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François-Régis Sarhan, Matthieu Olivetto, Khalil Ben Mansour, Cécilia Neiva, Emilien Colin, et al.. Quantified analysis of facial movement: a reference for clinical applications. *Clinical Anatomy*, 2023, 36 (3), pp.492-502. 10.1002/ca.23999 . hal-03936727

HAL Id: hal-03936727

<https://u-picardie.hal.science/hal-03936727v1>

Submitted on 22 Feb 2024

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Quantified analysis of facial movement: A reference for clinical applications

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Funding information

Agence Nationale de la Recherche, Grant/Award Number: ANR-10-EQPX-01-01; Conseil Régional de Picardie, Grant/Award Numbers: N° 1012011207, 10120211208; European Regional Development Fund, Grant/Award Number: 21004127; Fondation des Gueules Cassées, Grant/Award Numbers: 43-2014, 63-2015

Abstract

Most techniques for evaluating unilateral impairments in facial movement yield subjective measurements. The objective of the present study was to define a reference dataset and develop a visualization tool for clinical assessments. In this prospective study, a motion capture system was used to quantify facial movements in 30 healthy adults and 2 patients. We analyzed the displacements of 105 reflective markers placed on the participant's face during five movements (M1–M5). For each marker, the primary endpoint was the maximum amplitude of displacement from the static position (M0) in an analysis of variance. The measurement precision was 0.1 mm. Significant displacements of markers were identified for M1–M5, and displacement patterns were defined. The patients and age-matched healthy participants were compared with regard to the amplitude of displacement. We created a new type of radar plot to visually represent the diagnosis and facilitate effective communication between medical professionals. In proof-of-concept experiments, we collected quantitative data on patients with facial palsy and created a patient-specific radar plot. Our new protocol for clinical facial motion capture (“quantified analysis of facial movement,” QAFM) was accurate and should thus facilitate the long-term clinical follow-up of patients with facial palsy. To take account of the limitations affecting the comparison with the healthy side, we created a dataset of healthy facial movements; our method might therefore be applicable to other conditions in which movements on one or both sides of the face are impaired. The patient-specific radar plot enables clinicians to read and understand the results rapidly.

KEYWORDS

facial anatomy, facial asymmetry, facial expression, facial movement, facial muscles, kinematics, mimics, motion analysis, motion capture, three-dimensional

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1 | INTRODUCTION

In contrast to the other muscles in the human body, the muscles of facial expression move soft tissues and not bones (Flynn et al., 2013). In fact, facial movements are made possible by the contraction of mimic muscles, which are particular in that they have at least one skin insertion. The contractions lead to tissue displacements (e.g., eyelid closure, cringing, smiling, and opening and closing of the mouth). These tissue displacements are essential for biological functions (such as feeding, and protection of the eye through blinking) and social interactions (such as non-verbal communication) (Dusseldorp et al., 2019).

Several facial movement scales and scores have been described in the literature (Brenner & Neely, 2004). Most are based on a qualitative description of movements (e.g., the House-Brackmann facial nerve grading system [House, 1983] and the Sunnybrook facial grading system [Ross et al., 1996]) or manual muscle testing (Freys et al., 1971). However, these grading systems are based on subjective, poorly reproducible clinical observations that introduce bias (Gaudin et al., 2016; Popat et al., 2009) in routine use or during the long-term follow-up of patients with persistent sequelae (Fattah et al., 2015; Revenaugh et al., 2018; Scheller et al., 2017).

In recent years, information and communication technology (ICT) has increasingly contributed to quantitative assessments and rehabilitation techniques. Motion capture (MoCap) is currently the gold standard (Simon, 2004) for human body motion analysis. MoCap systems based on stereophotogrammetry algorithms and optoelectronic technology can track passive reflective markers in three dimensions.

In order to overcome the disadvantages of subjective observations and thus accurately quantify the movements of healthy or diseased muscles of facial expression, several researchers have developed MoCap approaches (Feng et al., 2014; Frey et al., 1994; Hontanilla & Aubá, 2008; Sforza et al., 2012; Sforza, Galante, et al., 2010; Sidequersky et al., 2016; Trotman, Stohler, & Johnston, 1998). Some of these studies (Sforza et al., 2012; Trotman et al., 2018) quantified tissue displacement and face symmetry (Table 1). In studies of unilateral facial palsy, the other side of the face has often been used as a reference (i.e., for determining a paretic/healthy side ratio [Frey et al., 1994; Hontanilla & Aubá, 2008; Katsumi et al., 2015; Sforza et al., 2012]). However, the supposedly healthy side is not always completely normal. Indeed, synkinesis (the involuntary contraction of healthy muscles) is the most common complication and often occurs in cases of facial palsy. Moreover, muscle compensation and prior treatment with botulinum toxin injections might impair movements on the healthy side. Hence, in order to reliably quantify impaired facial movements, it is necessary to (i) precisely quantify several reference facial movements (considered to be normal values), (ii) perform an overall face analysis for the personalized management of patients with facial damage (whether unilateral or bilateral), (iii) define standardized, quantitative criteria for clinical analysis, and (iv) develop a consensus on the visual representation of the diagnosis and thus enable effective communication between medical professionals.

The primary objective of the present study was therefore to define and build a comprehensive database of healthy facial movements. Our

TABLE 1 A comparison of the main marker-based facial MoCap protocols described in the literature

First author and publication year	MoCap system	Capture frequency (Hz)	Accuracy (mm)	Static reference point	Type of data	Number of reflective markers	Reflective markers size (mm)	Limitations
Frey et al. (1994)	Vicon®	60	<1	Tip of the nose	Percentage of maximum displacement	18	6	Large markers and low capture frequency
Trotman, Stohler, and Johnston (1998)	Motion Analysis™	60	0.53	Maxilla	Displacement (mm)	33	4	Large markers and low capture frequency
Green and Wilson (2006)	Vicon®	60	Nc	Forehead	Displacement (mm)	15	2	Suitable for children only, low capture frequency
Hontanilla and Aubá (2008)	Facial CLIMA	50	0.13	Resting position	Displacement (mm), angulation, area (mm ²), speed (mm/s)	17/21	2	No overall analysis of the face, low capture frequency
Sforza et al. (2012)	SMAT	120	0.121	Tragus and tip of the nose, for the upper face. Glabella and temporal point, for the lower face	Displacement (mm)	14	2	The static reference points depend on the movement analyzed
Jorge et al. (2012)	Vicon®	100	0.19	Resting position	Displacement (mm)	11	4–9.5	Low marker density, large markers
Feng et al. (2014)	Evision CCD 1360	100	0.19	Helmet	Displacement (mm), angulation (rad), area (mm ²), speed (mm/s)	21	3	Low marker density
The present study	Vicon®	100	0.1	Maxilla	Displacement (mm)	105	1.5	

intention was to use the database as a benchmark for the analysis, diagnosis and follow-up of patients with impaired facial movements. By way of an illustrative application, we compared patterns in healthy adults with patterns in two patients with facial palsy.

2 | PARTICIPANTS AND METHODS

The study was approved by the local independent ethics committees (CPP Nord Ouest II, Amiens, France; references: ID-RCB 2011-A00532-39; CPP 2011-23, ID-RCB: 2016-A00716-45, and CPP 2016-55), registered at clinicaltrials.gov (NCT02002572 and NCT03115203), and performed in accordance with the ethical standards of the 1964 Declaration of Helsinki and its subsequent revisions. All patients provided written informed consent for study participation and the publication of photographs that could potentially identify them in an online Open Access publication.

In order to define objective analytic criteria for the facial movements resulting from mimic muscle contraction, we performed a prospective, quantitative study in which facial movements of healthy adults and patients were studied with a MoCap system.

As described previously (Dagnes et al., 2019; Mansour et al., 2014; Olivetto et al., 2019), our MoCap system included 17 optoelectronic cameras (resolution: 4704 × 3456 pixels; T160, Vicon Motion Systems Ltd, Oxford, UK) and two video cameras (resolution: 1280 × 720 pixels; Bonita, Vicon Motion Systems Ltd) at a frequency of 100 Hz. A set of 105 reflective markers (diameter: 1.5 mm) was placed on anatomic landmarks by a trained physiotherapist (Figure 1). The distance between markers was 15 mm. The facial landmarks were defined in accordance with standard anatomic and biomechanical criteria (Dagnes et al., 2019; Mansour et al., 2014). Of the 105 markers, 96 were placed symmetrically (48 pairs) and seven were placed on the midline of the face (see the Table in Supplementary Appendix 1). Reproducible marker positioning during each participant's follow-up was guaranteed by our use of a perforated resin mask (see the Figure in Supplementary Appendix 2 and the computer-aided design file in Appendix 3) obtained by three-dimensional (3D) stereolithographic printing (Form 2, Formlabs, Somerville, MA), and a stereophotogrammetric system (Vectra[®] M3 Imaging System, Canfield Scientific, Parsippany, NJ) (Figure 2). To provide fixed points as references for relative movements of the markers, a rigid dental splint bearing three markers was set on the maxilla (Mansour et al., 2014; Trotman, Stohler, & Johnston, 1998) (Figure 1). The resin mask and rigid dental splint were subject-specific.

Patients and healthy adults were included between 2014 and 2018 by the Maxillofacial Surgery Unit at Amiens-Picardie University Hospital (Amiens, France). The MoCap experiments were performed in the "Technology Sport Health" facility at Compiègne University of Technology (Compiègne, France).

Potentially eligible individuals (healthy adults or patients) were selected by a maxillofacial surgeon and a physiotherapist. Healthy adults had to be aged between 20 and 31 years, with no history of facial palsy and no disorders affecting the face. Individuals whose facial appearance had changed markedly during the study period (due to substantial weight gain or loss, pregnancy, breastfeeding,

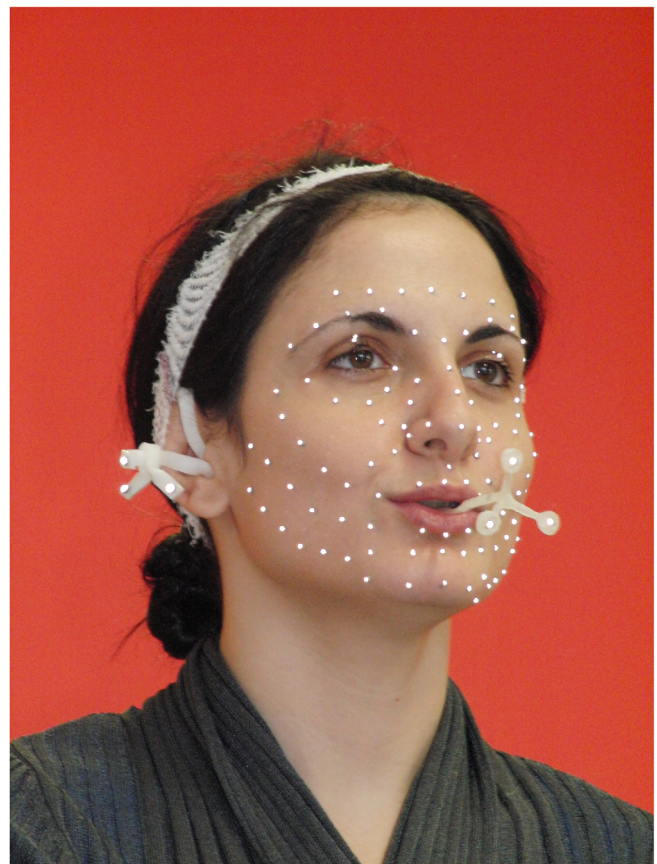


FIGURE 1 Reflective markers (diameter: 1.5 mm) are placed on the face, depending on the person's morphology and the anatomic regions of the face. Three markers are placed on a dental splint set on the maxilla, and are used as a fixed reference for movement

orthodontic care, beard growth, body piercing, etc.) were excluded. The main inclusion criteria for patients were a history of facial palsy, incomplete recovery, and an age between 20 and 31 years.

During a MoCap session, five movements were chosen from among those usually evaluated during manual muscle testing in the clinic (Freys et al., 1971). These movements were focused on specific areas of the face: the face at rest (M0), gentle eyelid closure (M1), forceful eyelid closure (M2), mouth puckering while pronouncing the [o] sound (M3), mouth puckering while pronouncing the [pμ] sound (M4), and voluntary smiling, showing the teeth (M5). The production of non-verbal sounds during mouth puckering is known to improve the reproducibility of movements (Sidequersky et al., 2016).

Prior to each MoCap session, the Vicon[™] system was calibrated according to manufacturer's instructions; the accuracy of the system and the 3D reconstruction error were determined by measuring unexpected displacements of fixed markers. 3D data were reconstructed with Vicon Nexus software (Vicon Motion Systems Ltd; see the video in Supplementary Appendix 4). All calculations were performed using MATLAB[®] software (R2015b, MathWorks, Natick, MA).

We have described the amplitude calculation methods elsewhere (Dagnes et al., 2018, 2019). The primary endpoint was thus the maximum amplitude of displacement of all markers (relative to the static position M0) in an analysis of variance (ANOVA).

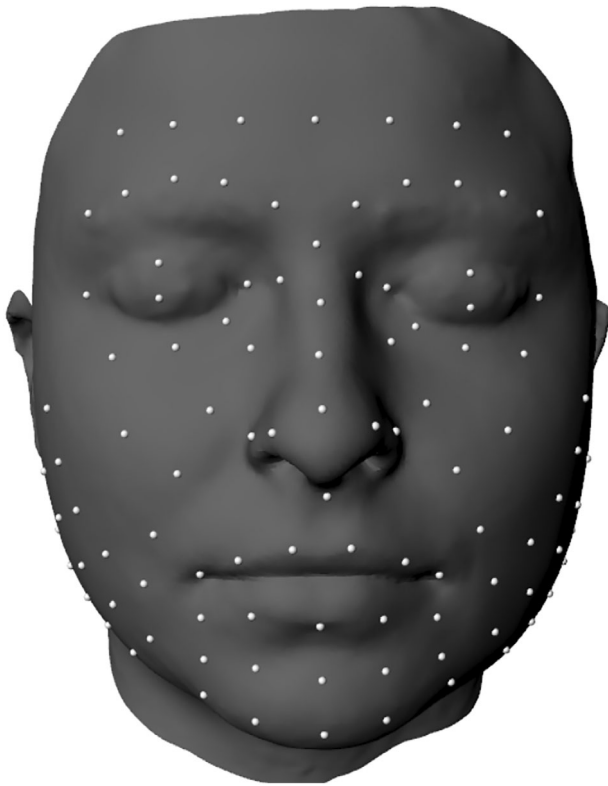


FIGURE 2 A facial mask obtained by stereophotogrammetric 3D printing is used to obtain reproducible marker placements

All the data collected in the cohort were summarized in a graph generated using MATLAB[®] (see the file in Supplementary Appendix 5). The maximum amplitudes of displacement (expressed in millimeters) were represented as a bar chart and as a radar plot. The markers were grouped by anatomic region (Figure 3).

To evaluate potential sex-related differences, the amplitudes of displacement were evaluated in a Wilcoxon signed rank test. Facial symmetry was quantified by comparing the maximum amplitudes of displacement for symmetrical markers in a mixed-model analysis of variance (ANOVA). All statistical analyses were performed using SAS[®] Enterprise Guide (version 7.15, SAS Institute Inc., Cary, NC) and MATLAB[®] software. The threshold for statistical significance was set to $p < 0.05$. The protocol's feasibility of use in routine clinical practice was evaluated with regard to the duration of the examination and the number of exploitable movement captures.

The two patients' maximum amplitudes of displacement were compared with the corresponding normative values from 30 healthy adults of a similar age. The results were illustrated on a radar plot, with the patient's data in gray and the normative data in black.

Lastly, to assess the consistency of our data, we compared our results for amplitude displacement with those published by Sforza, Galante, et al. (2010). Indeed, 17 of the markers and two of the facial movements were used in both studies. Sforza et al.'s data were also reported as a displacement (in mm). Displacements were compared by applying Wilcoxon's signed rank test.

3 | RESULTS

Thirty healthy adults (11 men and 19 women) were included in the study. The mean \pm standard deviation (SD) age (in years) was 25.64 ± 2.92 overall, 25.40 ± 3.15 for women, and 26.05 ± 2.58 for men. Two patients with facial palsy were also evaluated (Table 2).

The system's precision (as measured with a calibration tool) was 0.1 mm. The 3D reconstruction error (relative to the maxillary reference) ranged from 0.08 to 0.14 mm. This reflects our use of the smallest possible reflective markers (diameter: 1.5 mm) and the highest possible camera pixel resolution.

Of the 411 movement captures obtained for the 30 healthy adults, 375 (91.24%) were usable. The non-usable captures contained artifacts or lacked data. The mean total examination time was 32 min for healthy adults and 15 and 52 min for the two patients. Given the large amount of data, the results are summarized in table format in Supplementary Appendix 6.

Displacement patterns were defined for the five studied movements (Figure 3). For each movement, we could locate the area of movement and measure the range of motion of each marker (see the data in Supplementary Appendix 7). Movements were characterized by a displacement profile (pattern), and the radar plot provided a quickly and easily understandable overview of the movement pattern.

For gentle eyelid closure (M1), significant marker displacements were located on the eyelids ($p = 0.001$ vs. M0), the eyebrow ($p < 0.0001$), the orbicularis oculi ($p = 0.01$), the middle of the forehead ($p < 0.05$), and the top of the cheeks ($p < 0.05$). The maximum amplitude of displacement was located on the eyelids (mean: 9.6 ± 0.6 mm), and the displacements in the other areas were all below 1 mm.

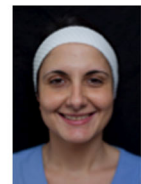
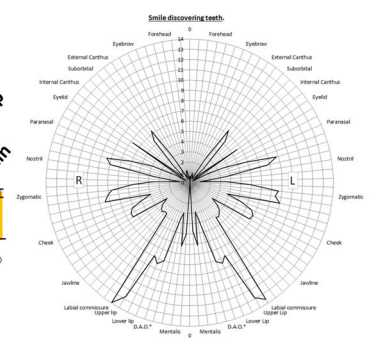
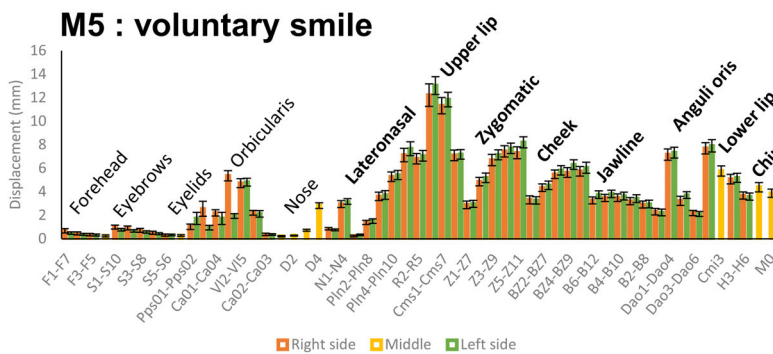
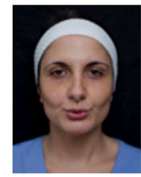
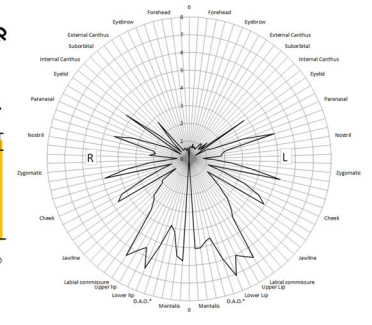
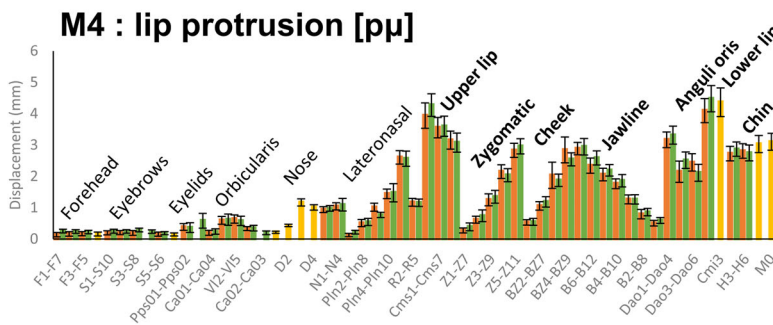
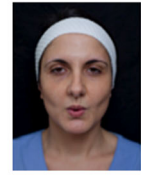
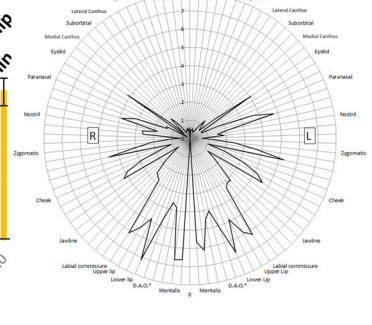
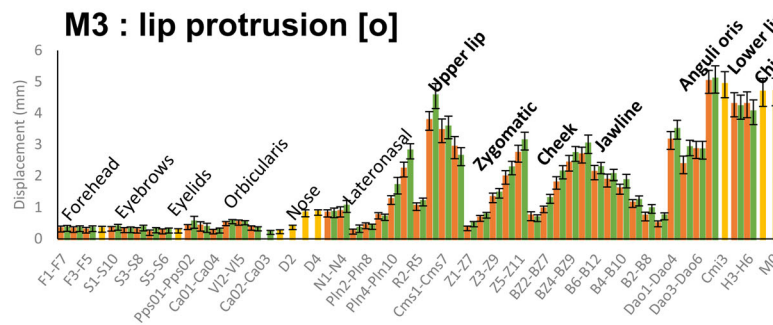
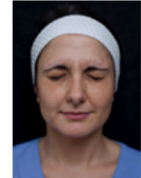
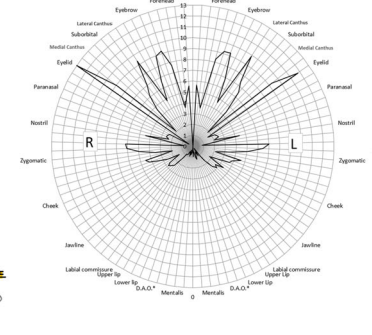
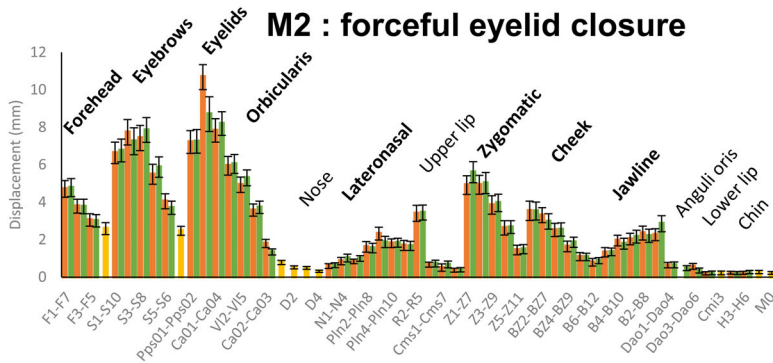
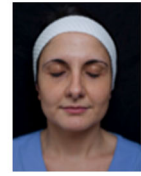
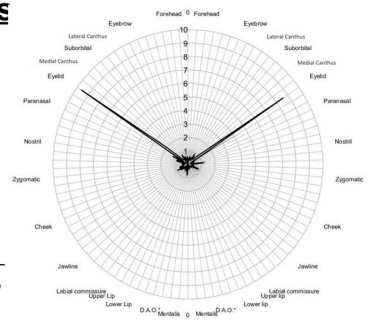
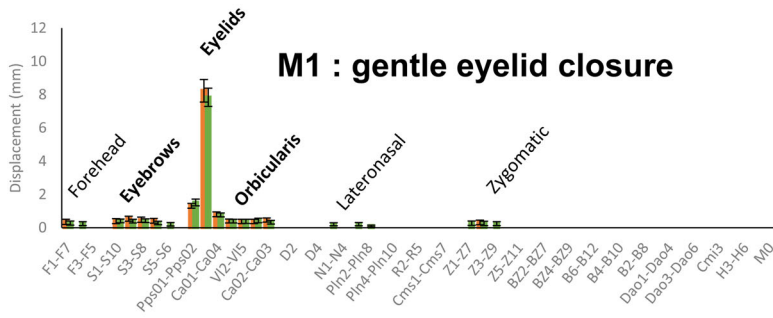
For strong eyelid closure (M2), significant marker displacements were observed all over the face except for the lower lip and the chin. The maximum amplitude of displacement was located on the eyelids (mean: 13.0 ± 0.6 mm; $p < 0.0001$). The amplitudes of displacement on the nose, upper lip, and jawline were all below 1 mm.

For mouth puckering while pronouncing the [o] or [pɥ] sound (M3 and M4, respectively), the displacements patterns were generally similar. However, a significant difference between M3 and M4 was observed for some areas: the displacements in M4 were greater than in M3 for the jawline ($+0.8$ mm; $p = 0.01$ vs. M0) and the upper lip ($+1.1$ mm; $p = 0.01$).

For the "voluntary smiling, showing the teeth" movement (M5), we observed displacements of all the markers. The corners of the mouth moved the most (mean: 14.0 ± 0.8 mm; $p < 0.0001$ vs. M0) and the whole lower part of the face was very mobile. With the exception of the orbicularis oculi, the upper part of the face presented displacements (albeit < 1 mm). The nasal area and the medial canthi were characterized by small displacements (means: 2.3 ± 0.1 and 2.6 ± 0.3 mm, respectively).

In a comparison of women and men, no statistically significant differences were found for M1 or M3 ($p > 0.05$). Two of the 105 markers showed a statistically significant difference for M2 and M3, and three other markers showed a significant difference for M5. The significant differences in M2, M3, and M5 all involved different markers, and the value was always below 1 mm (Supplementary Appendix 8). We did not observe significant asymmetry in the facial

Movement patterns



Right side Middle Left side

FIGURE 3 Legend on next page.

TABLE 2 Characteristics of the two patients with facial palsy included in the study

Age	Sex	Side of facial palsy	Etiology	House-Brackmann score	Sunnybrook score	Synkinesis
28	Female	Right	Temporal bone fracture	III	38	Yes
31	Male	Right	Traumatic nerve injury	II	75	Yes

movements: the mean \pm SD difference was 0.1 ± 0.5 mm (see Supplementary Appendix 9).

As a proof of concept, we collected quantitative data on two patients with facial palsy. The radar plot provided a graphical comparison with normative data (Figure 4) and constituted a quickly and easily understandable overview of the patient's performance versus healthy adults with respect to the side of the face and the different areas of the face. It can be seen as a frontal view of the face, with the forehead at the top and the chin at the bottom. This graphical method ensures that few data are lost and enables an accurate 3D analysis of facial disorders and their components (voluntary movements and sequelae) against reference patterns. Each movement is illustrated by a pattern.

Figure 4 shows the maximum amplitudes of displacement during movements. In particular, Figure 4A shows the data for forceful eyelid closure (M2) by a 31-year-old patient with sequelae (synkinesis) following a partial section of the lower and frontal branches of the right facial nerve. On the left (healthy) side, the amplitudes were greater than the normative values. On the right (paretic) side, the amplitudes were lower than the normative values for the eyelid, eyebrow, and forehead. Hence, we were able to quantify the patient's hypertonicity on the left side (compensation), localized palsy of the area innervated by the frontal branch of the right facial nerve, and "eye-mouth" synkinesis on the right side. The maximum amplitudes of displacement during voluntary smiling, showing the teeth (M5), for a 28-year-old patient with right-side facial palsy (caused by fracture of the temporal bone) are shown in Figure 4B. On the left (healthy) side, the amplitudes were similar to the normative values. On the right (paretic) side, the amplitudes were lower than the normative values. We were therefore able to quantify the patient's right facial palsy, together with compensation by the healthy side (hypermobility of the lower lip and depressor anguli oris areas). All these displacements were quantified (in mm) and so could potentially be used for to follow up the patient.

A comparison of our amplitudes of displacement with those published by Sforza et al. is shown in Table 3. There were no significant differences between the two sets of measurements for voluntary smiling (M5). In contrast, there was a significant difference for forced eyelid closure (M2); the associated mouth movements were more ample in Sforza et al.'s study than in our study.

4 | DISCUSSION

In many fields of medicine, technological progress has enabled accurate diagnoses and personalized treatments. In this respect, several

researchers have contributed to our understanding of facial movements (Samsudin & Sundaraj, 2014; Griffin & Kim, 2012; Lee et al., 2015; Popat et al., 2009; Revenaugh et al., 2018) by investigating facial biomechanics and disease-related changes in facial mobility. Following on from these literature data, our present study of a cohort of healthy adults was one of the most exhaustive to date (Sforza, Galante, et al., 2010; Sforza, Mapelli, et al., 2010; Trotman et al., 2018). It allowed us to build a comprehensive database for use as a reference when evaluating impaired facial movements. Furthermore, we introduced a graphical tool, which provides the clinician with a quickly and easy understandable overview of the patient's performance and movement disorders.

We obtained these results by tracking a set of 105 markers on 30 healthy adults and two patients. The small diameter (1.5 mm) meant that the participants could not perceive the markers and also enabled us to achieve a high marker density. To the best of our knowledge, our new technique (which we refer to as the "quantified analysis of facial movement" [QAFM]) is the most technically advanced facial MoCap protocol developed to date with regard to the marker size, the number of markers, and the capture frequency. To obtain the most accurate measurements possible, we fixed a dental splint to the maxilla (Trotman, Faraway, et al., 1998); this head reference is known to be the most accurate way of defining a fixed biomechanical reference for movement (Mansour et al., 2014). Furthermore, we used a perforated mask to ensure that the markers were placed reproducibly. Lastly, our facial MoCap platform was very precise (0.1 mm) and had a high capture frequency (100 Hz).

The large volume of raw data collected by MoCap is cumbersome and is not readily understandable by clinicians. We therefore developed a simple, relevant data representation that facilitated clinical applications. The radar plot provides a clear, complete representation of the whole face. It was obtained with respect to the side of the face and the various areas of the face, and can thus be considered as a frontal view of the face in which the forehead is on the top and the chin is at the bottom (Figure 3). This graphical method ensures minimal data loss and allows an accurate 3D visual representation of all components (movements, palsy, and synkinesis) of facial movement disorders.

One of the first questions we asked ourselves related to the representativeness of our database. Indeed, the population of healthy adults was composed of women and men aged between 18 and 30. We found that sex and symmetry had limited influences on overall facial movements. In view of the results of a previous study (Sforza,

FIGURE 3 The maximum amplitude of displacement for the five movements studied (M1–M5). The left-hand graphs represent statistically significant marker displacements, with the range of movement and the SD. The right-hand graphs are radar plots that provide a rapidly and easily understandable overview of the movement pattern: the plot corresponds to face movements in a mirror view. The accompanying photograph shows the facial position with maximum displacement

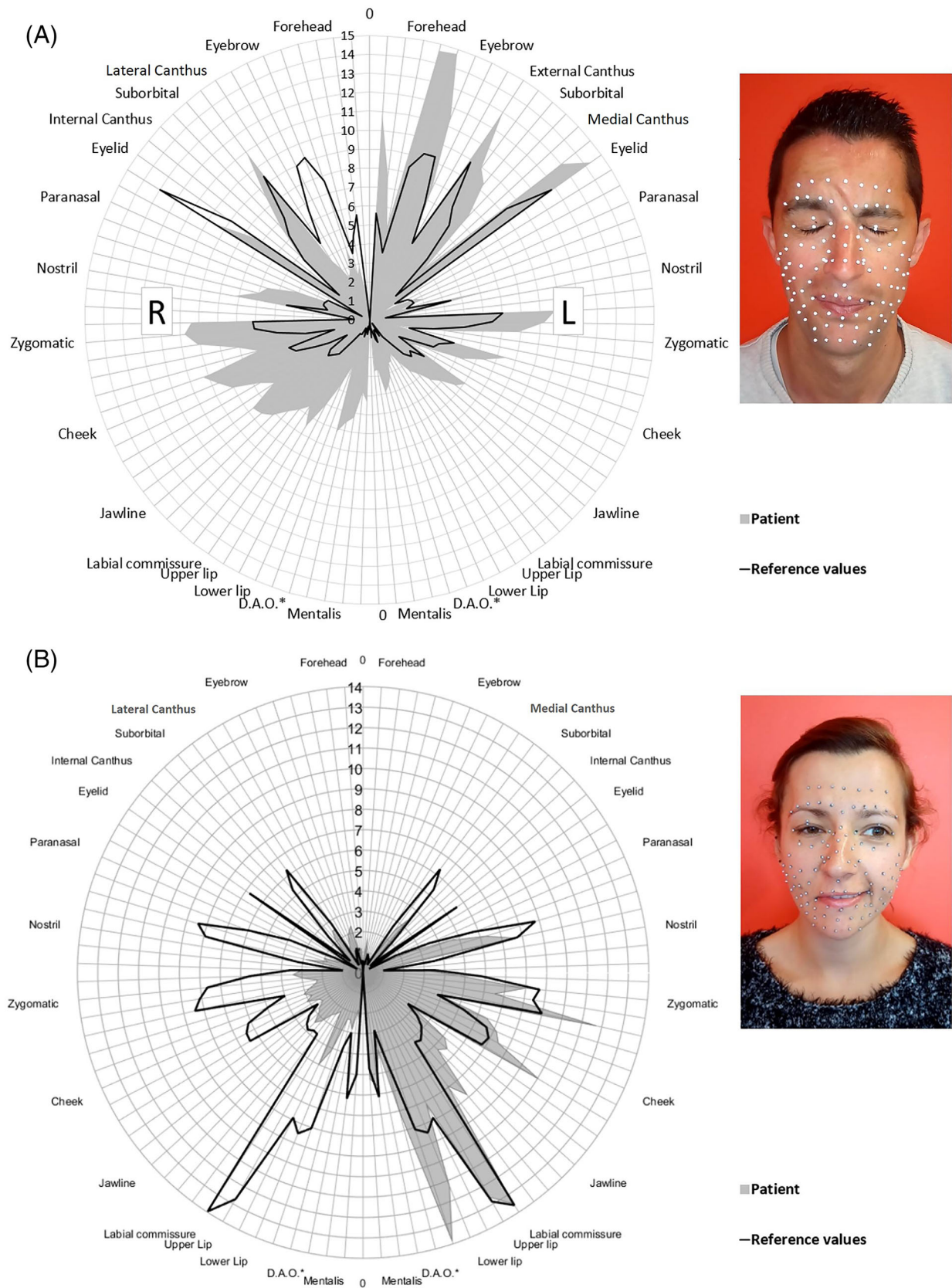


FIGURE 4 The radar plot. The mean maximum amplitudes of displacement for 30 healthy adults are illustrated by a black line. The maximum amplitudes of displacement for a patient with facial palsy are indicated as the gray shaded area

TABLE 3 Displacements (in mm) for markers used in both Sforza et al.'s study and the present study

Voluntary smile (mm)				Forceful eyelid closure (mm)			
Marker name	Sforza et al.	The present study	p-value	Marker name	Sforza et al.	The present study	p-value
Tr/F4	1.7	0.3	$p = 0.286$	Tr/F4	3.0	3.1	$p = 0.011^*$
N/G0	1.9	0.3		N/G0	4.4	3.0	
Sci (R)/S4	1.9	0.6		Sci (R)/S4	7.1	6.6	
Sci (L)/S7	1.9	0.6		Sci (L)/S7	7.5	6.8	
Ex (R)/Ca01	2.3	2.9		Ex (R)/Ca01	8.5	9.4	
Ex (L)/Ca04	2.4	2.7		Ex (L)/Ca04	8.8	9.9	
Or (R)/VI2	3.0	5.3		Or (R)/VI2	8.7	6.1	
Or (L)/VI5	2.9	5.3		Or (L)/VI5	9.3	6.5	
Ac (R)/Pln4	3.8	6.0		Ac (R)/Pln4	4.5	2.6	
Ac (L)/Pln10	4.4	5.8		Ac (L)/Pln10	4.9	2.5	
Pm/D3	2.6	1.0		Pm/D3	2.3	0.7	
Ch (R)/C01	11.5	14.0		Ch (R)/C01	3.6	0.9	
Ch (R)/C02	11.8	13.6		Ch (R)/C02	3.9	0.2	
Li (R)/Cmi1	7.6	8.5		Li (R)/Cmi1	2.7	0.5	
Li (R)/Cmi5	7.1	8.5		Li (R)/Cmi5	2.9	0.6	
SI/Cmi3	4.0	6.8		SI/Cmi3	2.2	0.7	
Pg/M0	4.0	5.4		Pg/M0	2.4	1.0	

*p value result is significant.

Mapelli, et al., 2010), we considered that this submillimetre difference was not clinically relevant. Given that aging might influence facial movements (Bartlett et al., 1992; Sforza, Mapelli, et al., 2010), we nevertheless intend to expand these measurements to both older and younger people.

Of the other researchers having applied facial MoCap technologies, only Sforza, Galante, et al. (2010) published data that are similar to ours. The absence of significant differences between the two sets of measurements for voluntary smiling (M5) confirmed the consistency of our results. In contrast, there was a significant difference for forced eyelid closure (M2); this might have been due to differences in the fixed reference point or in the verbal instructions used to direct the movement. In fact, Sforza et al. defined the tragus as a fixed point, for which we observed a displacement of around 0.7 mm; this might have been source of error in Sforza et al.'s study (see Appendices 6 and 7).

These results confirm the importance of having a reliable, fixed reference; in the latter's absence, the relevance of the results can be called into question. Even though a dental splint is restrictive, it is more reliable than markers placed on the soft tissues of the face. However, we suggest that further studies of the most relevant fixed reference points are warranted.

In a literature review, Dulguerov and Marchal (1999) defined the criteria that an ideal, objective method for QAFM should meet. The present protocol meets these requirements, as follows: (i) the patient can move freely, and the small size of the markers makes them imperceptible, (ii) our results are consistent with the literature data, (iii) 3D MoCap enables movements of both sides of the face to be monitored simultaneously, (iv) the MoCap is based on the reflection

of infrared light, (v) there is no contact with the face, which might otherwise interfere with the measurements, (vi) quantitative data was obtained on submillimetre relative displacements, (vii) the post-processing can be automated, which allows the export of data of value to clinicians, (viii) the duration of a patient's facial MoCap session is similar to that of an EMG or MRI session, (ix) the MoCap is not invasive and the measurements were well tolerated by the participants, and (x) the data can be archived easily for monitoring patients over time.

5 | STUDY LIMITATIONS

One might consider that our method is technically burdensome because it involves a face mask and a dental splint. However, our protocol used tools that are routinely available in rehabilitation and maxillofacial surgery units. During MoCap sessions, we noted that the examination time differed markedly from one patient to another. This was because (i) we had to provide a fuller explanation to some patients than others, and (ii) the number of defective markers (and thus the time spent checking them) varied. Although this step took time and had a financial cost, it was essential for establishing a reference database. Indeed, marker-based motion capture remains the gold standard for motion analysis relative to markerless methods, which are mostly based on statistical models (Frey et al., 1999; Hsu et al., 2014; Popat et al., 2010; Zinkernagel et al., 2019). The markerless approach does not always work with people with a high degree of dissymmetry. Hence, our patient-specific, mask-based approach

guarantees reproducible marker placement and thus enables personalized follow-up from one measurement session to another.

We acknowledge that our research is in the pilot phase. Our method could benefit from improvements and simplifications prior to transfer to clinical structures equipped with motion analysis facilities (gait analysis systems, for example). We expect that in a particular clinical context, it will be possible to adapt and simplify the protocol and select the most relevant markers (Dagnes et al., 2019). We also expect our method's cost-effectiveness to increase as the technology develops. Markerless systems might emerge, as has been the case for gait analysis (Nguyen et al., 2021). However, it should be borne in mind that markerless gait monitoring systems are mainly being developed for home-based self-monitoring and rehabilitation. Although Zhong et al. have written that "the recent innovative technologies seems to provide cost-effective opportunities for gait assessment (wearable devices as smartphone)" (Zhong & Rau, 2020), conventional assessment devices (such as 3D motion analysis systems and force plates) still constitute the reference methods. Solutions like "eFACE" (Banks et al., 2015) are emerging in the clinical field but are based on the manual scoring of videos, which is also time-consuming.

Other expert researchers in the field of facial rehabilitation have used MoCap to follow up patients during rehabilitation (Demeco et al., 2021; Sforza et al., 2012, 2015). MoCap gait analysis platforms have been used in the clinic for more than 10 years (Kawamura et al., 2007; Simon, 2004); it might be possible to adapt these platforms for facial movement analysis.

6 | CONCLUSION

Our clinical protocol for QAFM with MoCap was highly accurate and thus might allow long-term follow-up during the rehabilitation of patients with facial palsy. Furthermore, the high marker density might make it possible to precisely locate an impairment on a patient's face and to monitor recovery. As described above, we are now able to quantify a patient's facial movements. The patient data can be compared with reference data in order to evidence possible paralysis, synkinesis, or abnormal movements. In this respect, we are currently using the protocol to monitor facial rehabilitation in patients having undergone a face allograft (Devauchelle et al., 2006; Olivetto et al., 2019).

QAFM appears to be a promising, reproducible tool for improving patient management. The present objective measurements should aid communication between practitioners, facilitate the comparison of results, provide useful decision-making support for clinical examinations, and enable objective long-term follow-up.

ACKNOWLEDGMENTS

We are thankful for "Picardie Council," "Fondation des Gueules Cassées," ANR-FIGuRES Equipex and the European Regional Development Fund (ERDF) that has provided financial support for the larger project from which this paper grew.

FUNDING INFORMATION

The present study was funded by Picardie Regional Council, the "Gueules Cassées" Foundation, the ANR-FIGuRES Equipex facility, the Institut Faire Faces, and the European Regional Development Fund (ERDF) as part of the FaceMoCap project.

CONSENT FOR PUBLICATION

All patients provided written informed consent for study participation and the publication of photographs that could potentially identify them in an online Open Access publication.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Sarhan, F.-R., Olivetto, M., Ben Mansour, K., Neiva, C., Colin, E., Choteau, B., Marie, J.-P., Testelin, S., Marin, F., & Dakpé, S. (2023). Quantified analysis of facial movement: A reference for clinical applications. *Clinical Anatomy*, 36(3), 492–502. <https://doi.org/10.1002/ca.23999>