the facial movements as well as superior and inferior, medial and lateral oriented electrode positions, and between the right and the left side of the face (n.s., $p > 0.05$). The electrode positions named in parentheses were arranged in statistical models of the ANOVA, and correspond with Fig. 2. Facial movements T1–T29 see Section 2.

all individuals, tasks and electrodes:

$$x'_{s,t,e} = \frac{x_{s,t,e}}{\tilde{x}_s} \cdot \tilde{x}$$

The normalized mean EMG amplitude values $x'_{s,t,e}$ were used to calculate median and quartiles and these are presented in the EMG profiles (box plots) for each of the motor tasks.

2.4. Statistics

The mean EMG amplitudes were normal-distributed at all electrode positions and for all motor tasks within the sample (Kolmogorov–Smirnov Procedure, SPSS®). Nevertheless, because upper quartiles were frequently higher than the lowers, a skewness of the distribution of the mean EMG amplitudes was indicated. For this reason nonparametric tests were preferred. Statistical differences between the 48 electrode positions were examined by the Friedman test (SPSS®), a rank-order analysis of variance for multiple related samples. Differences between the EMG values of two electrode positions were proved by the Wilcoxon test (SPSS®) for related samples. The Bonferroni corrections ($p' = p/n$) was applied, if the Wilcoxon test was used to address a multiple statistical question. Moreover, multivariate analysis of variance (ANOVA, repeated measures, SPSS®) was used to prove differences between the facial movements, superior and inferior, medial and lateral measurement points and between the right and the left side of the face (Table 1).

3. Results

The SEMG profiles (Figs. 3 and 4), representing the normalized mean EMG amplitudes, characterize the different facial muscle activation and elucidate muscle coordination patterns with respect to the facial movements (examples in Fig. 1). In Fig. 3 the SEMG profiles of six motor tasks (pressing the lips together (T7), smiling (T9), depressing the lower lip (T10), pursing lips (T14), wrinkling the nose (T21), closing the eyelids forcefully (T26)) are presented because these movements in particular (1) caused distinctly different activation patterns of the facial muscles; (2) demonstrated considerable increases in EMG activity in all the registered facial muscles; and (3) these motor tasks were well understood, easy, and reliably performed by the subjects. In Fig. 4 the SEMG profile of voluntarily right-sided smiling (T22) was demonstrated to give an example of asymmetrical facial muscle activation.

The base line of the normalized mean EMG amplitude of all electrode positions was 11 μV with a mean standard deviation of 4 μV. All performed facial movements caused significant increases in the EMG activity in comparison to the base line in all measurement points of the facial muscles (Wilcoxon test at 48 electrode positions: Bonferroni corrected, two-tailed $p < 0.048$). For each of the motor tasks tested, a statistically significant difference was proved between the mean EMG amplitudes of all 48 electrode positions (Friedman test: $p < 0.001$). Within topographically differentiated facial muscle regions significant differences were proved by multivariate analysis of variance (ANOVA, repeated measures) between the facial movements as well as superior and inferior and between medial and lateral measurement points (Table 1). The mean EMG amplitude between right and left localized facial muscles was not systematically different (ANOVA, $p > 0.05$, Table 1). Nevertheless, individual side-differences of facial movements were observed during the examination and found in the EMG data.

For reference purposes Table 2 gives a quantitative overview about facial muscle activation during the performed side-symmetrical motor tasks. These EMG values do not demonstrate means or medians of the sample but represent lower critical values of the EMG increase: the lowest values of the normalized EMG amplitude which were ascertained in 27 of 30 healthy subjects, i.e. in 90% of subjects, regardless whether recorded from the right or the left side of the face. With other words, lower EMG values than the data, displayed in Table 2, were only found in three subjects. In Fig. 3, these lower critical values are located between the lower quartiles and the lower fences and are marked by half bars. Moreover, accentuated values in Table 2 indicate which motor tasks caused a particularly high EMG increase for particular muscle regions.

For example, pursing lips (T14) evoked a strong activation of the orbicularis oris muscles. This muscle was also distinctly activated while pressing the lips together (T7), blowing out the cheeks (T15) and exhaling forcefully with moderate closed lips (T19), especially the inferior part during depressing the lower lip (T10 and T13), whistling (T17) and opening the lips as wide as possible (T20). During T7, T14, T15, T17 and T19 the EMG activity was higher laterally than medially. During T10 and T13 a reverse relation was found. The difference between lateral and medial electrodes of the orbicularis oris muscle was significant (Table 1, ANOVA, $p < 0.05$). The mentalis, depressor labii and in part the depressor anguli oris muscles were highly activated while depressing the lower lip (T10 and T13), pursing lips (T14) and opening the lips (T20). In the region of the depressor anguli oris, the depressor labii and the mentalis muscles, significant differences were found between lateral and medial, as well as inferior and superior electrode positions (Table 1, ANOVA, $p < 0.01$). The highest EMG activity of the zygomatic muscle appeared during smiling (T9), and for the levator labii muscle, while wrinkling the nose (T21). There were significant differences along the inferior–superior direction in both muscle regions (Table 1, ANOVA, $p < 0.001$). The orbicularis oculi and the frontalis muscles were strongly activated if the eyelids were closed forcefully (T26). Although more weakly, a distinctly increased EMG activity of the

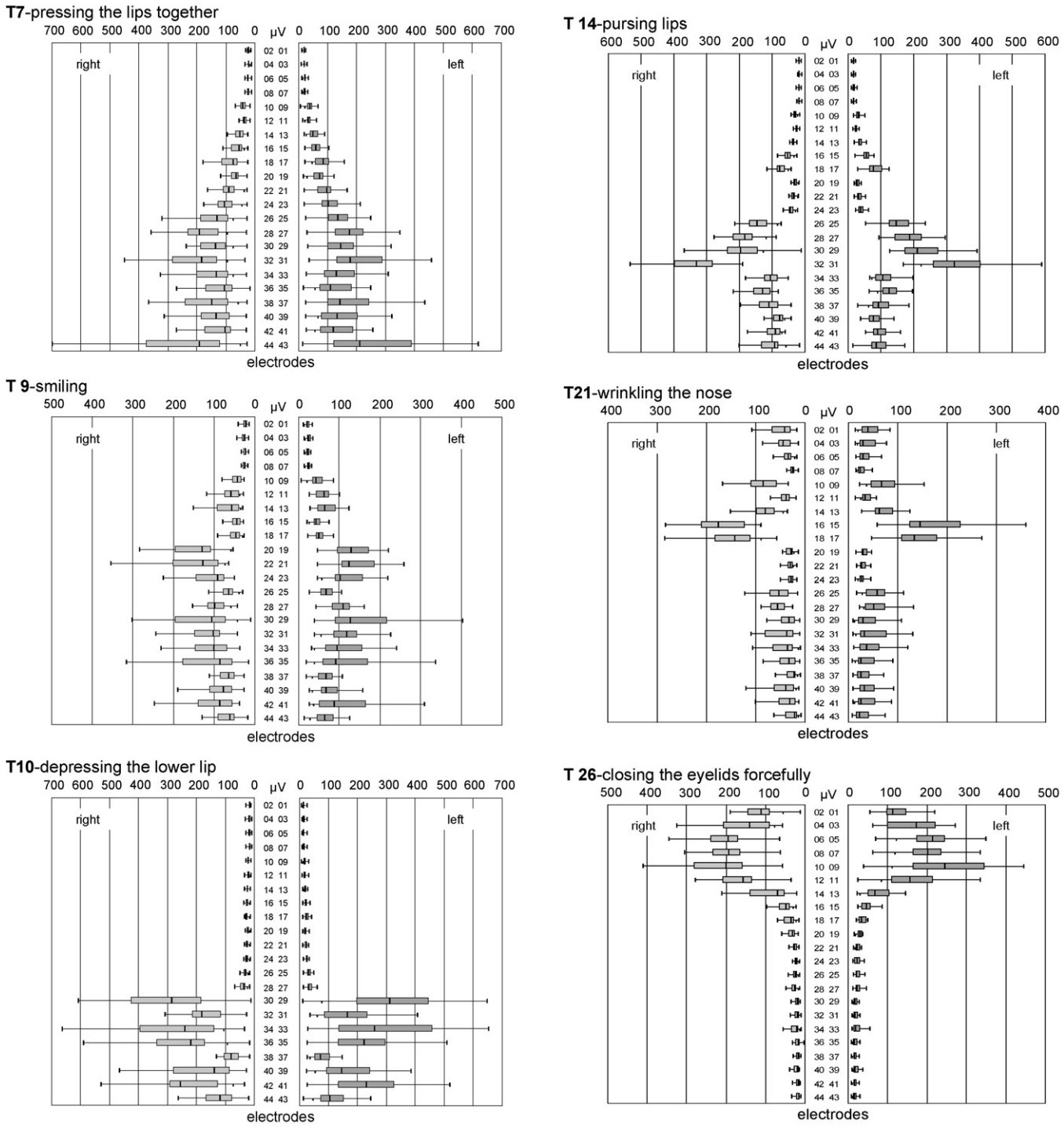

Fig. 3. SEMG profiles of the facial movements displayed in Fig. 1. Box plots demonstrate lower (LQ) and upper quartiles (UQ), median, lower and upper fences of the normalized EMG amplitude values (in μV; with lower fence ≥ LQ − 1.5 × interquartile range (IQR) and upper fence ≤ UQ + 1.5 × IQR). Outliers occurred only above the upper fences and were not presented. The lower fences are in accordance with the lowest values. The half bars between lower quartiles and lower fences correspond with the lower critical EMG values listed in Table 2 and were drawn either on the left side (if left EMG value < right value) or on the right side (if right < left).

orbicularis oculi muscles (Table 2) was recorded during smiling (T9), opening the lips as wide as possible while the jaw was closed (T20), and wrinkling the nose (T21). SEMG activities recorded from medial and lateral electrode positions of the orbicularis oculi and the frontalis muscles were significantly different (Table 1, ANOVA, $p < 0.001$). The difference between the inferior and the superior part of the orbicularis oculi muscles was significant while raising the eyebrows up (T24), contracting the eyebrows (T25) and squinting the eyes (T27) (Table 1, ANOVA, $p < 0.05$), but not while closing the eyelids forcefully (T26).

4. Discussion

This presents the first highly detailed bilateral symmetric electrode surface EMG study of the facial muscles, and it is the first to include both the oral and ocular regions. The study has shown

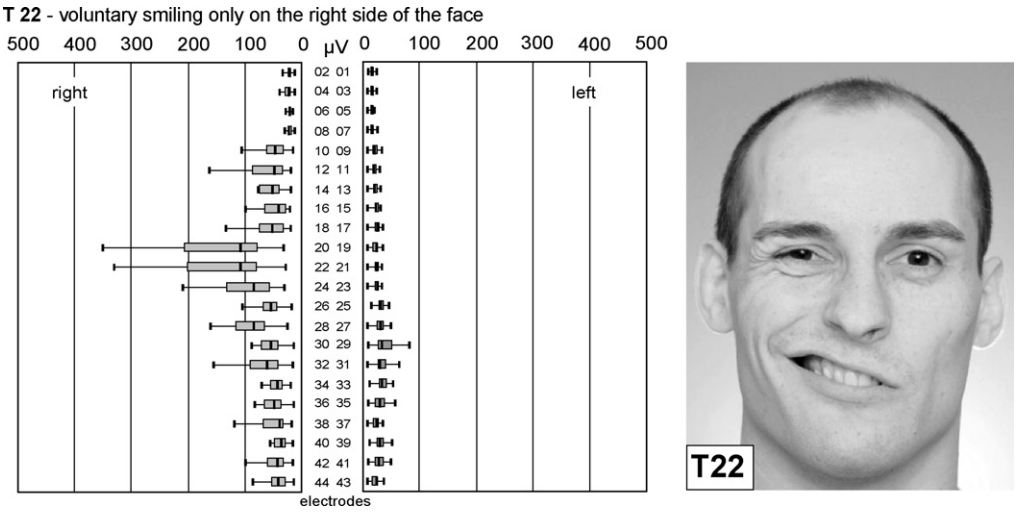

Fig. 4. The SEMG profile during voluntary smiling only on the right side of the face (T22) demonstrates an asymmetrical facial muscle activation (box plots see Fig. 3).

that all the performed facial movements evoke a differentiated activation of the facial muscles. The EMG activity patterns, as demonstrated by SEMG profiles, are objectively quantified correlates of muscle coordination patterns evoked by the performing of different motor tasks. For each task the EMG activity significantly differed between the 48 measurement points, i.e. a significant EMG discrimination between the muscles was possible. Moreover, we could show that almost all functionally relevant facial movements are based on a specific interplay of several facial muscles. To reveal the relevance of the findings the results were compared with other facial muscle examinations accomplished with invasive intramuscular fine wire electrodes (Isley and Basmajian, 1973; O'Dwyer et al., 1981) and with surface electrodes (Cacou et al., 1996; Lapatki et al., 2003).

The inferior and superior orbicularis oris muscle, the sphincter muscle of the mouth, was activated during several facial movements. A strong and selective increase of EMG activity was found while pursing lips (T14) and blowing out the cheeks (T15). This was consistent with the results of Isley and Basmajian (1973), O'Dwyer et al. (1981) and Cacou et al. (1996). Pressing lips together (T7), and exhaling forcefully with moderate closed lips (T19) also evoke a distinct activation of the orbicularis oris muscle (Fig. 3, Table 2). In comparison between the right and the left side, the EMG activities were almost the same, which is a precondition of a symmetrical lip closure. Furthermore, the orbicularis oris muscle showed significantly different EMG activity between medial and lateral electrode positions, partly in reverse relations. In the inferior orbicularis oris region, such a functional muscle partitioning was already demonstrated by Abbs et al. (1984). The motor endplates were found evenly spread over the orbicularis oris muscle (Happak et al., 1997) enabling the focus of activation to shift between more lateral or more medial located motor units. Thus, the force vector is adjusted to facial movement.

During depressing the lower lip (T10, T13) high EMG activity was found in depressor labii muscles, which pull the lower lip downwards. But there was also higher activity in the mentalis and in the inferior orbicularis oris muscle, although the muscle force directions do not support a lip depression. The measured activity of the inferior orbicularis oris and the mentalis muscles represent co-activation, probably stabilizing of the soft tissue. This assumption is additionally supported by the anatomical finding that the muscle fibres of the depressor labii muscles are interdigitated with that of the orbicularis oris muscle (Blair and Smith, 1986).

In contrast to the observations of the aforementioned authors a selective contraction of the depressor anguli oris muscle is hardly possible considering the results of the present study (T8). We observed that most of the subjects had difficulties pulling the corners of the mouth voluntarily downwards (T8). Neighbouring muscles in this region were recruited for compensation. While protruding and everting the lower lip (T11), typically the depressor anguli oris was co-activated with, e.g. the mentalis muscle. Also pursing lips (T14) led to high EMG amplitudes, not only in the orbicularis oris muscle, but also in the depressor anguli oris muscle, which is considered to have a stabilizing function for the modiolus (Nairn, 1975; O'Dwyer et al., 1981). In accordance, Isley and Basmajian (1973) also found activation in the depressor anguli oris muscle during this facial movement.

The zygomatic muscles were activated most intensely during voluntary smiling (T9), which involve pulling the corners of the mouth up and back, as was also demonstrated during broad laughing, or broad smiling (Isley and Basmajian, 1973; O'Dwyer et al., 1981). But activity in the orbicularis oris, the mentalis, and the depressor labii muscles was always present. The levator labii superioris (-alaeque nasi) muscles could be considered unique because most subjects were easily able to activate these muscles in isolation from other facial muscles with the appropriate facial movement of wrinkling the nose (T21). The levator anguli oris muscles might be also active during wrinkling the nose, but because they are located in a deeper tissue layer their influence to the SEMG was low. The finding was equal to those of O'Dwyer et al. (1981) and Lapatki et al. (2003) investigations.

The subjects performed the facial movements in the ocular and forehead regions without any difficulties (closing the eyelids (T28, T29), raising eyebrows up and wrinkling the forehead (T24), contracting the eyebrows (T25), squinting the eyes (T27)). Nevertheless, the mean EMG amplitudes of the orbicularis oculi and the frontalis muscles in general were lower than that of the perioral muscles during test movements of the oral region. Only forced closure of the eyelids (T26) produced EMG activities comparable to those of sphincter and dilator muscles of the mouth (Table 2). The higher EMG activities in the oral region are consistent with force measures in the oral and ocular region. The maximum forces during lip closure were distinctly higher than during the closure of eyelids (Jacobs, 1954; Jung et al., 2003; Trotman et al., 2007). This is not surprising if one considers, how the orbicularis oris, in comparison to the orbicularis oculi muscle, is strained, e.g., while opening the jaw with closed lips during chewing.

The presented investigation showed similar EMG activity patterns of perioral facial muscles as revealed by other authors who used fine wire electrodes or bipolar surface electrodes.

Table 2
Lower critical values of the mean EMG amplitude during facial movements.

	Frontalis muscle		Superior orbicularis oculi muscles		Inferior orbicularis oculi muscles		Levator labii sup. muscles (-alaeque nasi)			Zygomatic muscles			Orbicularis oris muscles pars superior		Orbicularis oris muscles pars inferior		Mentalis muscles		Depressor labii muscles		Depressor anguli oris muscles	
epos	med	lat	med	lat	med	lat	sup	med	inf	sup	med	inf	med	lat	med	lat	sup	inf	sup	inf	sup	inf
left	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	39	35	41	37	43
right	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	40	36	42	38	44
T1	12	11	11	11	14	16	16	17	16	16	17	18	18	19	28	25	25	22	24	23	17	16
T2	12	12	12	12	15	15	16	15	16	17	18	19	18	21	32	27	30	23	24	28	16	17
T3	11	11	11	11	15	15	15	16	16	16	18	20	17	19	28	25	31	24	23	29	18	18
T4	10	10	10	10	13	13	13	13	15	15	16	16	17	17	42	25	34	27	35	35	19	20
T5	11	11	10	11	15	13	15	18	21	13	16	18	27	32	37	52	27	23	28	23	22	21
T6	11	11	11	11	16	15	18	21	23	15	17	19	28	38	41	**75**	30	24	29	26	28	24
T7	14	14	15	14	22	21	27	36	46	29	35	42	**74**	**93**	**74**	**94**	**73**	67	58	56	55	46
T8	15	15	14	14	17	18	19	19	21	17	19	20	24	29	35	38	53	46	44	45	40	51
T9	15	15	15	16	22	35	33	27	29	57*	**72***	58*	38	57	42	55	39	33	39	37	33	28
T10	10	10	10	10	12	13	15	13	13	14	15	16	21	22	**78**	62	**102***	55	**90**	**71**	39	47
T11	14	13	14	14	18	16	21	30	33	16	17	21	61	67	43	54	62	54	50	51	53	63*
T12	10	11	12	10	22	18	25	46	44	15	16	14	29	32	19	21	19	18	18	17	12	13
T13	12	12	14	14	20	21	27	31	32	21	22	23	44	53	**128***	**93**	**85**	62	**113***	**107***	49	56
T14	13	12	14	13	21	15	23	33	50	18	21	27	**83***	**117***	**126**	**224***	**73**	59	**91**	69	62*	56
T15	14	14	15	14	19	17	23	30	38	22	25	25	**73**	**89**	**92**	**100**	**71**	68*	58	54	38	36
T16	12	12	12	12	14	14	16	21	25	14	15	17	30	34	46	41	60	45	37	36	23	24
T17	10	10	11	10	15	13	17	23	28	16	18	19	44	63	**75**	**121**	47	37	56	44	42	29
T18	11	10	11	11	15	13	15	20	25	13	15	17	29	39	37	32	58	61	43	42	27	31
T19	11	10	11	11	18	15	20	26	36	17	18	23	51	**75**	68	**97**	42	36	45	39	31	31
T20	18	21	17	17	27	32	34	35	40	32	29	27	38	46	**87**	**88**	**70**	47	**88**	**93**	39	40
T21	20	18	20	16	38	26	43*	**89***	**88***	22	23	19	28	31	13	16	13	16	13	13	14	13
T24	29	26	12	12	8	8	7	8	8	7	8	7	7	7	7	7	8	8	7	8	7	7
T25	32	33	21	13	9	8	7	11	10	6	6	6	7	7	7	7	9	8	7	6	7	6
T26	53*	**75***	**123***	**118***	**111***	**84***	37	28	21	20	17	14	16	16	11	12	51	37	61	39	26	30
T27	15	17	18	17	21	24	14	13	12	10	10	8	10	10	10	9	13	11	10	9	9	8

The table clarifies which side-symmetrical motor task (T1–T21, T24–T27 see Section 2) has to be performed to cause a distinct activation in a certain facial muscle. The demonstrated SEMG values (normalized mean amplitude in μV) represent the lowest values which were ascertained in 27 of 30 healthy subjects, i.e. in 90% of the examined subjects, regardless whether recorded from the right or the left side of the face. With other words, lower EMG values were only found in three subjects. Mean EMG amplitudes ≥70 μV were accentuated by bold numeric characters. The three highest EMG amplitude values of each muscle (electrode position) were underlined, the maximum value additionally marked by an asterisk. Electrode positions (epos: inf, inferior; sup, superior; med, medial; lat, lateral) of the left and right side of the face are stated in Fig. 2.

Nonetheless, this study was intended to be more comprehensive related to a potential clinical utilization. The monopolar multi-electrode application allowed comparisons between facial muscles and because of the higher spatial resolution also determination of intramuscular differences (Schumann et al., 1994, Kleine et al., 2000; Schumann et al., 2002) was possible. Therefore the number of measurement points was distinctly increased in comparison to previous needle-EMG or SEMG examinations (Isley and Basmajian, 1973; O'Dwyer et al., 1981; Abbs et al., 1984; Cacou et al., 1996; Lapatki et al., 2003). With respect to the number of measurement points, the monopolar SEMG technique requires half as much electrodes as a bipolar technique. Monopolar recordings represent EMG sources directly below the electrode; bipolar recordings represent myoelectrical activity between the both corresponding electrodes (Basmajian and De Luca, 1985). A monopolar registration reflects superficial and deeper EMG sources; a bipolar technique reflects only superficial sources (Scholle et al., 2001). On the other hand, the monopolar EMG is more susceptible to artefacts and crosstalk. Although crosstalk cannot be avoided totally, it is unlikely that the EMG profiles were fundamentally changed. The EMG amplitudes decrease with the square of distance (Williamson and Kaufman, 1990). The EMGs of the masseter and the temporal muscles, the potentially biggest crosstalk sources, were recorded simultaneously and the mean EMG amplitudes were in the range of the few activated facial muscles. Moreover, in the presented study crosstalk ratios between neighbouring facial muscles were similar to the results of Lapatki et al. (2003).

In clinical applications, it is necessary to have a fast and easy to handle diagnostic tool for the examination of facial paresis. The application of 48 surface electrodes is time consuming, but it was a necessary step to get an overview of the diversity of facial muscles activation patterns in response to facial movements and to decide which electrode positions are required for a comprehensive examination in facial palsy. Statistically significant differences of the mean EMG amplitude were proved not only between the facial test movements, but also between inferior and superior, and medial and lateral measurement points of the same muscle region (Table 1). Only in the orbicularis oculi muscle differences between superior and inferior electrodes were not so clear and probably depended on the performed movement (Table 1, T24–T27). The orbicularis oculi muscle can be considered a true sphincter muscle with a circular shaped muscle plate: it contracts, therefore, potentially as a whole. In contrast, the orbicularis oris muscle is morphological not a closed circular system and therefore different parts contract more or less independently (Wohlert and Goffman, 1994). If further examinations confirm that the SEMG activities of the upper and lower eyelids are truly redundant, the electrode number could be reduced. Moreover, there were electrode positions and accordingly muscle regions, where relatively low SEMG activities were registered (Table 2): the inferior electrodes above the mentalis muscles (electrodes 39, 40), both above the depressor anguli oris muscles (37, 38, 43, 44), the inferior and superior above the zygomatic muscles (19, 20, 23, 24), and the medial above the frontalis muscle (1, 2). Nonetheless, because of the interindividual variability, it is hard to draw conclusions about the necessity of those electrode positions, especially about a potentially clinical relevance without further examinations.

For a better intermuscular differentiation referring to clinical examinations of facial paresis it was decided to evaluate both ocular and oral facial regions simultaneously and to perform a symmetrical SEMG registration from both sides of the face. This has two reasons: (1) in healthy humans oral and ocular sphincter systems are functionally independent, but aberrant facial nerve regeneration in patients can lead to synkinesis of the oral and ocular muscles (Stennert, 1982) and (2) facial nerve paresis is predominantly restricted to one side of the face, therefore comparisons between the not involved side and palsied side can be made.

The approach of this study was to investigate a wide diversity of facial movements including the ones performed by facial grading systems (Stennert et al., 1977; Murty et al., 1994; Ross et al., 1996; Chee and Nedzelski, 2000) to determine, firstly, which one is able to activate specific facial muscles and, secondly, which is more easily accomplished by the subjects. The ability to realize a distinct facial movement was different between subjects which led to an unavoidable increase of the inter- and intra-individual variability in the associated SEMG patterns. The test-persons could try to perform the facial movements repeatedly, and they were corrected by the examiner. But a longer training seemed to be not practicable in future clinical applications. Our sample contained 30 subjects who performed 29 different facial movements. To characterize this dataset, median, upper, and lower quartiles of the normalized mean EMG amplitude were demonstrated in movement-related SEMG profiles (box plots, Fig. 3). Nevertheless, these statistical characteristics are hardly helpful for the evaluation of a single individual. Therefore, lower critical EMG values were ascertained which were reached or exceeded by the majority of the subjects during the performed motor tasks. Table 2 displayed the lowest muscle specific SEMG increase measured, on the right or left side, in 27 of the 30 healthy subjects. That means, a lower EMG increase was only found in three subjects (further illustration in Fig. 3). Table 2 should help to identify the most applicable facial movement for clinical diagnostics. To monitor the course of the disease it is crucial that the intra-individual variability is as low as possible. Thus consistent electrode placement and easily performed motor tasks are absolutely necessary for retest reliability. First re-examinations have shown the retest reliability to be high (data not shown). However further research is required to confirm a superior reliability of the method.

This study demonstrated objective and statistically representative SEMG patterns of symmetric facial muscle functions in healthy subjects. The presented results are highly relevant for better planning of facial movement restoration in patients with permanent facial paresis. Standard muscle transposition techniques, such as temporal or masseter muscle transpositions only allow the reconstruction of one or two directions of tension. Correspondingly, the functional results are limited (Guntinas-Lichius and Sittel, 2004). The presented results of this study clearly show that optimal restoration of a distinct movement needs more than the reconstruction of two force vectors. Moreover, changes in bilateral symmetric electrode measured SEMG patterns due to facial paresis, can be objectified and compared to this reference data. Such an investigation is planned as the next step. For clinical routine, an easy and reliable objective method to evaluate a facial palsy still is missing. We suppose that the presented facial surface EMG technique can take over this role in near future.

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