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Research Paper
Imaging

Three-dimensional assessment of restored smiling mobility after reanimation of unilateral facial palsy by triple innervation technique

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Abstract. The aim of this study was to assess surgically restored facial mobility using an optical 3D instrument. Eleven patients (age range 42–76 years) with unilateral facial palsy, treated by triple innervation procedure (masseteric and partial hypoglossal reinnervation, plus double cross-face facial grafting), performed five facial animations: rest position, smiling by contracting the healthy side, clenching the teeth, and pushing the tongue against the lower incisors and Mona Lisa smiling. These were recorded by stereophotogrammetry. Sixty healthy subjects were also recorded. The 3D reconstruction of each facial expression was registered onto the rest position scan, and the root mean square (RMS) point-to-point distance between the two 3D surfaces was calculated automatically for the facial thirds. RMS values on the rehabilitated hemiface were 74.8% (upper third), 46.6% (middle third), and 54.1% (lower third) of those recorded in healthy subjects. RMS values were higher in the middle and lower thirds than in the upper third, and during smile provided by masseteric stimulus ($P < 0.05$). The rehabilitated hemiface differed more from healthy subject values than the healthy hemiface did ($P < 0.05$). On average, patients were more asymmetric than healthy subjects ($P = 0.004$). The proposed method is non-invasive and non-contact, and it can quantify localized facial movements after surgical procedures.

Key words: facial reanimation; triple innervation technique; facial palsy; stereophotogrammetry; facial thirds.

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Facial palsy represents a widespread pathological condition, with important consequences from a clinical point of view. In addition, the loss of mimicry and the facial deformation and asymmetry deriving from the palsy may have a severe impact on the patient's social quality of life, with a decrease in inter-personal interaction and consequent isolation[1–3]. Over time, several surgical procedures have been developed to partially restore facial mimicry. For short-term palsy, the most popular facial reanimation techniques provide novel stimuli through the reinnervation of the damaged facial nerve by other nerves, mainly the hypoglossal and masseteric nerves[3,4]. In addition, one or more branches of the healthy (contralateral) facial nerve are often used to evoke an emotional activation, through cross-face grafts via the sural nerve[5]. After these procedures, patients can recreate a smiling expression by clenching the teeth (masseteric stimulus), pushing the tongue against the lower incisors (hypoglossal stimulus), and evoking a smile on the healthy side (cross-face stimulus). All of these neural stimuli may be provided together using the recently devised triple innervation technique[6].

The clinical assessment of patients affected by facial palsy and treated through facial reanimation procedures is crucial during follow-up. Several classifications and scales have been developed to evaluate mimicry, the most commonly used being the House–Brackman scale and the Facial Nerve Grading System 2.0[7–9]. These methods are affected by important limitations: the assessments are mostly qualitative, usually based on personal observations, and are therefore subjective and potentially not repeatable[10]. A quantitative method for assessing facial mimicry would be of great importance to assess not only the residual function in patients affected by facial palsy, but also the restored mimicry in treated patients, and ultimately to measure the percentage of success of the facial reanimation[11,12].

The introduction of three-dimensional (3D) optical image acquisition systems has allowed researchers to perform quantitative analysis of the face in different clinical and surgical contexts, ranging from aesthetic surgery[13,14] to the early diagnosis of genetic syndromes[15,16]. The main advantages are represented by the non-invasiveness of the acquisitions, the lack of biological risks, and the opportunity to improve traditional measurements (including distances and angles) with surface areas, volumes, and point-to-point linear distances between two registered digital models of the face. The latter measurement is based on the registration of a 3D surface onto a reference one and is automatically extracted, together with a chromatic map of facial areas affected by variations between the two models[17]. This specific method of assessing movement may represent a useful tool for quantifying the variations in different facial areas according to the rest position.

3D analysis has already been applied to patients affected by facial palsy, usually through the assessment of landmark displacement during different movements[1,18]. It appears that only one study has assessed the movements of patients affected by facial palsy and treated through masseteric and hypoglossal neurorrhaphy and cross-face grafts, applying a contactless 3D surface analysis[19]. This preliminary study first analyzed the different movements evoked by each stimulus on the healthy and treated/ paralyzed hemiface. However, it did not examine movements in different facial regions and, more importantly, did not perform a comparison with an adequate control group to assess the success of the facial reanimation procedure, i.e. the percentage of restored mobility in comparison with the normal standard.

The aim of this study was to compare recorded facial movements during smiling expression between 11 patients affected by unilateral facial palsy who were treated by triple facial reanimation technique (masseteric and hypoglossal reinnervation, and cross-face grafts) and 60 healthy subjects. The main aims were to compare the movements recorded on the rehabilitated and healthy facial sides and according to the facial thirds of the patients, and to quantify differences in facial mobility between patients and healthy subjects.

This study provided quantitative information regarding the success of the facial reanimation procedures, thus confirming the importance of 3D acquisition systems to assess the performance of facial mimicry.

Materials and methods

Recruitment of subjects and 3D acquisition

Eleven consecutive patients aged between 42 and 76 years (six male, five female; mean age 58.0 ± 11.2 years) with unilateral short-term facial palsy were recruited for the study. The palsy was a consequence of the surgical removal of an acoustic neurinoma (nine patients), a traumatic injury of the facial nerve (one patient), and a neoformation of the petrous portion of the temporal bone (one patient). All patients signed an informed consent agreement, in accordance with the local university ethics committee requirements (26.03.14; n° 92/14) and the guidelines of the Declaration of Helsinki.

Between September 2015 and March 2017, the patients underwent a triple innervation procedure, consisting of the following[6]: end-to-end masseteric to temporofacial branch neurorrhaphy, side-to-end hypoglossus to cervicofacial branch neurorrhaphy (30% of hypoglossus axon coaptation), and two cross-face sural nerve grafts (end-to-end at the proximal coaptation and end-to-side at the distal one). All of the procedures were performed in a single intervention. On average, the interval between the onset of facial palsy and the operation was 11 ± 3 months. Fig. 1 shows the pre- and postoperative characteristics of one of the patients; in addition, a video taken of the same patient is available in the Supplementary Material online (Video S1).

At approximately 2 years (average 24 ± 10 months) after the surgical intervention (between February 2017 and April 2018), all patients underwent 3D facial photography by stereophotogrammetry (VECTRA 3D; Canfield Scientific, Inc., Fairfield, NJ, USA). The instrument comprises three pods, each with one high-resolution black-and-white camera and one colour camera. The cameras image the facial soft tissues from different points of view with a single shot lasting less than 2 ms, and a digital 3D model is provided. The entire scanning procedure is not invasive and is without biological risks[17,19,20]. Each patient performed five acquisitions in different facial animations: rest (neutral) position, smiling by contracting the healthy side (cross-face stimulus), clenching the teeth (masseteric stimulus), pushing the tongue against the lower incisors (hypoglossal stimulus), and corner-of-the-mouth smiling (Mona Lisa smile)[21]. For the last one, reported to be the most frequent in the general population[21], the patients were requested to use all the available strategies and stimuli to produce the most natural expression. The patients were instructed about the requested smile expression and practiced before the acquisitions. The smiling animations were recorded at maximum displacement and repeated if necessary.

A control group of 60 healthy subjects, aged between 40 and 82 years (30 male, 30 female; mean age 54.4 ± 10.5 years), was recruited. Exclusion criteria applied to the control group were facial deformity, neurological impairment, and recent or

Fig. 1. (a) Preoperative smile, and (b) postoperative smile in a patient treated by triple facial reanimation procedure.

previous traumatic injury affecting the face. All healthy subjects, as well as all 11 patients, were Caucasian. After signing the informed consent agreement, they underwent the same stereophotogrammetric procedure and were imaged in rest (neutral) position and Mona Lisa smiling. The healthy subjects were divided into three age groups, separately for sex: 40–49 years, 50–59 years, ≥60 years.

3D facial elaboration

3D facial models were further elaborated using VAM software (VECTRA Analysis Module; Canfield Scientific, Inc., Fairfield, NJ, USA). For each 3D model obtained from the patients and healthy subjects and for each side (right, left; paralyzed, rehabilitated), a facial area of interest (FAI) was automatically selected according to the surface encompassed by trichion, nasale, pronasale, columella, stomion, sublabiale, gnathion, frontotemporalis, zygion, tragion, and gonion (Fig. 2)[22].

Each FAI was then automatically registered onto the rest position FAI according to the least point-to-point distance between the two 3D facial models. For the patient and control groups, four (cross-face, masseteric, hypoglossal stimulus, and Mona Lisa smile) and one (Mona Lisa smile) registrations onto the neutral position were performed, respectively. After registration of the two FAIs, the root mean square (RMS) point-to-point distance between the 3D surfaces was calculated automatically. This measurement is the square root of the arithmetic mean of the squared point-to-point distances between the two models (Fig. 3). To determine regional movement differences, RMS values were calculated for each facial third, defined according to the trigeminal territory distribution (Fig. 2)[22].

Statistical analysis

The repeatability of the smile animations was tested in a subgroup of subjects, and the intra-class correlation coefficients (ICC) and absolute and relative technical errors of measurement (TEM and rTEM) were assessed[23]. The entire procedure from selection of the FAI to RMS calculation was repeated for 20 superimpositions by the same and another operator to verify intra-operator and inter-operator error.

The percentage of facial movement (displacement from the rest position expressed as the RMS) was obtained for the patients in comparison with the healthy subjects. An asymmetry index was calculated from the RMS values of each facial third as follows: $AI = |(1 - RMS_{\text{rehabilitated or paralyzed side}}/RMS_{\text{healthy side}})| \times 100$. Asymmetry index values closer to zero indicate a more symmetric patient face.

The comparison between patients and healthy subjects was performed only for the Mona Lisa smiling expression; this was done by calculating a *z*-score for each patient, as follows: *z*-score = (RMS − mean)/SD, where the RMS is

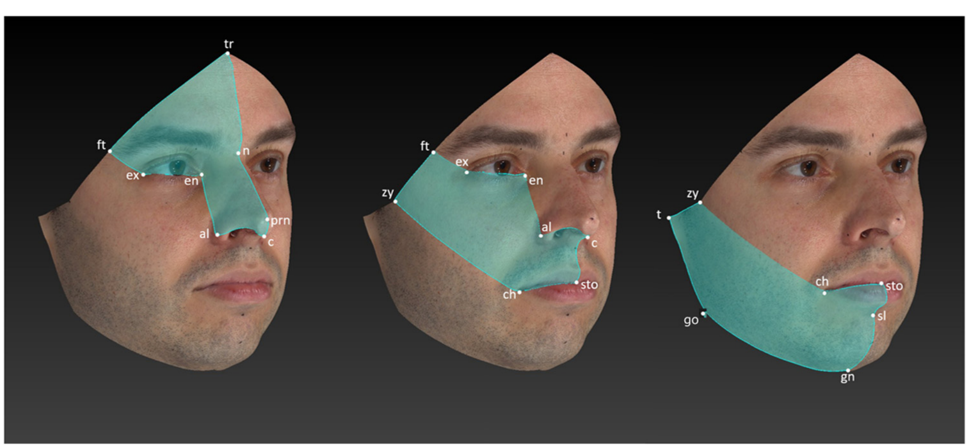

Fig. 2. Facial area of interest (FAI) selected as the surface included between landmarks trichion (tr), nasale (n), pronasale (prn), columella (c), stomion (st), sublabiale (sl), and gnathion (gn) on the midline, and frontotemporalis (ft), zygion (zy), tragion (t), and gonion (go) bilaterally. Each FAI was further divided into upper (trichion, nasion, pronasale, columella, alare (al), endocanthion (en), exocanthion (ex), frontotemporalis), middle (endocanthion, alare, columella, stomion, cheilion (ch), zygion, frontotemporalis, exocanthion), and lower facial thirds (stomion, sublabiale, gnathion, gonion, tragion, zygion, cheilion) defined according to the trigeminal territory distribution.

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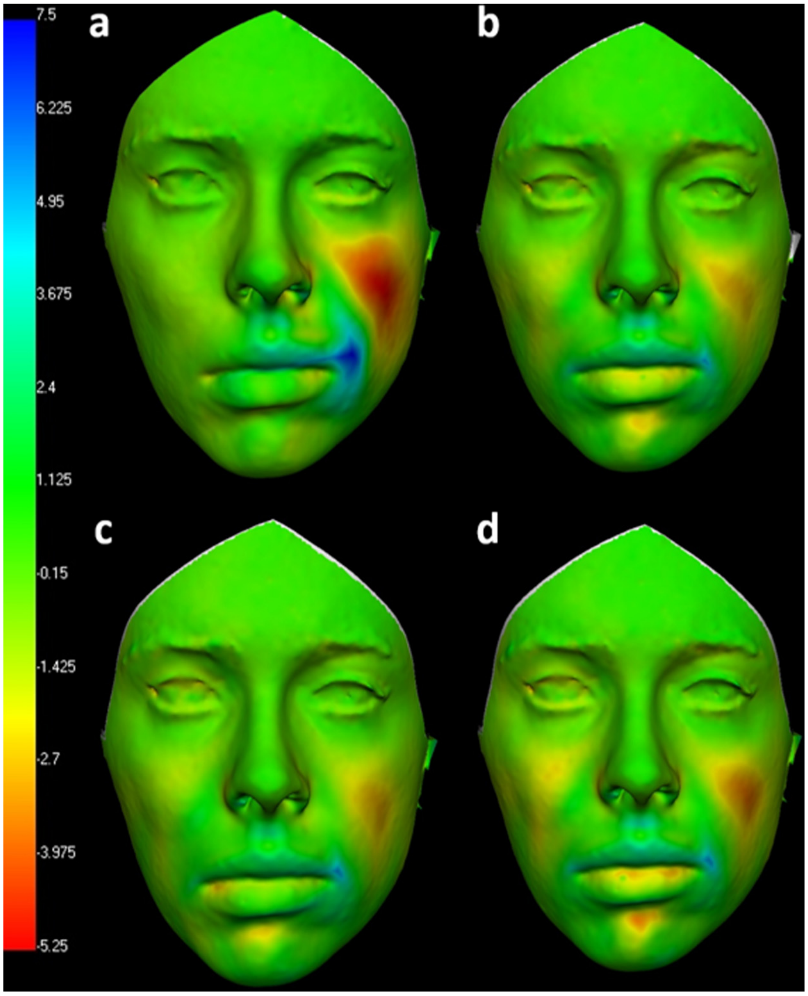

Fig. 3. Different results of 3D surface registration of each expression onto the rest position and calculation of the RMS point-to-point distance (the paralyzed hemiface is the right one): (a) cross-face; (b) masseteric stimulus; (c) hypoglossal stimulus; (d) Mona Lisa smile. The unchanged areas are shown in green; areas in other colours differ in comparison with the rest position. The RMS values, expressed in millimetres, are shown on the scale on the left (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the value calculated for each facial third in the patients, and the mean and standard deviation (SD) are computed in the same sex and age group of healthy subjects (right side). Smaller *z*-scores indicate patient values closer to the reference ones.

Normality and homoscedasticity of the RMS, *z*-score, and asymmetry index were assessed using the Levene test and Shapiro–Wilk test, respectively ($P < 0.01$). In the case of normal and homoscedastic data distributions, parametric statistical tests were applied. For the patient group, three-way analysis of variance (ANOVA) was used to analyze RMS values according to the side, type of stimulus, and facial third. Differences in *z*-scores according to the side and facial third were assessed by two-way ANOVA. Differences in asymmetry index according to group (patients/healthy subjects) and facial thirds were tested through two-way ANOVA. First-level interactions were calculated as well. The Tukey HSD (honestly significant difference) test was used as a post-hoc test in the case of differences according to facial third and/or stimuli. The partial eta-squared (ηp^2) according to Cohen was calculated to estimate the effects of the differences[24].

When the normality and homoscedasticity of RMS, *z*-score, or asymmetry index could not be confirmed, the same tests were applied to the natural logarithm or the square root of the same values. If data again did not show a normal and homoscedastic distribution, non-parametric tests were applied (Kruskal–Wallis). All statistical analyses were performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA); significance was set at 5%.

Results

The intra-individual variation in repeated smiles resulted in an ICC of 0.967, TEM of 0.13 mm, and rTEM of 8.7%. Intra- and inter-operator TEM and rTEM for the measurement protocol were 0.01 mm and 1.2%, and 0.03 mm and 3.3%, respectively.

Table 1 reports descriptive statistics for the RMS and asymmetry index. Natural logarithms of the RMS values and *z*-scores showed a normal and homoscedastic distribution ($P > 0.01$), but not asymmetry indices in any form ($P < 0.01$).

The RMS values for the rehabilitated hemiface were 74.8% (upper third), 46.6% (middle third), and 54.1% (lower third) of those measured in the healthy subjects (Table 1). Within the patient group, three-way ANOVA highlighted significant differences according to side, facial third, and stimulus ($P < 0.01$) (Table 2): in all of the cases, the eta-squared showed a high effect for each factor[24]. The post-hoc Tukey test revealed that RMS values were higher in the middle and lower facial thirds than in the upper third ($P < 0.05$). Regarding the stimuli, the masseteric one evoked a more pronounced facial movement than the others ($P < 0.05$).

A significant interaction was found between side and stimulus ($P = 0.01$, Fig. 4a) and between side and third ($P = 0.005$, Fig. 4b). However, their effects (eta-squared) were lower than those observed for the single factors (respectively low and medium according to Cohen)[24]. Passing from the rehabilitated to the healthy side, facial movements increased with each stimulus, with the largest ones observed for the masseteric stimulus. Regarding the facial thirds, the upper third yielded the lowest modifications. Facial excursions in the middle and the lower thirds were close on the rehabilitated side and increased on the healthy side, with the largest increment observed in the middle facial third.

Z-scores were significantly lower for the rehabilitated side (upper facial third, −0.5; middle, 1.2; lower, −1.0) than for the healthy side (respectively, 0.0, −0.2, and −0.2) ($P < 0.05$). No significant difference was found according to facial third ($P > 0.05$). The side × facial third interaction was negligible as well.

On average, the asymmetry index was higher in patients than in healthy subjects ($P = 0.004$). No statistically significant

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Table 1. RMS values and asymmetry indices for all stimuli in patients and healthy subjects; mean (SD) values.

Patients		Cross-face stimulus	Masseteric stimulus	Hypoglossal stimulus	Mona Lisa	Healthy subjects	Mona Lisa
Rehabilitated side (mm)	Upper third	0.37 (0.12)	0.60 (0.24)	0.57 (0.25)	0.48 (0.13)	Right side (mm)	0.61 (0.29)
	Middle third	0.51 (0.18)	1.22 (0.64)	0.92 (0.51)	0.77 (0.31)		1.57 (0.68)
	Lower third	0.57 (0.22)	1.08 (0.54)	0.92 (0.49)	0.69 (0.19)		1.19 (0.50)
Healthy side (mm)	Upper third	0.55 (0.22)	0.71 (0.31)	0.60 (0.24)	0.60 (0.13)	Left side (mm)	0.61 (0.28)
	Middle third	1.77 (0.66)	1.91 (0.90)	1.33 (0.66)	1.37 (0.36)		1.61 (0.73)
	Lower third	1.20 (0.53)	1.41 (0.69)	1.11 (0.57)	1.04 (0.37)		1.21 (0.51)
Asymmetry index (%)	Upper third	31.2 (15.2)	25.4 (17.6)	24.6 (22.4)	25.0 (19.0)	Asymmetry index (%)	13.4 (12.4)
	Middle third	69.8 (10.2)	47.8 (36.9)	53.0 (37.8)	43.5 (17.0)		13.0 (12.1)
	Lower third	50.8 (17.9)	50.0 (33.6)	42.1 (29.5)	32.7 (19.2)		13.6 (10.0)

RMS, root mean square; SD, standard deviation.

Table 2. Results of ANOVA test applied to RMS values and *z*-scores.

RMS values	Three-way ANOVA			
Factors	df	*F*	*P*-value	Partial eta-squared
Side	1	55.030	<0.01	0.183
Third	2	51.622	<0.01	0.296
Stimulus	3	10.671	<0.01	0.115
Side × third	2	5.438	0.005	0.042
Side × stimulus	3	5.696	0.01	0.065
Third × stimulus	6	0.457	0.84	0.011
z-scores	Two-way ANOVA			
Factors	df	*F*	*P*-value	Partial eta-squared
Side	1	22.972	<0.01	0.277
Third	2	2.768	0.071	0.084
Side × third	2	0.588	0.559	0.019

ANOVA, analysis of variance; df, degrees of freedom; RMS, root mean square.

differences were found according to facial third, either in the patients ($P = 0.100$) or in the control group ($P = 0.502$).

Discussion

Over the last years, the spread of facial reanimation techniques has allowed facial movements to be restored within certain limits[3–6]; however, the assessment of restored function is often still performed through qualitative scales, which provide a standardized description of facial movements without a true quantification[7–9].

Some attempts at quantifying facial movements by photographic and video recording have already been made[25–27]. Among the most recent instruments, a combination of standardized images, visual analogue scales, and grading tutorials such as the eFACE model[28], and the use of machine learning[29], have been proposed. However, photographs and videos provide only linear distances and angles without a 3D surface analysis. In addition, different orientations of the patient's head and differences in the quality of photos may occur in longitudinal records and influence the results[29]: even slight deviations from photo documentation protocols have proved to result in important errors in facial assessment[30]. 3D motion capture instruments have been used successfully to track the movements of sets of selected facial landmarks, providing time-related information on facial mimicry[1,11,12,18,20], but they lack data about the surface among landmarks. Additionally, they require the positioning of adhesive markers on the skin, a long and potentially disturbing procedure.

3D assessment by optical, contactless systems represents a valid method for quantifying facial movement. According to both laboratory data and literature findings, the intra-individual variation in instructed smiles is clinically undetectable, and social, posed smiles are reported to be reproducible[17,20,31].

The surface registration procedure has already been applied to patients affected by facial palsy and has been found to be highly repeatable[18], as was confirmed by the data from the present study. This study aimed to build on previous work by assessing movements in different facial thirds and sides (paralyzed/rehabilitated side versus healthy side). Another aim was to compare the results observed in patients with those of a control group of healthy subjects, to provide a quantification of surgical success.

Regarding this latter point, facial movement in patients while smiling, as assessed by the RMS distance between the rest position relative to the smiling position, was on average between 46.6% and 74.8% of the same value observed in healthy people when performing the same smiling expression. In other words, considering the facial thirds altogether, on average patients treated with the facial reanimation procedure described here expressed more than half of the normal facial mobility in smiling. This information may be useful for identifying thresholds for the success of facial reanimation procedures. However, differences in RMS and asymmetry index values between patients and healthy subjects were still statistically significant: the intervention can restore facial mobility, but not entirely, as reported previously[4]. Patients were still 0.85 SD distant from the average RMS value of the reference population (*z*-score).

Analysis of RMS values highlighted that modifications in the middle and lower third were higher than in the upper one: this result was expected, as facial reanimation procedures mainly affect these facial territories. In addition, the magnitude of smiling movements is less pronounced in the upper than in the other

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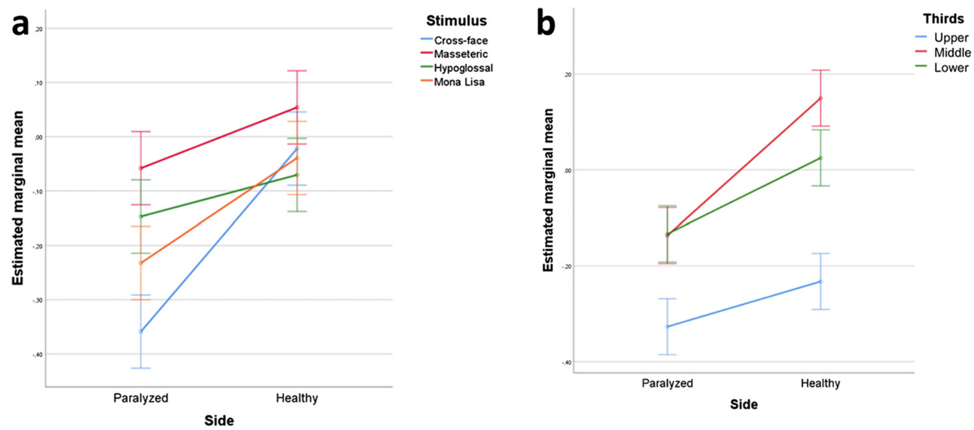

Fig. 4. (a) Estimated marginal mean values according to the stimulus and facial side of the RMS distances between the rest position and facial movements. (b) Estimated marginal mean values according to the facial third and side of the RMS distances in the different facial thirds.

thirds, not only in patients, but also in healthy people. Moreover, whereas on the healthy side the middle third expressed the highest RMS values, on the rehabilitated one the middle and lower thirds showed superimposable amplitudes of facial movements. This result may suggest that the gain in facial mobility resulting from facial reanimation procedures affects different facial thirds in different ways, and mainly affects the lower third.

Patients and healthy subjects also differed in smiling asymmetry: the control group expressed the same asymmetry in all the facial thirds, ranging between 13.0% and 13.6%, whereas patients showed higher values (between 25.0% and 43.5%).

The results of this study provide additional hints for better interpreting the outcomes of facial reanimation. First, the masseteric stimulus proved to produce the widest facial movements in comparison with the other stimuli, especially on the rehabilitated side; on the healthy side, facial modifications caused by different stimuli widely superimposed, although the masseteric one produced the highest RMS values as well. The prevalence of masseteric stimulus in evoking facial movements has already been observed[4,19]. On the other hand, the cross-face stimulus was the weakest one, as it is the basis for spontaneous facial expression rather than for strength; this is also confirmed in the literature[4]. The Mona Lisa smile is the best posed, social smile that the patient can voluntary perform, where symmetry of movement is more important than amplitude (in both middle and lower facial thirds, it had the smallest asymmetry indices). Intra-individual variation in smile performance was in line with literature findings[17,20,31].

This study is affected by some limitations. First, sex- and age-based differences in restored facial movements still need to be analyzed. It has been reported in the literature that facial mobility after facial reanimation procedure decreases with age[4]. In addition, sex and hormonal factors may have an influence in modifying the restoration of facial movements. However, unfortunately, the size of the patient sample divided according to age and sex groups was too limited to draw any conclusions concerning these topics, which should be analyzed further in future studies.

Second, the comparison of the present restored mobility with the same condition before the surgical intervention and the reinnervation of the facial musculature may provide data concerning the percentage of movement entirely due to the surgical intervention. In particular, we did not assess facial mobility in control subjects during clenching, pushing the tongue against the lower incisors, and cross-face smiles, as they are not normally expected to provoke smiles, but the topic needs further investigation.

Finally, another future field of research will consider the follow-up of the same patients to determine whether facial mobility changes over time. This study represents the starting point to quantify the role of rehabilitation in improving facial mobility.

In conclusion, the study data quantified facial movements in a group of consecutive patients affected by facial palsy and treated through reinnervation procedures. The use of a non-invasive 3D acquisition technique, the high repeatability of surface registration, and the existence of normal standards in healthy people represent important advantages for application to the clinical and surgical context.

Funding

None.

Competing interests

None.

Ethical approval

Ethical approval was obtained from the Università degli Studi di Milano, in accordance with the local university ethics committee (26.03.14; n° 92/14).

Patient consent

Consent obtained.

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.ijom.2019.07.015.

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