The Assessment of Distorted Facial Muscles Movements in Facial Palsy

Mahmoud Amir M. Mounzer Alagha

DDS., MSc. (Dent Sci) Oral and Maxillofacial Surgery

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ABSTRACT

Introduction

The clinical evaluation of facial palsy remains the routine approach for the assessment of facial muscle movements. However, there is a lack of data to link the mathematical analysis of 3D dynamic facial morphology with the subjective clinical assessments. Quantifying the degree of distortion of facial expressions is a vital step in evaluating the clinical impact of facial palsy. 4D imaging is a reliable modality for recording the dynamics of facial expressions.

This study aimed to assess distorted facial muscles movements in unilateral facial palsy and mathematically validate clinical grading indices.

Material & Method

The study recruited 50 patients who suffered from unilateral facial palsy and a control group of an equal number (50) of age- and sex-matched cases.

The dynamics of facial expressions were captured using a stereophotogrammetric 4D imaging system. Six facial expressions were recorded (rest, maximum smile, cheek puff, lip purse, eyebrow-raising, eye closure), each one took 4 seconds and generated about 240 3D images for analysis.

An advanced geometric morphometric approach using Dense Surface Models was applied for the mathematical quantification of the 3D facial dysmorphology over time. The asymmetries of 10 facial anatomical regions were calculated. For each participant, six mathematical values which quantify asymmetry were measured per expression (the minimal, mean, median, maximum, range, and standard deviation).

The 4D image data of sixteen facial paralysis patients were assessed by 7 expert assessors using two clinical grading indices for the assessment of unilateral facial palsy, the modified Sunnybrook index, and the Glasgow Index. The reproducibility of the clinical gradings between two rating sessions was examined.

The measured asymmetries of the 4D images were treated as the gold standard to evaluate the performance of the subjective grading indices. Cross-correlations between the mathematical measurements and the subjective grades were calculated. The Modified

Sunnybrook index assessed 8 parameters (3 at rest and 5 at individual facial expression). The Glasgow index assessed 29 parameters for the assessment of dynamic facial abnormalities with considerations for the directionality and severity of asymmetry. The similarities and dissimilarities between the two clinical assessments and to the mathematical measurements were investigated.

Results

The modified Sunnybrook index was reproducible for grading the dysmorphology and dysfunction of unilateral facial paralysis. The Glasgow Index was reproducible after excluding three parameters of poor reproducibility.

The modified Sunnybrook index and the Glasgow index correlated reasonably well with the mathematical measurements of facial asymmetry at rest and with facial expressions.

- The minimal value of facial asymmetries of the rest expression had a stronger correlation coefficient than that of other values.
- The mean and median values of facial asymmetries of the other five nonverbal expressions had a stronger correlation coefficient than that of other values.

The following were the main regions affected by facial dysmorphology which showed a correlation above -0.6 between the subjective and objective assessments:

- The full face at rest as well as the forehead, cheek, nose and nasolabial, upper lip, corner of the mouth, and chin regions.
- The full face, cheek, nasolabial, upper lip, and lower lip of the smile.
- The full face, upper and lower lips of the lip purse.
- Most of the facial regions, except the cheek, showed moderate to weak correlations with cheek puff.
- A strong correlation was detected between the subjective and objective assessments of the forehead and eye regions with eye closure.

Based on the correlation results between the mathematical measurements and clinical evaluation of facial asymmetry in unilateral facial paralysis, the study highlighted the following points:

- Smile expression: the assessors encountered difficulties to judge the direction of the asymmetry of the corner of the mouth. It is easier to observe the upper lip and the cheek instead of the corner of the mouth when assessing the smile.

- Lip purse: the evaluation of the directionality of lip movement was more accurate and sensitive at the lower lip.
- Cheek puff: grading the cheek may not grasp the severity of the asymmetry. We would suggest observing the corner of the mouth and lower lip in cheek puff expressions.
- Eyebrow raising expression: grading the 4D movement of the upper margin of the eyebrow may be more sensitive than depending on the assessment of the wrinkles of the forehead.
- Eye closure: the clinical assessment of the eyes based on 4D image data was not ideal due to the 4D imaging surface defects secondary to the reflective surface of the cornea.

Conclusion

The mathematical assessment of the dynamics of facial expressions in unilateral facial palsy using advanced geometric morphometrics provides a state-of-art approach for the quantification and visualization of facial dysmorphology.

The Glasgow Index and the Modified Sunnybrook Index were reproducible. The clinical assessors were reasonably consistent in the grading of facial palsy.

The significant correlations between the clinical grading of facial palsy and the mathematical calculation of the same facial muscle movements provided satisfactory evidence of objectivity to the clinical assessments. The Glasgow index provided more validated parameters for the assessment of facial palsy in comparison to the modified Sunnybrook index.

The mathematical quantification of the 3D facial dysmorphology and the associated dynamic asymmetry provides invaluable information to complement the clinical assessments. This is particularly important for the assessment of regional asymmetries and the directionality of the asymmetry for the evaluation of facial contour (anteroposterior direction), face drooping (vertical direction), especially in cases where surgical rehabilitation is indicated.

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Mahmoud Amir Alagha

AUTHOR'S DECLARATION

I declare that, except where explicit reference is made to the contribution of others, that this thesis is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Signature

Printed Name: Mahmoud Amir Alagha

May 2021

LIST OF ABBREVIATIONS

ABBREVIATIONS	*FULL NAME*
2D	Two Dimensions
3D	Three Dimensions
4D	Four Dimensions
FP	Facial Palsy
UCLP	Unilateral Cleft Lip and Palate
SD	Standard Deviation
ICP	Iterative Closest Point
CT	Controls
PCA	Principal Component Analysis
ICC	Intraclass Correlation
SB	Sunnybrook Facial Grading System
MSB	Modified Sunnybrook
GI	Glasgow Index
HB	House-Brackmann
FNGS 2.0	Facial Nerve Grading System 2.0
DSM	Dense Surface Model
DTW	Dynamic Time Warping
GPA	General Procrustes Analysis
RMS	Root Mean Square Distance
MAD	Mean Absolute Deviation
MSD	Mean Signed Distance
NLF	Nasolabial Fold Reset Surgical Technique
CNVII	Seventh Cranial Nerve
ANOVA	Analysis of Variance
X	Mediolateral Direction
Y	Vertical Direction
Z	Anteroposterior Direction
AAO	American Academy of Otolaryngology

Introduction

The Human Face Perspectives

"Who sees the human face correctly: the photographer, the mirror, or the painter?"

Pablo Picasso

The human face is complex in nature. The relationship between facial hard tissues, soft tissues, and dentition affects facial form and function, and extends to impact emotional expressions and human behaviors.

Self-perception of facial beauty, as well as deformity, is arguably subjective. An entity that is shaped by personal views and experiences and influenced by environmental factors and cultural ideals of beauty.

From a medical perspective, the evaluation of facial form and function has been traditionally based on clinical observation and assessment. The face may be subdivided into a number of areas based on interest, these could be anatomical regions, aesthetic zones, motor and sensory nerves supplied structures. Mastication, phonation, and facial expressions are different forms of facial functions utilised in the assessment.

In computer mathematics and opposing the subjective common wisdom "Beauty is in the eye of the beholder", the face is evaluated as a geometric shape. Geometric Morphometrics measure the geometry and morphology of the face by applying mathematical formulas for the objective assessment.

Facial Form and Function

Facial bones constitute the skeleton of the face which house and protect the brain, the organs of sight, and paranasal air sinuses. They provide anchorage for dentition, and attachment to the muscles and tendons of the face.

The numerous muscles of facial expression originate from facial bones or fascia and attach directly to the skin forming the distinct facial features of the eyes, lips, and cheeks. The muscles of facial expression are innervated by the seventh cranial nerve, the facial nerve. Voluntary facial movements like raising the eyebrows, eye-closure, cheek buff, lip purse, and smiling are controlled by this group of muscles. Emotional facial expressions of fear, happiness, pleasure, and pain are examples of involuntary facial muscles movements.

Facial expressions are complex and require fine coordination of complex neuromotor and psychomotor processes for facial muscle movements (Garcia et al., 2015). For example, smiling is the result of harmonious contraction and relaxation of the depressor anguli oris, zygomaticus major, zygomaticus minor, levator labii superioris, and the risorius muscles. These muscles are innervated by various branches of the facial nerve. Therefore, the integrity of neuromuscular units impacts the quality of the produced muscle movement. On the other hand, mandibular movements are controlled by another group of facial muscles, the muscles of mastication which are innervated by the fifth cranial nerve, the trigeminal nerve.

The congruous interplay between the different groups of facial muscles is essential during key facial functions such as mastication and speaking. During ingestion, the formation of the oral seal is the function of orbicularis oris, the muscles of mastication control jaw movements during chewing, the buccinator muscle counteracts the action of the tongue to bring the food bolus to the occlusal table.

Facial expressions form a crucial component of effective verbal and nonverbal communications (Byrne, 2004). Facial expressions are essential in human communication and social interactions (Morgan Stuart & Byrne, 2004), especially for emotional contagion, which is the ability to convey non-verbal emotional messages that communicates social cues, personal moods, and empathy (Falkenberg et al., 2008). Similarly, sexual interest, social perception of attractiveness, beauty, and friendship are forms of social interactions that are affected by facial expressions (Little et al., 2011).

Facial Dysmorphology and Abnormal Function

The human face is symmetrical in shape. Facial abnormalities may be broadly put into two levels of facial asymmetry, static and dynamic, which both involve skeletal discrepancies, muscular abnormalities, and functional distortion.

Facial muscle movements can be altered due to various pathologic conditions and malformations deriving from central nervous system diseases, neuromuscular and peripheral nerve paralysis, mainly affecting the facial nerve, as well as dentofacial deformities and congenital anomalies (Renault & Quijano-Roy, 2015). Abnormal movements of facial muscles could arise secondary to surgical intervention (Rai et al., 2008), cancer resection (Terzis & Konofaos, 2012), facial scarring, and drug administration. In these cases, facial expressions are disrupted affecting communication, emotional expressions, and social interaction which has a negative psychological impact. In a cross-sectional survey, patients with long-standing facial paralysis reported a diminished quality of life (Coulson et al., 2004).

Visible facial disfigurements may cause low self-esteem, deteriorated self-image, feelings of shame, and guilt because of the way they look (Valente, 2004). Facial disfigurements are linked with a social disability where meeting with strangers provokes feelings of embarrassment and fear of rejection. This might lead to social isolation and difficulty in finding employment (Rumsey et al., 2004).

A study by Grammer & Thornhill, 1994 demonstrated that perceived facial asymmetry adversely affects the observer ratings of attractiveness and health. Likewise, Ishii et al., 2011 studied society's perception of patients with facial paralysis, and reported that paralysed faces are considerably less attractive than normal.

Altered facial function in these patients could result in secondary features such as synkinesis, hemifacial spasms, and contractures (Placheta et al., 2014).

Analysis of facial movements is mainly focused on the facial expressions, their motor innervation via the facial nerve, and the improvement of the muscle flaps transferred to facial regions. Patients who suffer from facial paralysis are frequently treated with facial reanimation surgery where a new muscle source is transferred to the face to regain facial movement of the affected side (Biglioli, 2015a, 2015b).

Facial palsy and surgical interventions for the management of facial paralysis affect features of the face, such as the levels of eyebrows, palpebral fissure, the corners of the mouth, and facial contours (Coyle et al., 2013).

The rationale behind the management of facial nerve weakness or paralysis is to improve facial symmetry and muscle movements. Over the years, various methods have been proposed for the analysis of facial palsy (Brenner & Neely, 2004; Dulguerov et al., 1999; Fattah et al., 2015; Kang et al., 2002; Kleiss et al., 2015; Lee et al., 2013; Niziol et al., 2015; Samsudin & Sundaraj, 2012; Samsudin & Sundaraj, 2013, 2014; Tzou et al., 2012). The following sections provide an overview of the assessment methods of distorted facial muscles movements in facial palsy.

Subjective Assessments of Facial Palsy

There is a clinical need to quantify the morphological and functional abnormalities associated with facial muscle movements to improve the diagnosis and management of facial palsy. The need for the ideal clinical assessment method continues (Niziol et al., 2015).

Visual Evaluation Methods

The concept of the subjective assessment depends on the capacity of the expert eyes to detect facial abnormalities through systematic visual inspection and evaluation of facial form and function.

Seventeen facial grading systems were developed between 1955 and 2013 for the assessment of facial paralysis (Table 1). Appendix A: Facial Palsy Subjective Clinical Grading Systems.

Table 1: Subjective Clinical Grading Systems of Facial Palsy

Facial Palsy Subjective Clinical Grading Systems	
System	**Reference**
Botman and Jongkees Scale	(Botman & Jongkees, 1955)
Janssen Scale	(Janssen, 1963)
May Scale	(May, 1970)
Adour and Swanson Scale	(Adour & Swanson, 1971)
Pietersen Scale	(Peitersen, 1976)
Yanagihara Scale	(Yanagihara, 1977)
Stennert Scale Facial Palsy Score	(Stennert et al., 1977)
Stennert Scale Secondary Defect Score	
Fisch Scale	(Fisch, 1981)
House and Brackmann	(House & Brackmann, 1985)
Smith Scale	(Smith et al., 1992)
Sydney Facial Grading System	(Coulson & Croxson, 1995)
Sunnybrook Facial Grading System	(Ross et al., 1996)
FEMA Scale | Forehead, Eye, Mouth & Associated Defects	(Kim et al., 1998)
MoReSS System	(de Ru et al., 2006)
Facial Nerve Grading System 2.0	(Vrabec et al., 2009)
The Rough Grading System	(Alicandri-Ciufelli et al., 2013)

In general, the assessment of facial form was based on quantifying the asymmetry between the two sides of the face. This included the global facial appearance and regional facial features such as forehead wrinkles, eyebrows level, eye-slit length, palpebral fissure width, drop of angulus oris, and loss of nasolabial sulcus.

The evaluation of facial function was conducted mainly by observing facial movements during a set of facial expressions. The visibility of the teeth, nasolabial fold dynamic asymmetry, and corner of the mouth movement-asymmetry were considered in the analysis (Stennert Scale 1977 Facial Palsy Score).

Grading abnormal facial movements was guided by specific benchmarks, these varied between the different scales and were dependent on the patient's ability to perform various facial expressions (Janssen Scale 1963, Smith Scale 1992), the degree of muscle movement of the affected side compared to the healthy side of the face (MoReSS System 2006), the degree of exerted efforts (Facial Nerve Grading System 2.0 2009), the degree of functional recovery (Adour and Swanson Scale 1971) and, the presence of secondary features (Stennert Scale 1977 Secondary Defect Score, Fisch Scale 1981, Sunnybrook Facial Grading System 1996).

The global grading of facial muscle movements provided an overall measure of the function of the seventh cranial nerve (Botman and Jonkees Scale 1955, Pietersen Scale 1976, House and Brackmann 1985, The Rough Grading System 2013).

The regional grading of facial muscle movements was based on the motor units of each of the five main branches of the facial nerve (FEMA Scale 1998 | Forehead, Eye, Mouth & Associated defects), (Sydney Facial Grading System 1995), and of the coordination of a group of muscles of each facial expression (May Scale 1970, Yanagihara Scale 1977). The assessment included forehead wrinkling, eyebrow-raising, frowning, gentle and forceful eye-closure, blinking, smiling, whistling, lip-puckering, grinning, depressing lower lip and, neck-tensing.

The House-Brackmann and the Sunnybrook Facial Grading System are the two main scales to evaluate patients with facial nerve paralysis (Fattah et al., 2015). The House-Brackmann scale (House & Brackmann, 1985) was initially developed by House in 1983, following the assessment and analysis of the reliability of eight different facial nerve grading scales

(House, 1983). This was further refined by (Brackmann & Barrs, 1984; House & Brackmann, 1985) before it became the international standard scale for the assessment of facial palsy. The grades of facial palsy were originally based on the assessment of gross facial nerve function (Appendix A: House and Brackmann 1985), this was followed by the detailed analysis of regional abnormalities. However, there has always been a debate regarding the intra-rater and inter-rater reproducibility and agreement when subjective indices were used for the analysis of facial palsy (Lazarini et al., 2006; Reitzen et al., 2009; Yen et al., 2003).

(Yen et al., 2003) investigated the clinical significance of House-Brackmann facial nerve grading in the assessment of differential facial nerve function in thirty-eight facial palsy patients. The clinical assessment was conducted using the traditional HB scale in addition to a modified version the study introduced. The House-Brackmann scale assessed the gross facial nerve function, in which, the patients were assigned into one of the six grades representing the global score. The grades were compared with the regional scale that assigned one of six grades for each of the forehead, eye, nose, and mouth regions. The agreement between the global and regional scores was analyzed. In comparison to the regional scores, the single HB score was most strongly correlated with the regional scores at the eye (61%) this was followed by the nose (40%), mouth (32%), and forehead (18%). The study found the House-Brackmann single score was inadequate to describe facial nerve function in cases showing varying degrees of nerve weakness.

Similarly, in 2009, the significance and reliability of the House-Brackmann grading system for regional facial nerve function were further explored by (Reitzen et al., 2009). Digital videos were generated for eleven facial palsy patients who performed a protocol of facial expressions that assessed facial movements in the five branches of the seventh cranial nerve. The videos were made available to a group of fourteen assessors of different levels of clinical expertise. The assessment of facial palsy was conducted using the original House-Brackmann scale and a regional version for the forehead, eye, nose, and mouth. The study investigated the agreement between the two clinical scales as well as the inter-rater agreement. The single HB score was shown to be most strongly correlated with the regional scores for the nose (59%), followed by the mouth scores (51%), the eye (48%), and forehead scores (35%). The authors found that the single HB score does not represent the most affected area of the face. Furthermore, it does not correlate well with the regional scores (Kappa coefficients were 0.5 at nose scores, 0.41 at mouth scores, 0.33 at forehead scores, 0.30 at the eye). The study explored the agreement among assessors with similar levels of experience. Interestingly, it was found that the level of agreements among the regional scores increased as training and experience increased, whereas the agreement of the global scores remained the same.

In 2006, (Lazarini et al., 2006) proposed a new version of the House-Brackmann facial nerve grading in which a graphic representation of peripheral facial palsy was introduced (Figure 1). The face of thirty-two facial palsy patients was photographed. The pictures were taken with the face at rest, with the face showing mild effort and at maximum expression. Three professional assessors evaluated the degree of facial palsy using the original HB scale and after seven days using the graphical version. The assessment was repeated after 30 days. The gradings of the first rating session were compared using the concordance index for the validation of the new graphic version. The study assessed the reproducibility of the clinical gradings between the two sessions and found neither scales provided perfect reproducibility. The average values of reproducibility of the HB scale and the graphical version were 65%, 75%, respectively.

Figure 1: Graphical Version of House-Brackmann Scale

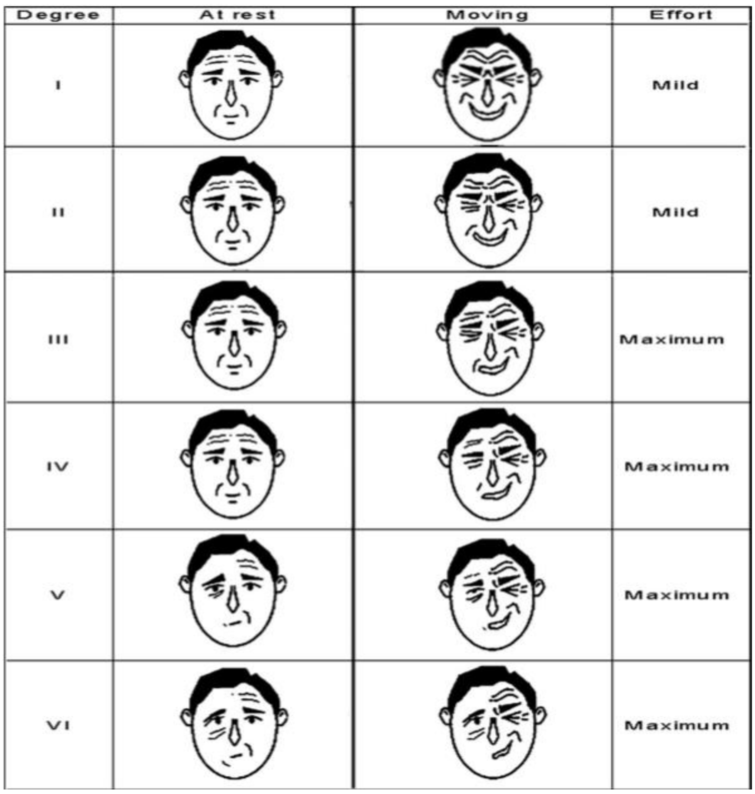


Figure 1 shows schematic representation of the face based on House-Brackmann scale, (Lazarini et al., 2006).

In 2009, a revised version of the original House-Brackmann scale was presented by the Facial Nerve Disorders Committee of the American Academy of Otolaryngology AAO (Appendix A: Facial Nerve Grading System 2.0 2009) (Vrabec et al., 2009). The grading scale incorporated regional scoring of facial movements on a six-points Likert scale for the assessment of dysmorphology at the brow, eye, nasolabial fold, and oral regions. The FNGS 2.0 evaluated the secondary sequelae of facial palsy (synkinesis) and provided a gross score. The sum of the regional scores and the secondary movement scores assigned the patient into one of five facial palsy grades. The performance of the FNGS 2.0 was compared to the original House-Brackmann scale. In that regard, videotapes of twenty-one facial palsy patients, who performed a set of standardised facial expressions (eyebrow raising, eye closure, snarl, and wide smile), were viewed by fourteen physicians committee members of the AAO. The evaluation of facial palsy using the two grading scales did not include a calibration protocol of the assessment criteria. The professional assessors had no special grading instructions and the assessors were allowed to view the video images an unlimited number of times before submitting the scores. The FNGS 2.0 and the House-Brackmann scale showed similar level agreements (Fleiss Kappa 0.38, 0.39 respectively, ICC 0.98 for both).

In a call for uniformity, (Fattah et al., 2015) conducted a literature review with the intended goal of assessing the best clinical scale that satisfies the objectives of the clinical assessment; these included the ease of clinical use, the assessment of the face at rest and during function, regional scoring with consideration to the secondary features of facial palsy and the sensitivity to track recovery over time. The authors evaluated nineteen facial nerve grading scales against the established criteria with the main emphasis on reproducibility, interobserver, and interobserver variability. Only the Sunnybrook facial grading system satisfied all the criteria. The Sunnybrook facial grading system has been proven to be reproducible with high intraobserver (ICC ranged from 0.83 to 0.98) and interobserver (ICC ranged from 0.83 to 0.99) agreement. In addition to its sensitivity to the changes over time and in response to therapy. The authors recommend Sunnybrook facial grading system as the standard for reporting abnormal facial nerve function.

The subjective nature of the methods remains the major inherent limitations in these methods (Lee et al., 2013). The limited objective evaluation of the facial muscle function has always been a major concern (Linstrom et al., 2000).

Facial Anthropometry

Direct facial measurement methods depend on the measurements of distances or angles between defined facial landmarks at rest and during function. Measurements are frequently expressed as a ratio or a percentage of normal function (Table 2).

Table 2: Anthropometric Measurement Methods of Facial Palsy

Facial Palsy Direct Facial Measurement Systems	
System	**Reference**
Linear Measurement Index	(Burres & Fisch, 1986)
Facial Nerve Function Index	(Fields & Peckitt, 1990)
The Facial Nerve Function Coefficient	(Peckitt et al., 1992)
Lip Length and Snout Indices	(Jansen et al., 1991)
The Nottingham System	(Murty et al., 1994)
Frey's Faciometer	(Frey et al., 1994)
Manktelow's Handheld Ruler Measuring Technique	(Manktelow et al., 2008)
Saito's Facial Grading System	(Saito, 2012)

The Nottingham System relies on the distance change between the supraorbital and infraorbital landmarks during wrinkling of the forehead and forceful eye closure, as well as the distance change between the lateral corner of the eye and the corner of the mouth at maximal smile (Murty et al., 1994).

The Snout Index is based on the distance difference between the corners of the mouth at rest and at maximal lip pucker to characterise face paralysis (Jansen et al., 1991).

(Manktelow et al., 2008) assessed the severity of facial palsy by measuring the distance between the philtrum, and both the commissure and mid lip at a maximal smile. The angles of lip-shift at rest and with expressions were used by (Saito, 2012) for the evaluation and grading of facial palsy.

While direct facial anthropometric methods bring objectivity to the assessment, these methods have limitations. The evaluation of distorted muscle movements in facial palsy using measurement tools, such as handheld ruler or caliper, does not describe the dynamics of facial expressions and is prone to human error (Niziol et al., 2015). The methods of assessment that are based on measurements of distances, angles, and ratios between a set of facial landmarks do not describe the dynamics of distorted facial expressions.

Digital Assessment Methods Using Two-Dimensional Imaging

(Table 3) shows the assessment of symmetry and distorted function of facial palsy based on the analysis of two-dimensional photographs and video images.

Table 3: Two-Dimensional Analysis Methods of Facial Palsy

Facial Palsy Digital Assessment Methods Using 2D Imaging		
System	**Method**	**Reference**
Asymmetry Indices (AI) of facial deviation	2D Photography	(Inokuchi et al., 1991)
Maximum Static Response Assay (MSRA)	2D Photography	(Johnson et al., 1994)
Indices of Facial Motion: anatomic and non-anatomic	2D Photography	(Bajaj-Luthra et al., 1997)
Facial motion analysis using Photoshop	2D Photography	(Pourmomeny et al., 2011; Sargent et al., 1998)
Scaled Measurement of Improvement in Lip Excursion (SMILE system)	2D Photography	(Bray et al., 2010)
Facial Assessment by Computer Evaluation (FACE system)	2D Photography	(Hadlock & Urban, 2012)
Oral-ocular synkinesis assessment method	2D Photography	(Mabvuure et al., 2013)
Facial Analysis Computerised Evaluation (FACE)	2D Video Analysis	(Neely et al., 1992)
Objective Scaling of Facial Nerve Function (OSCAR)	2D Video Analysis	(Meier-Gallati et al., 1998)
Video Micro Scaling	2D Video Analysis	(Wood et al., 1994)
Moiré Topography Index	2D Video Analysis	(Yuen et al., 1997)
Automated Facial Analysis (AFA)	2D Video Analysis	(Wachtman et al., 2001)
The Peak Motus Motion Measurement System	2D Video Analysis	(Linstrom, 2002)
Video Mimicography (VGM) Method	2D Video Analysis	(Dulguerov et al., 2003)
The Facial Reanimation Measurement System	2D Video Analysis	(Tomat & Manktelow, 2005)
Glasgow Facial Palsy Scale	2D Video Analysis	(O'Reilly et al., 2010)
Facegram for spatial-temporal analysis of facial excursion	2D Video Analysis	(Horta et al., 2014)
Interest Point Tracking	2D Video Analysis	(Truc Hung et al., 2015)

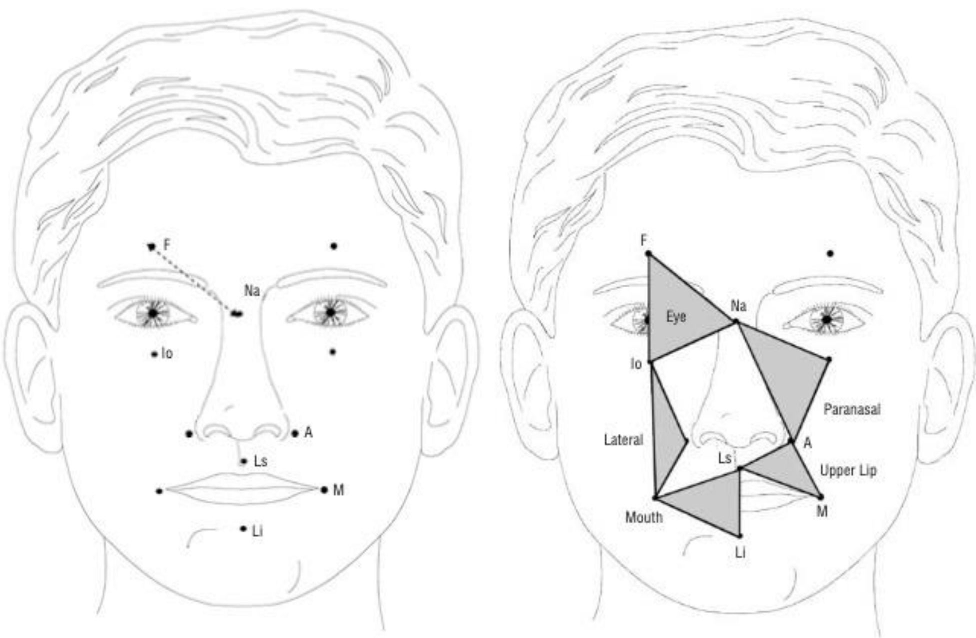
The analyses of the 2D facial images included Moiré Topography (Inokuchi et al., 1991; Yuen et al., 1997), optical flow (Minamitani et al., 2003), Pixel-subtraction of a digital facial image at rest and at maximal expression (Sargent et al., 1998), selective image opacity of overlaid facial images at rest and maximum expression (Tomat & Manktelow, 2005), subtraction of landmark position in 2D space (X, Y) at maximal expression (Johnson et al., 1994).

The distances between facial landmarks and a reference midline allowed the comparison between the two sides of the face (Bray et al., 2010; Hadlock & Urban, 2012).

Nina Franka Berlin, 2014 compared five different 2D methods for the analysis of facial asymmetry. These involved the utilisation of reference points, measurement of horizontal distances from a vertical reference line, measurement of vertical distances from a horizontal reference line, measurement of distances between bilateral points without a reference line, and angle measurements. The author highlighted the importance of proper selection and the accurate identification of reference points. The accuracy of the assessment was dependent on the availability of a sufficient number of reproducible facial landmarks.

Regional analysis of facial paralysis was considered. (Mabvuure et al., 2013) measured the ratio of altered muscle movements during facial expressions of the orbital region of the affected side in comparison with the opposite normal side. (Dulguerov et al., 2003) considered other areas of the facial region specified by a surface of a triangle between 3 facial points (Figure 2). (Li'an et al., 2010) measured the differences in the facial regions between the affected and the normal sides as a result of facial movements during eye closure and forehead wrinkling to quantify the distortion of muscles function.

Figure 2: Regional Analysis of Facial Palsy



Dynamic assessment of facial expressions

The dynamic asymmetry of facial expressions was assessed by tracking the movement of facial markers (Linstrom et al., 2002). This allowed the measurement of the magnitude, speed, velocity, and direction of facial movements (Wachtman et al., 2001), and the evaluation of the spatial and temporal positions of facial landmarks during muscle movements (Horta et al., 2014).

Features of facial movements were extracted by means of digital image analysis such as the local binary patterns in which the symmetry of facial movements was measured by the average distance between the local binary pattern features (Shu et al., 2008) and pixel change during facial movements (O'Reilly et al., 2011).

Two-dimensional versus 3D facial measurements

Traditional assessment methods of facial palsy do not account for the geometrical properties of facial shapes in the analysis. The accurate capturing of the 3D facial surface facilitated the assessment of facial morphology and function in the three dimensions of space which is of considerable clinical interest.

Anas et al., 2019 investigated the difference between 2D and 3D methods for the assessment of facial measurements in 150 participants. The face was captured with a 2D camera and 3D facial laser scanner. A set of 22 facial landmarks were digitised and the Euclidian distances between 13 pairs were provided by computer software. Statistically significant differences were detected between the 2D and 3D linear measurements at all paired differences, in which the 3D laser measurements were higher compared to the 2D measurements. The interclass correlation coefficient between the average 2D and 3D measurements was very low 0.26 (95% confidence interval, 0.15 – 038).

Gross et al., 1996 compared the amplitude of facial motion recorded using 2D and 3D video cameras. The movements of 15 facial landmarks were measured during smile, lip purse, grimace, eye closure, and cheek puff. Two dimensional underestimated the magnitude of facial movements at maximum expression by 43%, the authors concluded.

Geometric Morphometrics: General Principles and Applications

This section provides an overview of the general concepts of 3D facial measurements using advanced geometric morphometric methods and their clinical application for the assessment of the morphology at rest and during facial expressions. This provides an insight into the major technological advancements in this domain and debate the novel application of advanced morphometry in the analysis of facial palsy.

In Geometric Morphometrics, the face is evaluated as a mathematical shape that incorporates the facial geometry and its morphology simultaneously (Brunton et al., 2014).

The 3D recording of facial morphology

The quantitative assessment of facial morphology and function is crucial in the prospect of restoring normality in patients with facial dysmorphology. In a recent systematic review, (Petrides et al., 2020) investigated the accuracy, reliability, and usability of 3D scanners for facial assessments. The recording of the 3D morphology of the face was achieved using various imaging technology including laser-based scanning, stereophotogrammetry, structured-light scanning, RGB-D sensors. Stereophotogrammetry has been shown consistently to be excellent in recording facial morphology (Fourie et al., 2011; Kook et al., 2014; Tzou et al., 2014). It provides invaluable volumetric and morphologic analysis and allows the capture of facial movement over time.

To facilitate mathematical facial shape analysis using advanced geometric morphometrics, facial shapes were first defined by a set of descriptors. This was followed by the extraction and registration of the facial features to allow statistical shape analysis and modeling. The assessment methods varied in the ways they represent facial shapes and the approach of analyzing the extracted data (Cooke & Terhune, 2015).

Facial Shape Descriptors

Facial shapes were mathematically defined by three main approaches; facial anatomical landmarks, facial curvatures, and facial surfaces.

Anatomical Landmarks: The facial morphology is represented by a set of anatomical landmarks. The three-dimensional configurations of facial landmarks are utilised for the assessment of facial shape.

Facial curvature: Anatomical facial curves are extracted from the 3D facial image and analysed using statistical shape analysis methods. This may include the midline curve of the face, the curve of the bridge of the nose, nasal base curvature, and contours of upper lip.

(Bell et al., 2014) quantified residual facial asymmetry in surgically repaired unilateral cleft lip and palate using facial landmark-based analysis and facial-curve analysis. Mean group asymmetry scores were calculated and then compared between both groups and a control group.

One of the deficiencies of these facial representation methods is the limited number of facial anatomical landmarks that can be reliably identified on the face (Gwilliam et al., 2006). The majority of these landmarks are feature-bound and located at the centre of the face. Therefore, analyses of cheeks, forehead, chin regions were limited.

Facial curve analysis is a logical progression to landmark-based methods in which a set of mathematical points are generated between specific anatomical landmarks to form a 3D curvature. Facial curves extracted from 3D images allowed the analysis of facial asymmetry by measuring the changes in surface curvatures over time or comparing two groups of patients (Miller, 2009). But, the soft tissue analysis of the profile curvature is limited and does not describe the 3D facial surface (Lin et al., 2016).

Facial Surface:

Surface based methods take into consideration the entire facial surface which allows for a comprehensive assessment of the morphology. A common approach for the analysis of facial surface is based on a dense anthropometric mask (facial mesh). The mesh is composed of thousands of mathematical landmarks, which create a dense correspondence with the original 3D facial image, hence it provides a comprehensive representation of the 3D facial shape (Mao et al., 2006).

Figure 3: Surface-Based Shape Descriptors

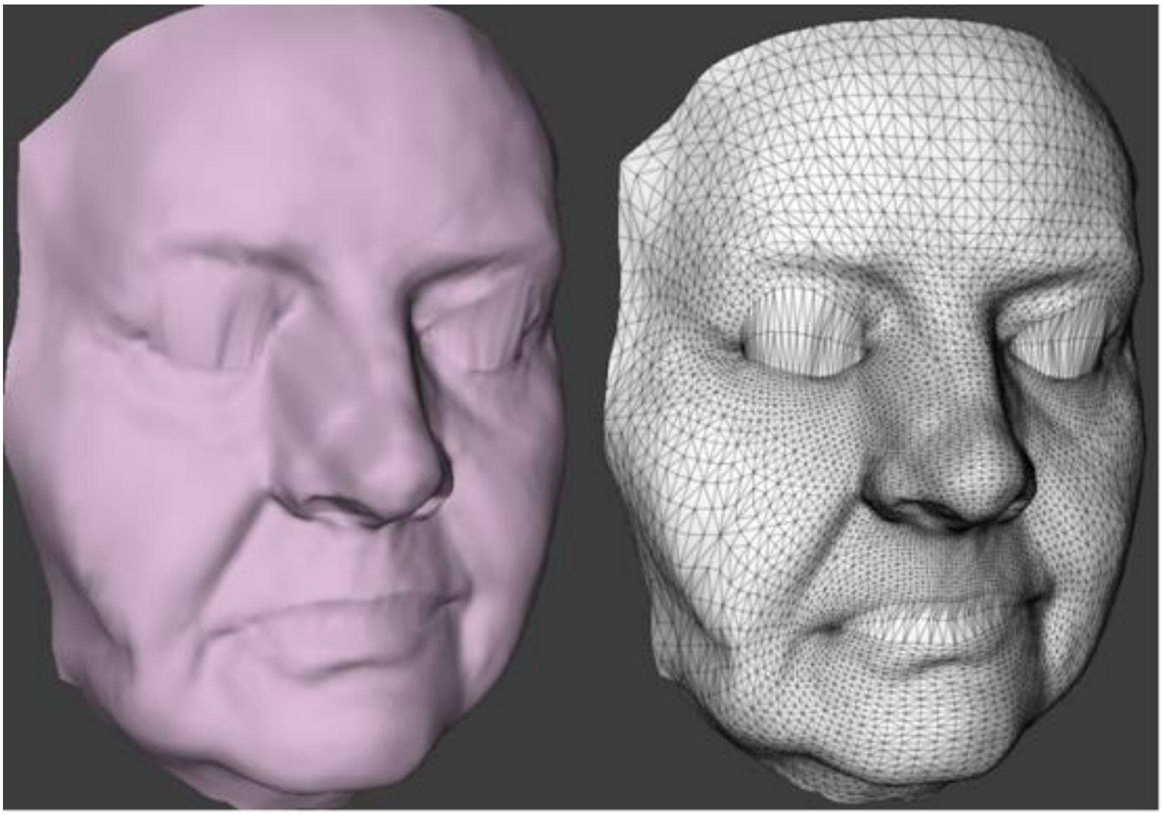


Figure 3 shows the facial surface represented by means of a 3D facial model (L) and a spatially dense anthropometric mask (facial mesh) (R).

The diagnostic information obtained by landmark- and surface-based 3D assessments was investigated by (Alqattan et al., 2013), both were proven to be accurate in the quantification of facial asymmetry of the face.

Facial Shape Registration

Shape registration establishes a relationship, mathematical correspondence, between two or more facial shapes (Tam et al., 2013). This general term is also known as shape alignment and shape superimposition.

Mathematically, the shape is defined as the geometric information after location, rotation, and size differences are removed (Dryden & Mardia, 1998). In advanced geometric morphometric approaches to model facial shapes differences, non-shape variables are the first to be filtered out by means of shape registration, including translation, rotation, and rescaling.

In landmark-based methods, shape registration is based on the 3D coordinates of facial landmarks representing the face (Webster & Sheets, 2010).

Procrustes analysis is a common approach for the registration of landmark data (Ross, 2004). The algorithm brings the sets of facial landmarks into a common coordinate system and centres the data by searching for a Procrustes fit, that is the least squared distance between corresponding sets of facial landmarks.

There are two distinct versions of the Procrustes algorithm; the Generalised Procrustes Analysis and Partial Procrustes Analysis. The distinction between them is whether the size difference between given facial shapes is accounted for or not. Generalised Procrustes Analysis is applied in the context of pure shape analysis where non-shape variables, including size, are removed. Whereas, in Partial Procrustes Analysis size difference is maintained.

(Hajeer et al., 2004) assessed the three-dimensional facial asymmetries in patients undergoing orthognathic surgery using a landmark-based approach. 3D facial images were captured before and after surgery to investigate facial asymmetry. Individual facial asymmetry was computed by superimposing the original landmark configuration on its mirrored configuration using Partial Procrustes analysis. The mean of the squared distances between all the pairs of corresponding landmarks was expressed as the facial asymmetry score.

Morphometric study on gender differences was conducted by (Bugaighis et al., 2011) to explore the variation in the 3D facial morphology among 8-12 years old Caucasian children (39 males, 41 females). The 3D facial images were captured using a stereophotogrammetry camera. Thirty-nine anatomical landmarks were digitised on the face. Statistical shape modeling was conducted on the 3D coordinates of landmark data which were extracted for each gender group. The corresponding landmark configurations were superimposed using General Procrustes Analysis GPA to build the average face of each gender group. Shape variations were analyzed using GPA and principal component analysis. No significant differences were found between the average facial morphology between males and females. In a further study, (Bugaighis et al., 2012) compared the average facial morphology between participants with cleft and non-cleft participants using the same approach.

Two types of surface-based registrations were considered in the literature the rigid registration or non-rigid registration (elastic deformation) (Audette et al., 2000). These differ in the way facial shapes are related to each other.

In rigid registration methods, facial shapes are aligned to achieve the best approximation. An established method for 3D image rigid registration is the Iterative Closest Point (ICP) algorithm. ICP is an automated process that involves two main steps; shape alignment "orientation" to achieve a good initial estimation of relative positions by identifying a corresponding set of landmarks, followed by rotation and translation "superimposition" to achieve closest point correspondence. This process is iterated until no further refinement could be achieved in approximating the corresponding surfaces (Padia & Pears, 2011).

(Dhelal Al-Rudainy et al., 2018) applied this method to assess the outcome of primary surgical repair of unilateral cleft lip. The 3D facial images were captured before and after surgery. Facial asymmetry was quantified using the ICP algorithm to measure the impact of surgery in improving facial symmetry, Figure 4.

Figure 4: Rigid Registration Method

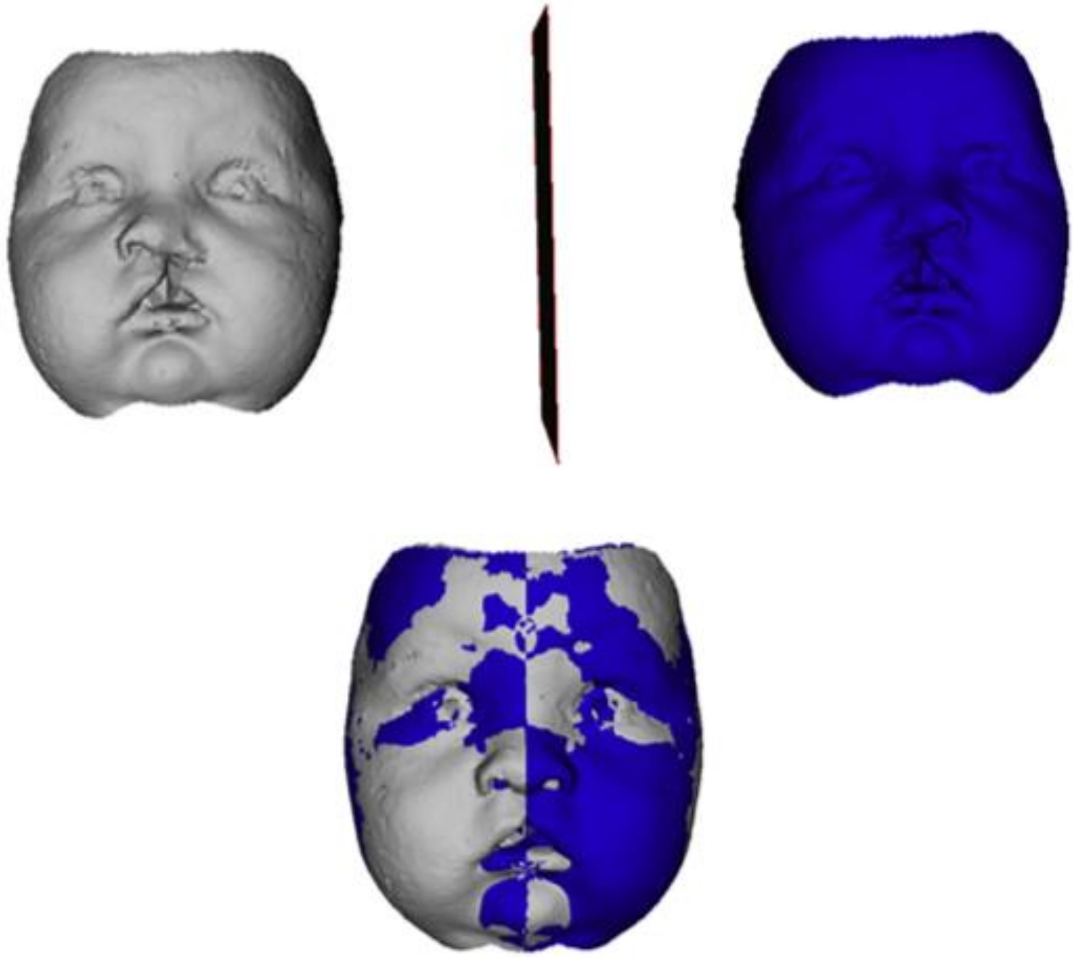


Figure 4 shows the surface registration method using the ICP algorithm. Top left: 3D facial model. Top right: mirror copy. Bottom: the superimposed original and mirrored replica (Dhelal Al-Rudainy et al., 2018).

In non-rigid registration methods, one facial shape is considered the target shape and to which other facial shapes are conformed, similar to the analogy of a glove that takes the shape of a surgeon's hand. The elastic deformation of one shape into another describes shape differences statistically and visually.

A dense anthropometric facial mask was applied by (Wong et al., 2018) to evaluate the residual nasolabial deformity in unilateral cleft lip and palate prior to orthognathic surgery. The 3D facial shapes of 16 adult patients and 48 controls were captured at rest using a stereophotogrammetric system. Forty-two anatomical landmarks were digitised on the face and these were used to conform a generic facial template of 3072 vertices on the 3D facial morphology of study cases. The conformed meshes of individual facial morphology were utilised to build an average facial template for each group. Statistical shape analysis between the conformed average facial templates of the UCLP and controls was conducted by quantifying and comparing the differences in mean average asymmetry.

D. Al-Rudainy et al., 2018, applied the elastic deformation method using a spatially dense anthropometric mask to assess facial asymmetry before and after surgical repair of cleft lip in UCLP patients. The novel technique provided new insights about the characteristics of facial asymmetry, Figure 5.

Figure 5: Elastic Registration Method

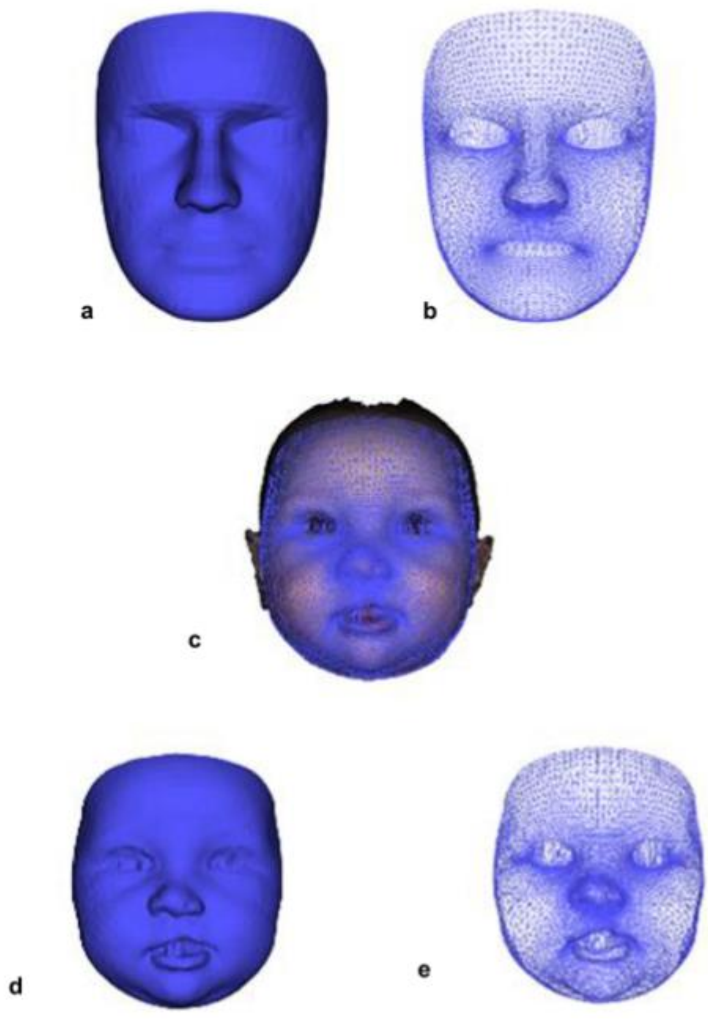


Figure 5 shows the surface registration method using deformable facial template. A: surface model. B: anthropometric mask. C: conformation of the generic mesh on the facial model of UCLP patient. D: surface model. E: conformed mesh, (D. Al-Rudainy et al., 2018).

Analysis of 3D Facial Asymmetry

Individual facial asymmetry may be quantified by computing the facial shape difference between a given shape and its mirrored copy. The assessment of facial asymmetry at different time points was applied to monitor the impact of the surgical correction on facial asymmetry in oral and maxillofacial surgery (Claes et al., 2012) and to assess facial asymmetry in growing individuals (Primozic et al., 2012).

According to the landmark-based approach, asymmetry is measured between the original 3D configurations of facial landmarks and their corresponding mirror images. This method is susceptible to the "Pinocchio effect" in which, large dissimilarities between a small number of superimposed landmark configurations may underestimate the degree of shape difference between the remaining landmark configurations (Zelditch et al., 2012).

In the surface-based approach, different calculation methods have been used to measure the distance between the registered facial surfaces (Miller et al., 2006), Figure 6.

Figure 6: Representation of Rigid Registration Methods

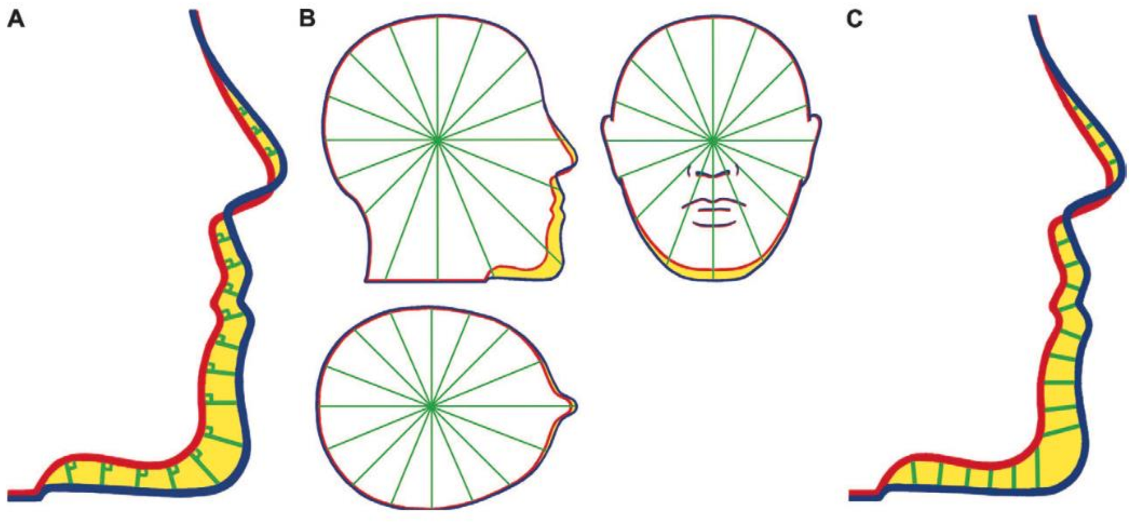


Figure 6 provides diagrammatic representation of three different calculation methods to measure the distance between the facial surfaces. A: the normal method (perpendicular line between the points of aligned surfaces). B: the radial method (involves constructing a line from the centroid of reference shape to the point of intersection with the surface of both scans. C: the ICP method (measures the distance and direction of the closest point between the two surface models), (Miller et al., 2006).

The Iterative Closest Point algorithm is mathematically robust for the registration of corresponding surfaces. However, from a clinical perspective, the best mathematical fit between the facial image and its corresponding mirror copy, may not necessarily maintain the anatomical correspondence and therefore misinform the analysis of the asymmetry (Verhoeven et al., 2016).

Ozsoy, 2016 analyzed the global (overall facial asymmetry) and partial facial asymmetry using three methods to calculate the surface distance between the facial shape and its mirrored replica. The root mean square distance "RMS", the mean absolute deviation value "MAD" and the mean signed distance value "MSD" were measured between the original surface model and its mirror replica. The authors found the RMS and MAD accurate and reliable for the assessment of facial asymmetry (RMS and MAD scores showed high correlation (r = 0.98) with similar coefficient of variation (30%). MSD showed lower correlation with RMS (r = -0.62) and MAD (r = -0.25). The coefficient of variation for MSD was significantly greater (133%). This highlights the impact of measurement method on the interpretation of facial asymmetry, Figure 7.

Figure 7: Facial Asymmetry Calculation Methods

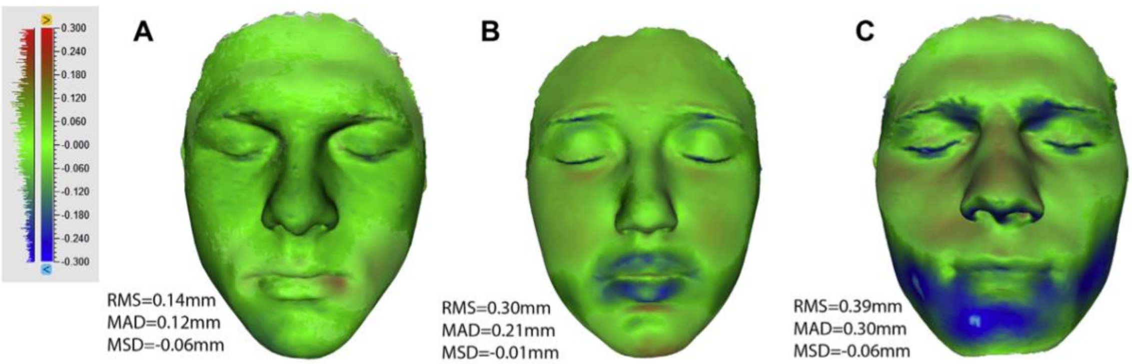


Figure 7 demonstrates the different calculation methods of facial asymmetry (RMS, MAD, MSD) in three individuals (A, B, C). The colour-coded maps after the superimposition of the facial shape of the same subject and its mirrored replica, (Ozsoy, 2016).

The application of deformable facial models overcame the limitations of the rigid registration methods. (Claes et al., 2012) Demonstrated the improved facial assessment using 3D anthropometric mask in comparison to the rigid registration method by the iterative closest point algorithm regarding the assessment of direction and magnitude of change. This is demonstrated in Figure 8. On the other hand, the facial mesh is composed of several thousands of mathematical landmarks which results in high dimensional data. When applied to large data set of facial movements, statistical shape analysis and modeling have been proven challenging (Bolkart & Wuhrer, 2015).

Figure 8: Comparison between Surface Registration Methods

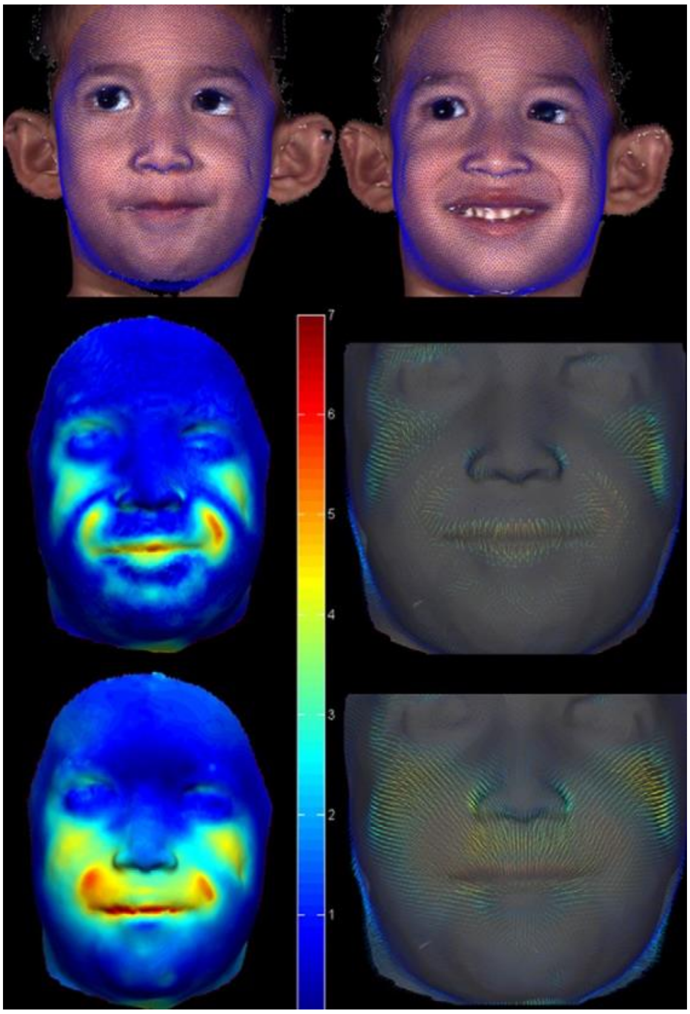


Figure 8 demonstrates the empowered ability of deformable models for the analysis of facial morphology. Top row shows the anthropometric mask conformed on the face of patient at rest and at smile expression. The middle row illustrates the distance map on the left and the vector field on the right generated by the iterative closest point algorithm. Discontinuities in the maps indicates the intersection between the superimposed surfaces. Conversely, no discontinuities are shown in the deformable method (bottom row). The differences between the surfaces were depicted in the distance map on the left and the vector of displacement on the right, (Claes et al., 2012).

Analysis of 3D Facial Movements

In an era of technological advancements and innovations, facial analysis can now be conducted in three dimensions over time (Tzou et al., 2014). The availability of 4D facial imaging systems allowed the recording of facial movements by capturing 3D facial image sequence at a given rate per second.

Facial muscle movements were investigated during a set of expressions (Trotman et al., 2010) and during phonation (Popat et al., 2012).

In 2011, Carroll-Ann Trotman described a statistical method for modeling facial muscle movements. In a time series of 3D facial images, the 3D movements of 38 landmarks were recorded during smile. The distance between any 2 landmarks at rest was considered a measurement unit. The change in the inter-landmark distance during smile from rest characterised the dynamic motion of landmarks, Figure 9, (Trotman, 2011). This approach was applied to assess the effect of lip revision surgery in cleft lip and palate “CLP” (Trotman et al., 2010). The study included three groups (patients with CLP who had lip revision surgery, patients with repaired CLP who didn’t have revision surgery, and a control group). Thirty-four participants were recruited for each group. For each participant, the changes of pairwise distances in 44 facial landmarks tracked in 3D during the performance of a set of facial expressions were calculated. The mean changes of the inter-landmark distances between the landmarks during facial expressions were calculated and analyzed (Trotman et al., 2010). The statistical shape modeling of the mean expression movement between the patient groups and the control group was analyzed using Principal Component Analysis (PCA) and Dynamic Time Warping (DTW). The PCA explained shape variations in 240 3D-image sequence of each facial expression per individual, in which the facial shape in each image was represented by the 38 3D landmarks. The first PC indicated the main movement in the expression and a motion curve was produced by plotting the PC1 scores against time. Dynamic Time Warping algorithm allows the measurement of similarities between motion curves (temporal sequences) which may vary in speed. The DTW algorithm identified the 4 transition points of time during the performance of facial expression (start from rest, reaching maximum expression, attainment of maximum expression, returning to rest) and the motion curves were aligned, Figure 10. This approach allowed a sophisticated analysis of facial movements, however, the analysis considered the motion itself independent of the facial morphology. Furthermore, the analysis was based on a set of landmarks and therefore is not comprehensive enough as dense surface correspondence methods.

Figure 9: The Change in the Interlandmark-Distance During Smile

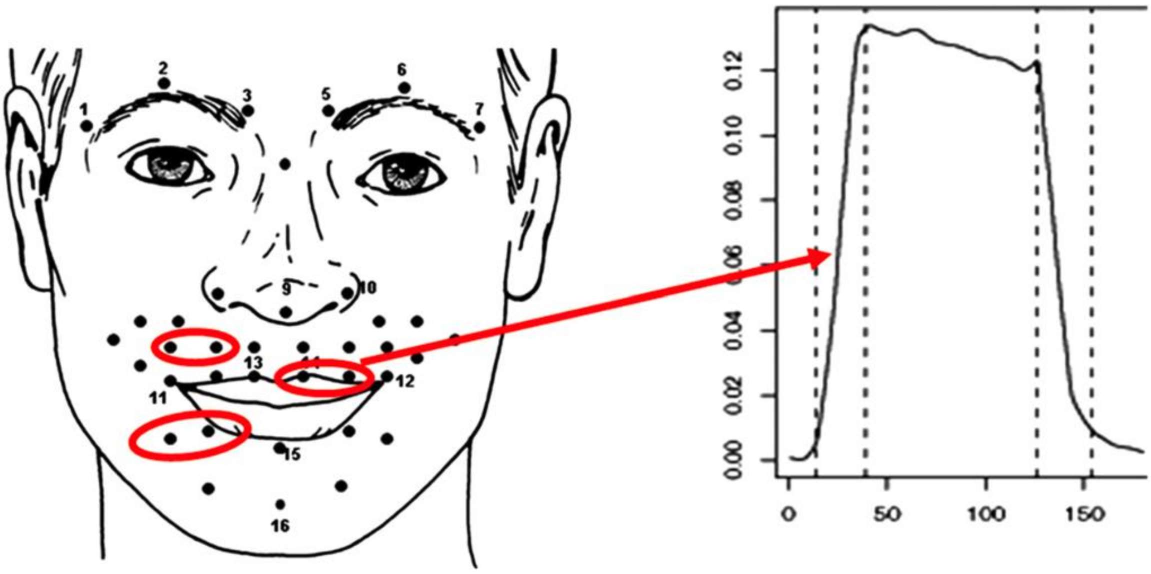


Figure 9 shows the graph featuring the change of inter-landmark distance between two landmarks on the upper lip. Upon the performance of the smile, the inter-landmark distance increased (indicated by the red arrow), then the horizontal line on the graph indicated the inter-landmark distance was maintained as the smile movement reached the maximum expression. This was followed by the decrease of the inter-landmark distance as the patient relaxed, (Trotman, 2011).

Figure 10: Motion curve analysis using DTW

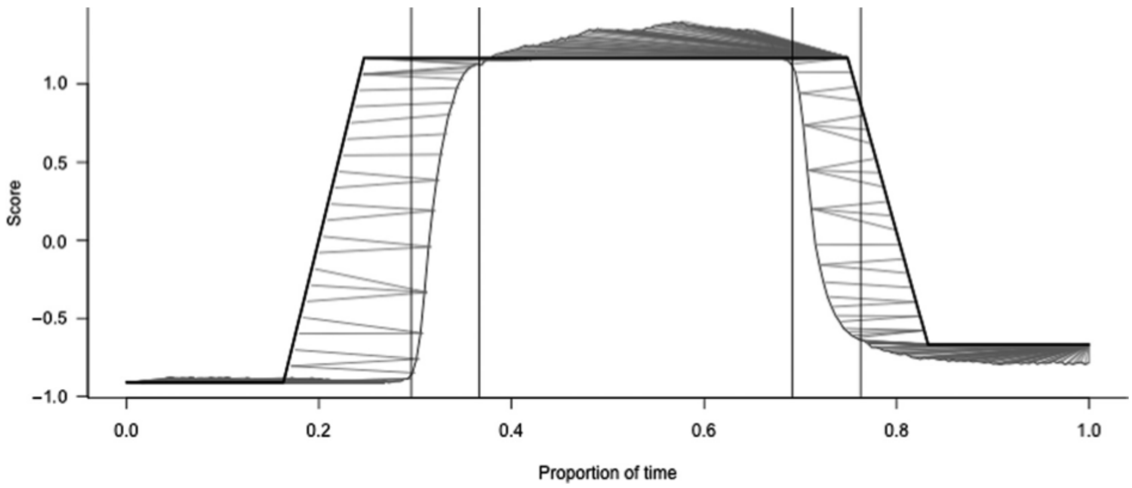


Figure 10 shows the motion curve produced by plotting the PC1 scores against time. DTW identifies and matches the corresponding points to allow the measurement of similarities between temporal sequences, (Trotman et al., 2010).

Statistical modeling of the average lip movement during speech in healthy subjects was conducted by (Popat et al., 2012). The 3D facial movements were recorded during the performance of 4 verbal gestures. Six facial landmarks were digitised on the face and the 3D coordinates of which were extracted from the 3D facial frames at rest and at maximal expressions. Landmark data were superimposed by Procrustes analysis, Figure 11. Principal component analysis was applied to the registered 3D landmark data to explore the variations in the movement of lip landmarks at each verbal gesture, Figure 12. The variations in the vector of the maximum landmark displacement were defined by the PC scores to measure the highest variation in the data set (PC1) as well as the subsequent components of the next highest variations (PC2, PC3.etc.). This landmark-based approach allowed the statistical modeling of the average lip movement. The application of PCA explained the main variations in the landmark displacements during different expressions. However, the assessment was limited to 6 landmarks representing the 3D facial morphology of the face. Therefore, it was not able to describe the morphological changes at the individual facial regions at the different verbal expressions.

Figure 11: Procrustes Superimposition

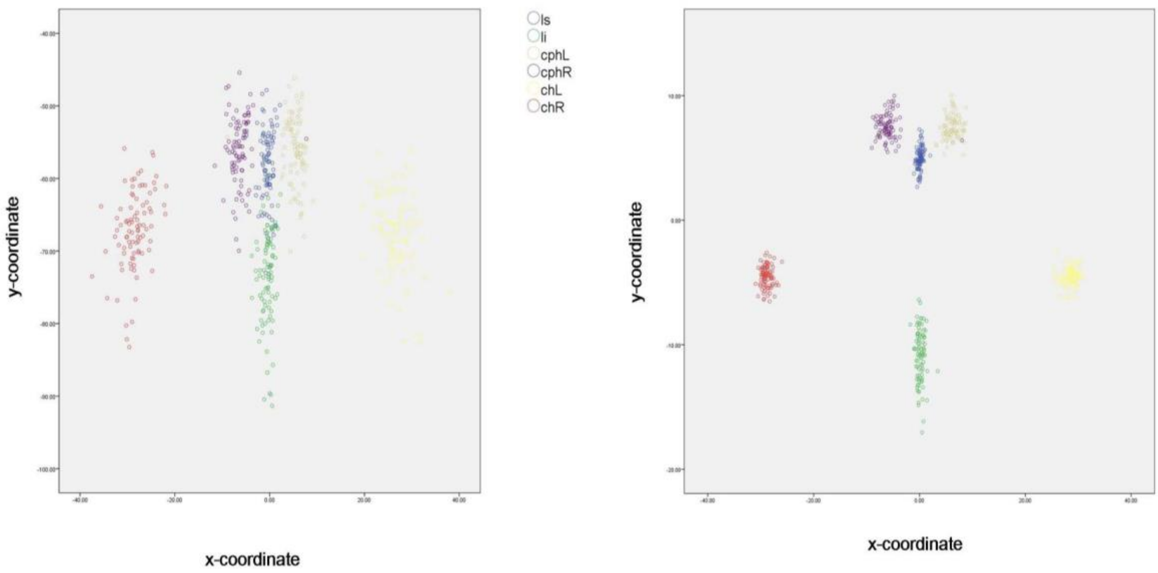


Figure 11 shows the extracted 3D landmark data of facial shapes at rest on left. The right image demonstrates the application of the Generalised Procrustes Analysis which removed the differences in the location and rotation in the landmark data, (Popat et al., 2012).

Figure 12: Modeling Average Lip Movement During Speech

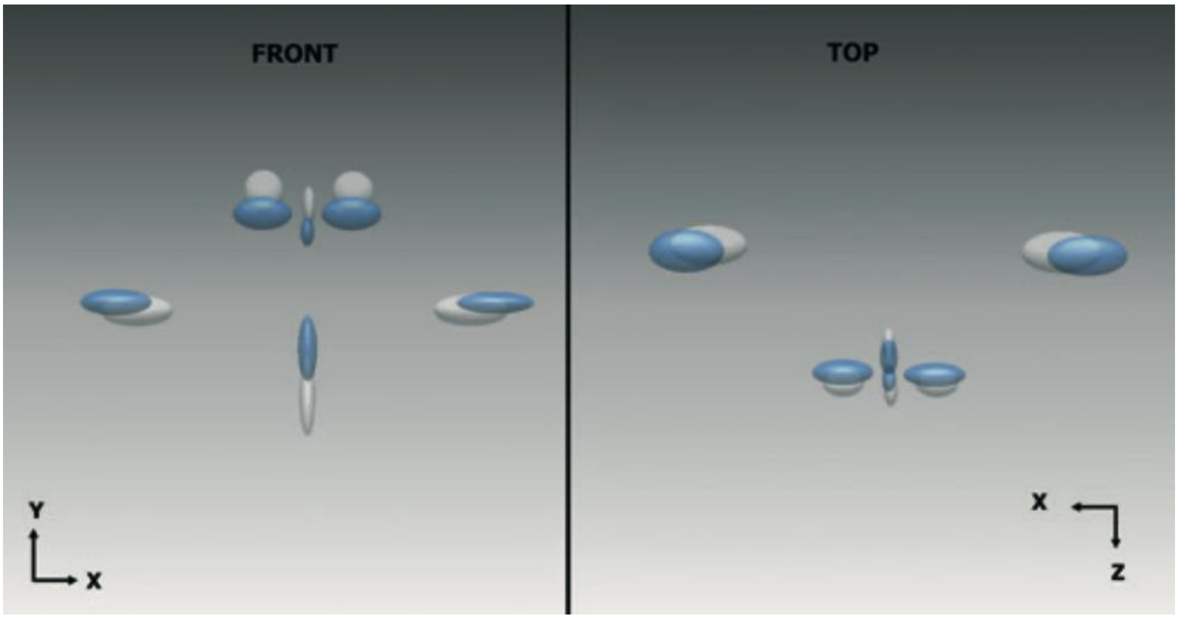


Figure 12 shows the variations in the movement of lip landmarks from rest (blue colour) to verbal gesture "bob" (white colour), (Popat et al., 2012).

The true strength of advanced geometric morphometrics relies on its ability to quantify and visualize shape differences, similarities, and variations between two or more facial shapes (Brunton et al., 2014; Stegmann & Gomez, 2002).

The change of facial morphology from rest and during facial movements were measured, in that regard, two main approaches have been reported in the medical literature for the 3D assessment of facial dynamics:

The static approach considered facial asymmetry at the maximum movement from rest. (Al-Hiyali et al., 2015) assessed the impact of orthognathic surgery on facial expressions in patients with dentofacial deformities. The study evaluated facial asymmetry at rest and at maximum smile before and after the surgical correction of facial deformities, Figure 13. The main drawback of the static approach is that the quantification of asymmetry at the maximum expression does not measure the patterns of dynamic facial dysmorphology throughout the course of muscle movements. Even though this may provide some information regarding the magnitude of facial movements it does not describe the pattern and most of these studies are limited to the assessment of facial asymmetry at the rest pose and at maximum expression.

Figure 13: Facial Asymmetry During Smile

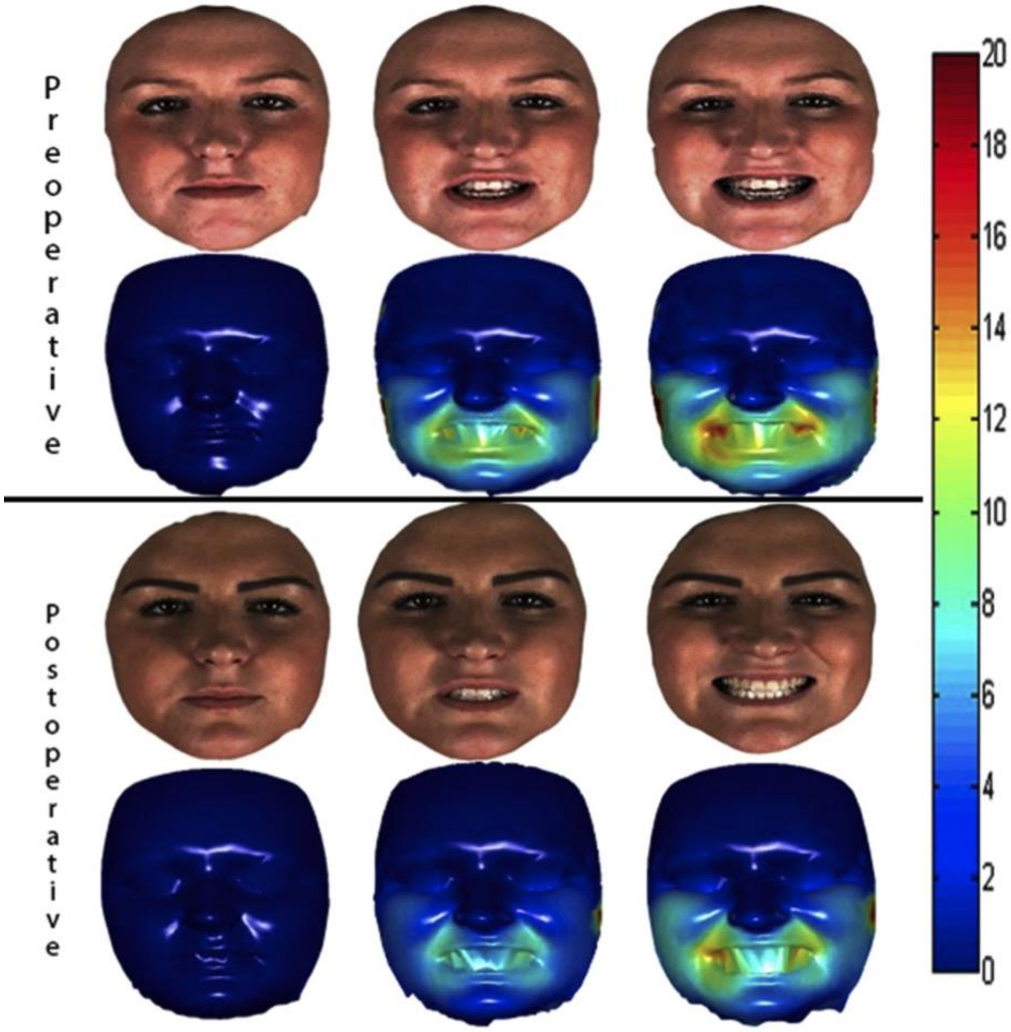


Figure 13 shows the improved facial asymmetry during the smile expression indicated by colour-coded facial maps postoperatively in comparison to the preoperative asymmetry (Al-Hiyali et al., 2015).

The dynamic approach which considers the change of facial morphology during muscle movements is now considered the contemporary approach for the assessment of facial movements. This allowed the magnitude, direction, speed, and motion path of facial expressions to be measured over time. The direction of facial movements may be described by the vector of landmarks displacement from the 3D capture image "frame" at resting position to the frame at maximum expression ending with the rest pose. The motion path of facial movements could be visualised by tracking the movements of 3D configurations of facial landmarks identified on a 3D facial frame at rest throughout the full 3D image sequence of facial expressions. (Shujaat et al., 2014), applied this method to quantify the dynamics of 3D lip movement in the head and neck oncology patients before and after lip split mandibulotomy.

Three-Dimensional and Four-Dimensional Assessments of Facial Palsy

The assessment of facial dysmorphology in facial palsy lags behind in comparison to other areas of technological advancements in the medical field (Neely et al., 2010).

Landmark-Based Methods

Different forms of landmark-based methods for the assessment of 3D facial symmetry and distorted muscle movements have been reported in the medical literature (Mishima & Sugahara, 2009). These include the use of reflective and non-reflective facial markers, marker-less approach by means of facial inkdots, and computer digitization of anatomical landmarks (Tzou et al., 2012).

In 2008, (Hontanilla & Aubá, 2008) presented the FACIAL CLIMA grades for the evaluation of facial muscle movements as a valid tool to assess the outcome of facial palsy reanimation surgery. The infrared cameras recorded the 3D facial muscle movements. Assessment of facial movements was based on the automatic tracking of reflective dots, applied on the face with adhesive. The distances and angles between tracked landmarks were measured and the velocities of facial movements were quantified, Figure 14. The accuracy of the facial measurements produced using the FACIAL CLIMA software was compared to known measurements marked with a scaling rode (2mm wide reflective markers) displaying a fixed distance of 90mm and an angle of 90 degrees. The software-based analysis was shown to be accurate within 0.13mm to 0.41mm. The study investigated the reliability of the assessment method, in which the reflective markers were removed and reapplied three times in the same session. High interrater reliability was noted (ICC > 0.9).

Figure 14: FACIAL CLIMA

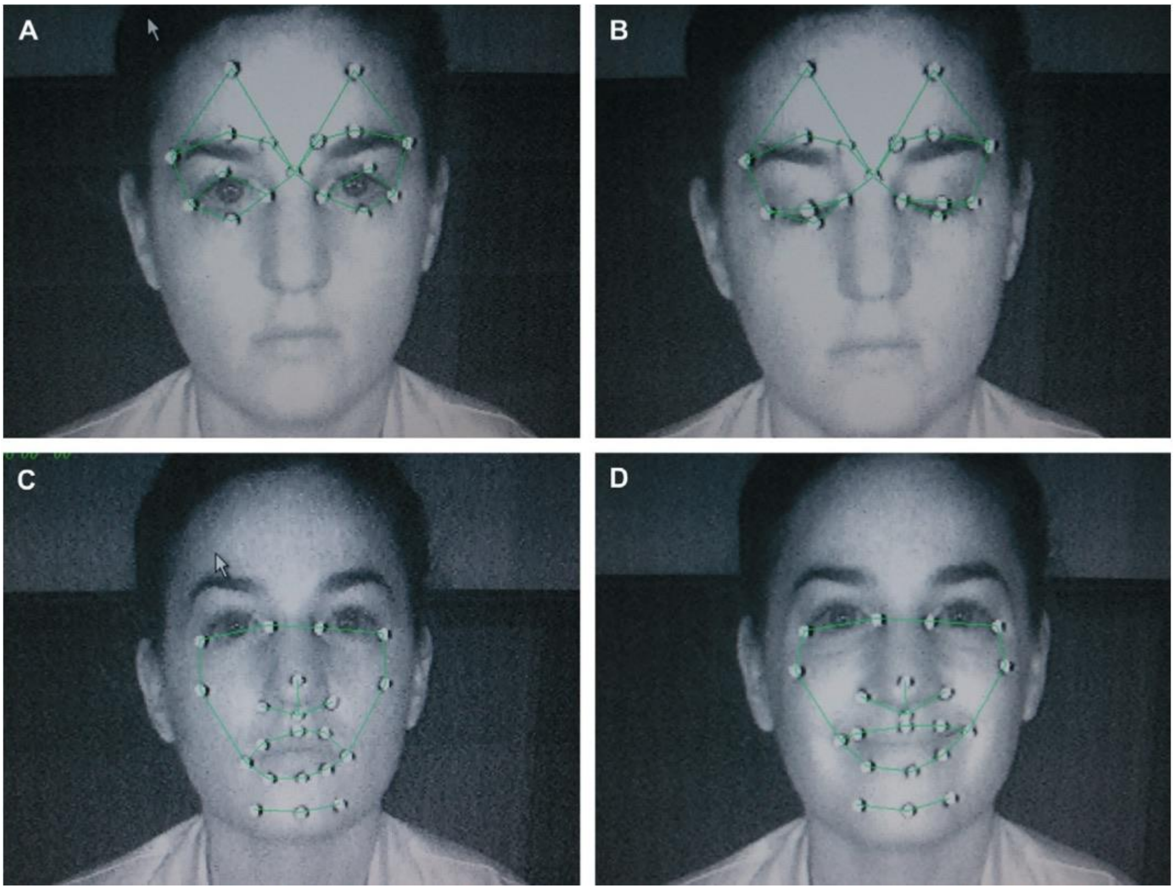


Figure 14 shows the FACIAL CLIMA software featuring the tracked reflective facial markers during two facial movements. A: the upper face at rest. B: the tracked movement of facial markers with eyelid closure. C: The lower face at rest. D: the tracked movement of facial markers with smile, (Hontanilla & Aubá, 2008).

The marker-based approach is time-consuming that limits its application for regular use in outpatient clinics. Furthermore, the assessment relies on the clinician accuracy and reproducibility in placing the reflective facial markers (Samsudin & Sundaraj, 2013).

Similarly, Demeco et al., 2021 proposed a protocol to evaluate the outcome of facial nerve palsy comprised of kinematic analysis of facial nerve paralysis using 6 reflective facial markers coupled with 4 surface electromyography wireless electrodes, Figure 15. The participants were asked to perform voluntary facial movements including forehead wrinkling, eye closure, and smile. Facial nerve function was assessed by tracking and measuring the distance of markers movement and the simultaneous recording of electromyography activity during muscular actions. Performing surface electromyography required shaving facial hair to reduce skin impedance. Measurement of the electromyographic activity of the facial muscles during a set of facial movements provides new measures of facial nerve function. However, it remains impractical for the regular utilisation in facial palsy outpatient clinics.

Figure 15: Reflective Facial Markers and Electromyography Electrods

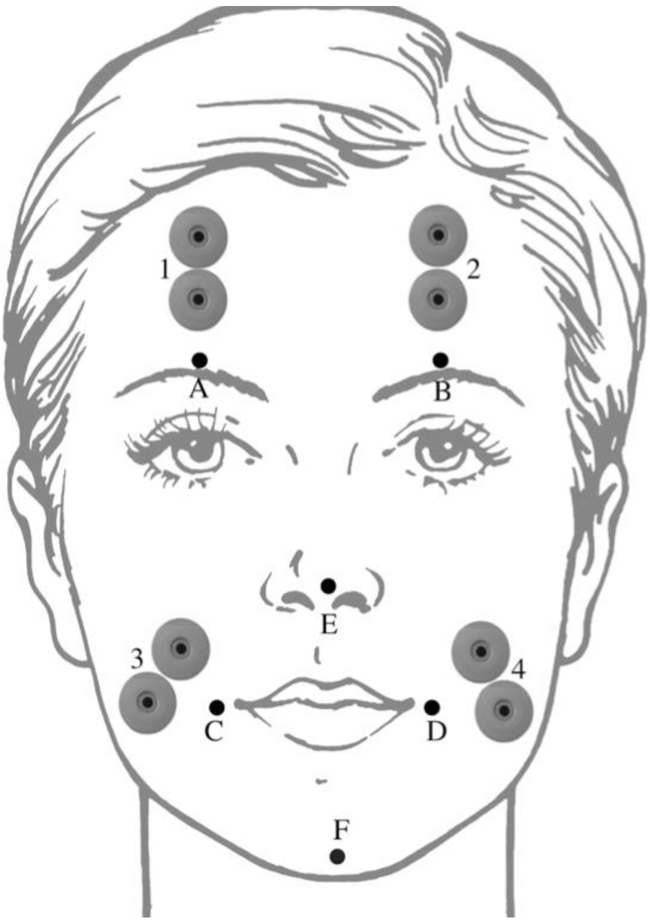
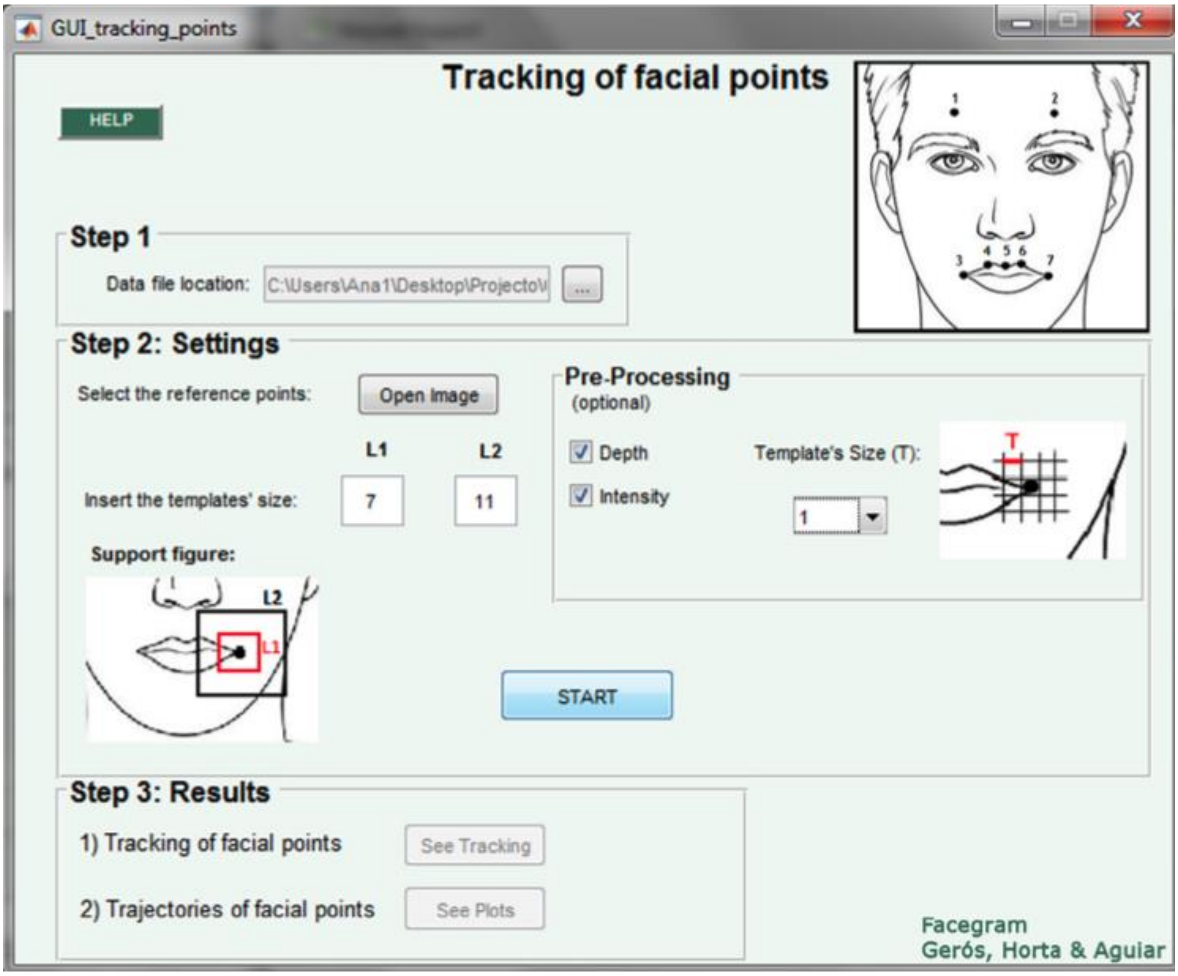


Figure 15 shows the 6 reflective facial markers indicated with letters and the surface electromyography wireless electrodes indicated with numbers, (Demeco et al., 2021).

In 2016, the 2D video analysis system, Facegram, was described by (Horta et al., 2014) for spatial and temporal analysis of facial movements, this was further developed and reintroduced for the analysis of 3D static and dynamic facial movements of facial palsy (Gerós et al., 2016). The system included Microsoft Kinect Models sensors to extract the third dimension (the depth) along with the automatic tracking of 5 facial landmarks, marked on the lips using ink dots, over time. The magnitude and the dynamics of the smile expression (speed, motion path, vector of landmark displacement) were analysed using a computer software, Figure 16.

Figure 16: Facegram Software



The main drawback of landmark based methods is the limited representation of the 3D facial morphology in comparison to surface based methods. Therefore, it does not allow the assessment of the global as well as regional abnormalities of facial symmetry or function distortion.

Surface-Based Methods

Codari et al., 2017 applied surface-based method for the analysis of facial asymmetry in facial palsy patients. The faces of 30 patients who suffered from unilateral facial palsy and 40 controls were captured using a stereophotogrammetric imaging system. The 3D facial models were divided into three hemifacial thirds (upper, middle, and lower facial thirds). Each facial third was defined by a set of facial landmarks to correspond with the facial surface area innervated by the distribution of the trigeminal nerve branches, Figure 17. Local facial asymmetries were quantified using the rigid-registration approach to measure shape-difference between the original and mirrored facial thirds.

The segmentation of the face into three facial thirds based on the distribution of the trigeminal nerve does not consider the individual facial regions representing the group of muscles group affected by the facial nerve paralysis. The performance of certain facial expressions including smiles involves the movements of muscle groups that span over facial regions.

Figure 17: Segmented Facial Regions

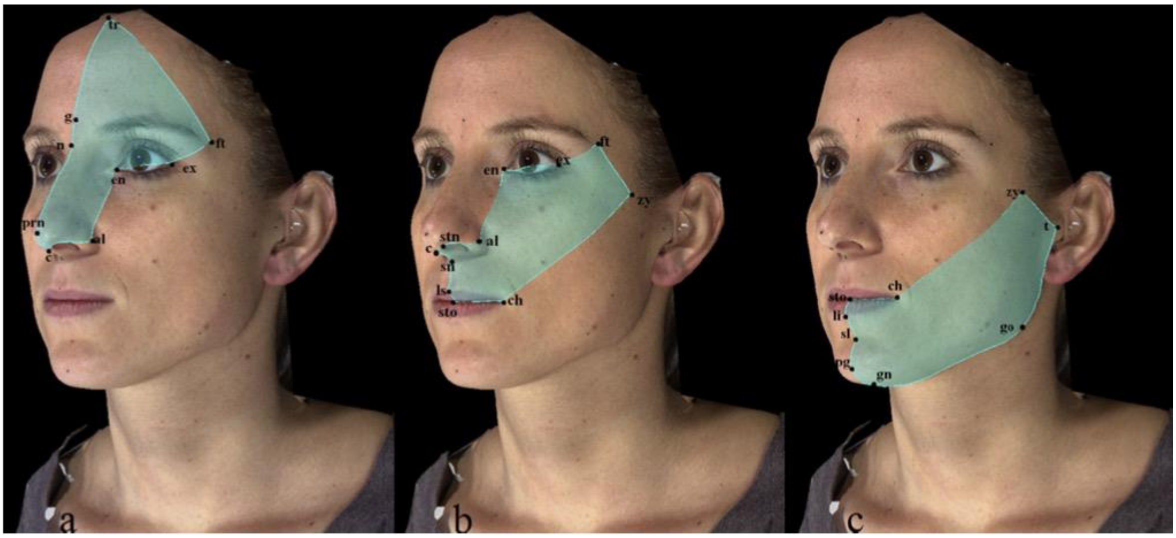


Figure 17 illustrates the segmented facial regions based on the distribution of the trigeminal nerve, (Codari et al., 2017).

Sforza et al., 2018 assessed the success of facial reanimation surgery in eleven unilateral facial palsy patients. The surgical procedure involved the innervation of the masseteric nerve branch to the temporal branch of the affected facial nerve, the hypoglossal nerve branch to the cervical branch of CNVII on the paralyzed side, and the cross-face nerve graft by the sural nerve. The primary facial stimulus was recorded by capturing the 3D facial morphology at five expressions (at rest, smiling on the normal side, biting, moving the tongue, moving the corner of the mouth as in the Mona Lisa smile. Each 3D scan was superimposed on the facial model at rest using the surface-based method (Figure 18), in which, the root mean square distance between the two superimposed models was automatically calculated on both sides of the face. The statistical difference between the different nerve stimuli was verified using ANOVA test on the RMS differences according to the type of the stimulus (*p*-value 0.039) and the side (*p*-value 0.031). The study indicated the highest asymmetry produced by the cross-face stimulus in which the smile movement on the healthy side invoked normal movement in comparison to the weakened affected side. Conversely, the masseteric stimulus resulted in the most symmetric smile.

The assessment of the right and left facial asymmetry was based on the identification of seven midline facial landmarks and following the superimposition of the 3D facial models, the face was divided into right and left halves. However, in severe cases of facial dysmorphology, it is difficult to identify the midsagittal plane and therefore hinder the accurate division of the face (Slice, 2007). Furthermore, the study did not analyse the dynamic facial movements over time. The directionality of asymmetry was not considered in this study.

Figure 18: Surface-Based Method for the Assessment of Facial reanimation

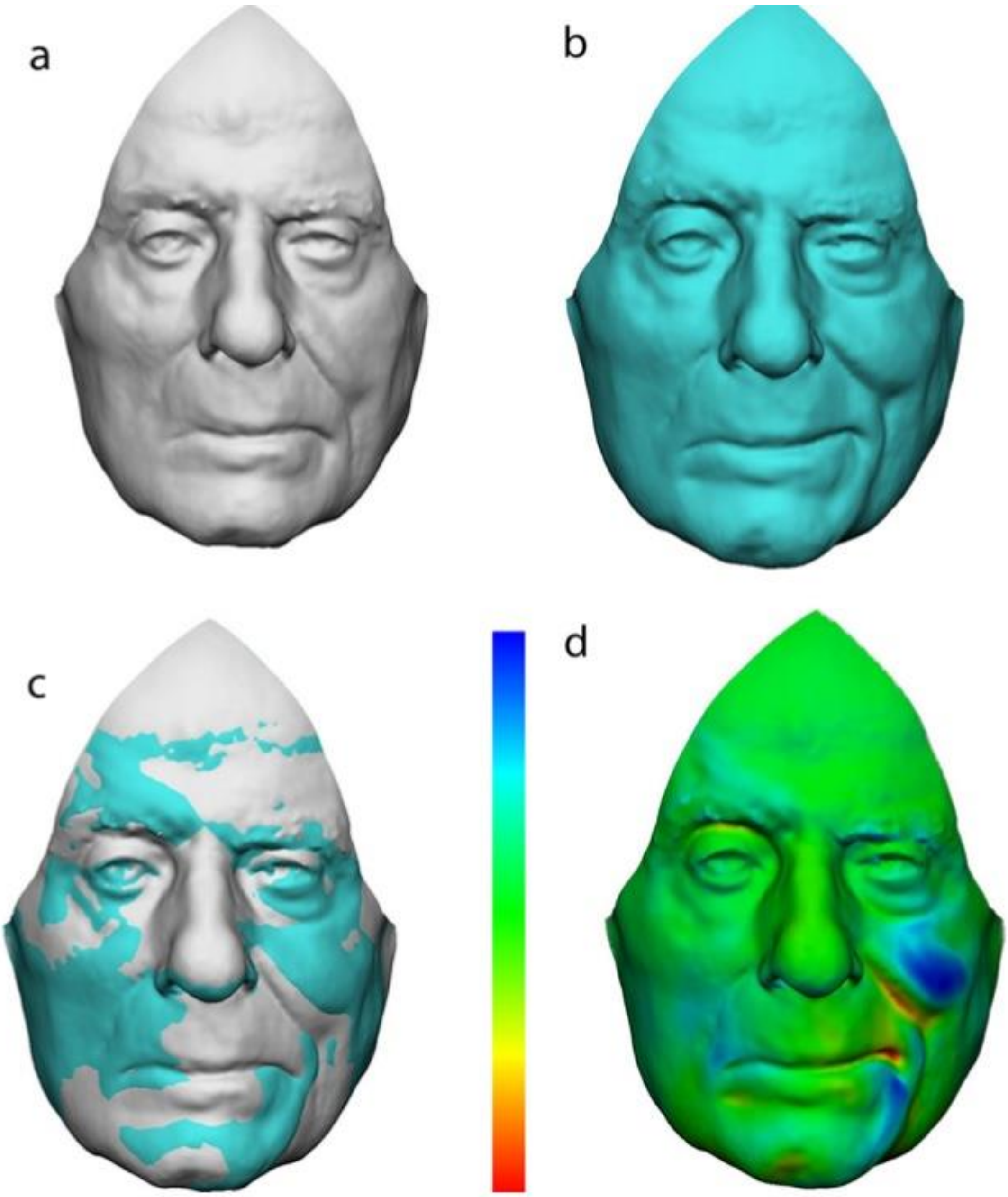


Figure 18 demonstrates the surface-based method applied for the assessment of facial reanimation. A: the 3D facial model at rest. B: the facial model featuring the corner of mouth movement in Mona Lisa smile. C: shows the superimposed models presented in A and B. D: Colour coded facial map of the distance between the aligned facial models. (Sforza et al., 2018).

In 2020, (Gibelli et al., 2020) quantified the restored smile in eleven patients who underwent facial reanimation surgery of unilateral facial palsy by triple innervation procedure (massertic and partial hypoglossal reinnervation and cross facial nerve grafts) and the results were compared with 60 healthy volunteers.

Patients were instructed to perform the rest position and four expressions to elicit a smile by the activation of the different motor stimulus such as clenching the teeth to activate the masseter nerve stimulus and pushing the tongue against the lower teeth to activate the hypoglossal nerve. The 3D facial morphology was recorded at rest and at maximum expression. The regained muscular movement was quantified using the rigid-registration approach to measure shape-difference between the 3D facial image at rest and at maximum expression (the root mean square distance between the two aligned 3D surfaces). The facial region was divided into three hemifacial thirds based on the distribution of the trigeminal nerve. RMS quantified facial movement from rest position at each facial third. Comparison with the control group was limited to the Mona Lisa smile only (corner of the mouth smiling). ANOVA test was applied to analyze RMS scores according to the side (left, right side of the face), (type of stimulus) and facial third (upper, middle, lower facial thirds). Statistically significant differences were found according to side, facial third, and stimulus. RMS scores were higher in the middle and lower thirds compared to the upper facial third. Differences in the rehabilitated facial third were higher than the healthy side. The patient group was more asymmetric than the control group.

The rigid registration method based on RMS scores of morphological differences between the facial image at rest expression and at maximal movement provided a mathematical index of the regained facial function. However, this method did not analyse the characteristics of facial movements including the magnitude of movement, the direction of asymmetric facial movement, and the motion path throughout the entire facial motions.

Kim & Oh, 2020, evaluated the 3D volumetric soft tissue changes after facial reanimation surgery with free muscle transfer in 43 facial palsy patients. In their study, the effectiveness of a new surgical approach, nasolabial fold reset surgical technique for enhancing midface lift, was tested on 20 patients (NLF group) compared to a conventional surgical procedure in 23 controls. The 3D facial morphology was captured at rest using a structured-light facial scanner. The operator digitised a number of anatomical landmarks to define 4 horizontal planes which the software utilised to divide the face horizontally into 3 volumetric proportions (upper, middle, and lower face) (Figure 19) and provide a mathematical measurement of segmented facial volumes. The pre-and post-operative volumetric measures were compared.

Statistically significant differences were found in the 3D midface postoperative volume difference in the NLF reset group in comparison to the control group (P-value 0.03). The authors concluded the NLF reset technique enhanced the surgical outcome.

The division of the face into 3 horizontal thirds did not consider the anatomical and biomechanical activity of individual facial muscle groups of facial expressions. Furthermore, the volumetric analysis was limited to mathematical values only, the presence of statistically significant differences between pre-post-operative volumetric measures, without representation of facial dysmorphology.

Figure 19: Volumetric Analysis of the Face

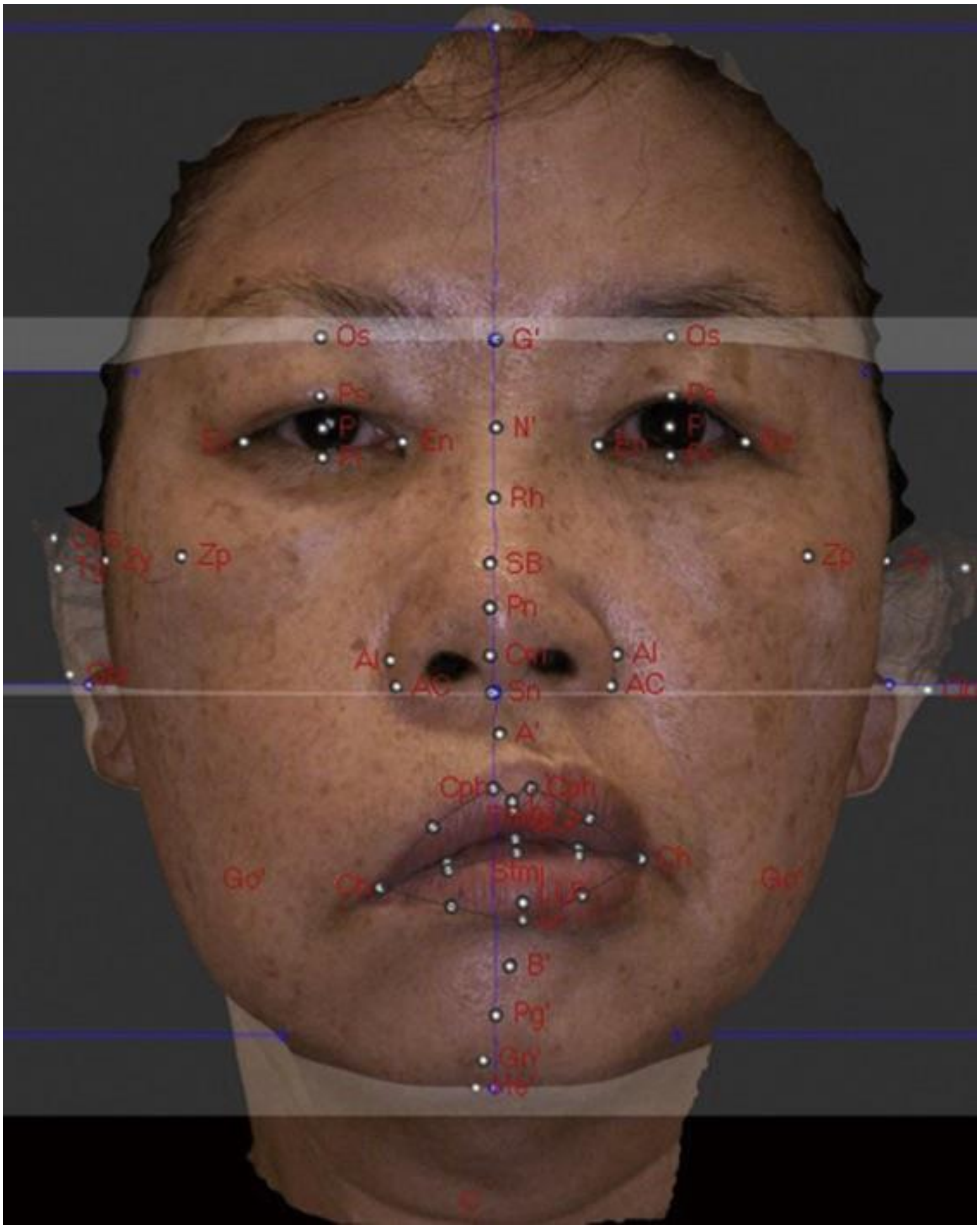


Figure 19 demonstrates the 3D facial morphology of facial palsy patient. The face was divided into 3 volumes based on the identification of 4 horizontal lines, (Kim & Oh, 2020).

Alagha et al., 2017 introduced the application of spatially dense anthropometric digital mask to assess the reproducibility of dynamic facial asymmetry in unilateral facial paralysis. Voluntary facial movements of 20 unilateral facial palsy patients were recorded twice using Di4D imaging technology. The system captured 60 3D facial frames per second during the performance of smile, cheek puff, lip purse, eyebrow raising, and eye closure which took 3-6 seconds each. A generic facial template, composed of 7K vertices, was conformed on the first frame of expression and tracked throughout the full 3D image sequence, from which, 5 frames were selected to represent the dynamics of facial expression at 4 transitions of time. These were the facial frame at the start of the expression from rest, facial frame at the 1st quartile of muscle movements, facial frame at the maximum expression, facial frame at the third quartile of the facial movement, mid-way between the maximum and the end of the expression and a final frame at the end of the expression, Figure 20.

The morphological dissimilarities of the 5 frames were compared between the corresponding frames for each of the repeated expressions. The 3D facial shape of each key frame was superimposed on the corresponding frame at rest using partial Procrustes analyses. Shape difference was quantified by measuring the mean root square distance between the corresponding vertices of the two aligned facial shapes. Paired sample t-test was applied to assess the statistical differences between each key frame at individual expression in the first capturing session to the corresponding frame in the second session.

This approach allowed, for the first time, the comprehensive analysis of the full facial surface in palsy patients by means of dense surface models. The analysis was limited to 5 key frames, selected manually, to represent the dynamic facial morphology. Furthermore, the study did not consider the patterns of facial movements (magnitude, speed, motion path). The assessment of facial morphology did not evaluate the reproducibility of measuring the regional facial dysmorphology.

Figure 20: Smile Expression at 5 Key Frames

Figure 20 demonstrates the 5 key frames representing the smile expression at four transitions of time, (Alagha et al., 2017).

The current state-of-the-art analysis of the dynamics of facial movements is based on the application of deformable models (facial mesh). In this approach, the 3D configurations of the spatially dense anthropometric mask are mapped on the 3D facial image at rest and the correspondences of the nodes are tracked throughout the 3D image sequence of facial expressions. This provided a comprehensive analysis of the dynamic of facial muscle movements (Gattani et al., 2020). The novel technique allows the analysis of the full facial morphology at rest and during movements with consideration to the regional facial asymmetry in the three direction of space: the mediolateral direction, vertical and, anteroposterior direction.

The Relationship between Subjective and Objective Assessments of Facial Palsy

The correlation between the mathematical measurements of newly developed methods with the subjective evaluation of facial palsy has not been fully investigated yet. This involved the correlation analysis between the objective measurements in 2D and the clinical assessments (Diego L. Guarin, 2020; Lee et al., 2019; Mothes et al., 2019). The correlation with 3D methods was limited to the measurement of facial movements using a small number of facial landmarks (Katsumi et al., 2015).

(Katsumi et al., 2015) introduced a 3D facial motion measurement system for the quantification of facial nerve palsy in 42 patients and compared the assessment results between the 3D assessment and the clinical gradings of two subjective clinical grading systems. Five clinical assessors graded the severity of facial palsy using the Yanagihara scores and House Brackmann facial grading index, the average scores of the five assessors were correlated to the mathematical measurements. The facial morphology was recorded at five facial expressions including the rest, eyebrow raise, gentle eye closure, smile with lips open, and whistling. For each image acquisition, the imaging system produced a 3D shape image and a 2D colour image. Using computer software, the 3D image analysis was based on the image registration technique guided by a set of vertical and horizontal lines. The software provided the 3D coordinates of nine facial landmarks which were digitised on the 3D facial model. Analysis of facial asymmetry was based on the measurement of 3 regional scores (forehead symmetry scores FSS, eye symmetry score ESS, mouth symmetry score MSS) in which the ratio of motion on the paralyzed side to the healthy side was calculated, Figure 21. For the analysis of the gross face asymmetry, the Yanagihara scores were measured according to the mathematical scores of the three regions of various facial expressions. The mathematical scores were correlated to the clinical grading scores. A strong correlation was shown between the 3D assessment and the clinical assessments of the Yanagihara scores (correlation coefficient 0.86) and the House-Brackmann facial grading system (coefficient of correlation 0.86). The study also explored the difference between the 2D and 3D measurements of facial movements. The MMS from the 2D assessment was deficient in measuring lip movements in the anteroposterior direction (correlation to Yanagihara score 0.25) compared to MMS from 3D assessment (correlation to Yanagihara score 0.80). This study, however, suffers from a number of limitations. Mainly, the assessment was based on landmark-based analysis that does not describe the 3D facial dysmorphology. Furthermore, facial muscle movements were measured using a static approach which measured the maximum displacement of facial landmarks from rest. The correlation analysis was based on comparing the ratio measurement of facial movements in comparison to the healthy side and these measurements were obtained from 9 facial landmarks only which may have underrepresented the complexity of facial muscles movements.

Figure 21: Analysis of Dynamic Facial Asymmetry

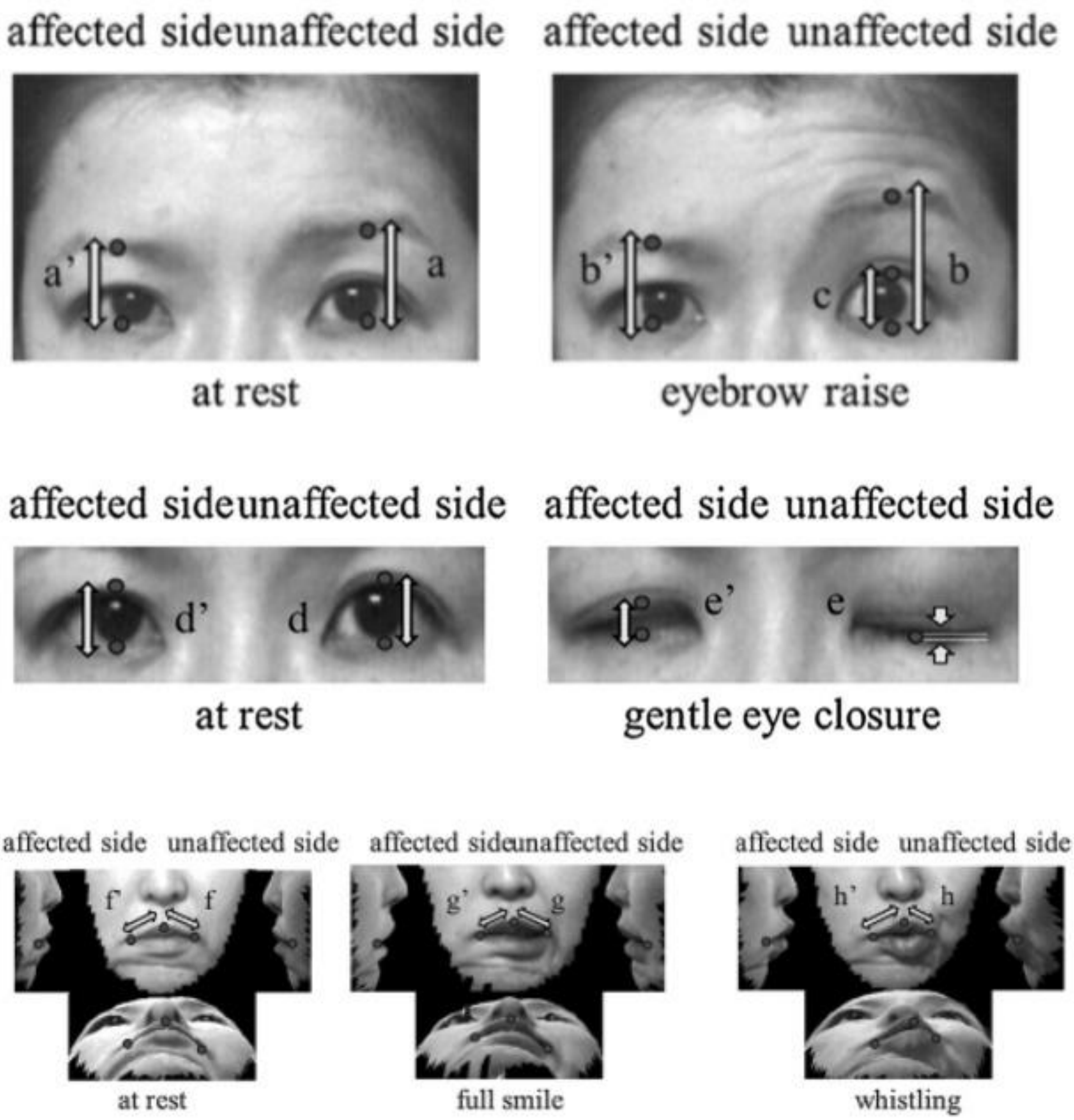


Figure 21 demonstrates the analysis of facial asymmetry at the forehead (top row), eyes (middle row), and mouth (bottom row). The left side demonstrate the rest position, the right side features the related facial motion. The arrows indicate the measured distances used for the calculation of the symmetry scores, (Katsumi et al., 2015).

Summary

In most of the studies, the clinical assessment of facial palsy relies on the visual evaluation and inspection of the face (Fattah et al., 2015). The lack of a universally accepted objective grading system of facial palsy results in substantial difficulty in comparing objective outcome measures of surgical techniques in facial reanimation surgery (Bos et al., 2016; Roy et al., 2019; Schlosshauer et al., 2020).

Quantifying the degree of distortions of facial expressions is crucial in evaluating the clinical impact of facial palsy (Tzou et al., 2012).

Three-dimensional and four-dimensional imaging of muscle movements were proven to be reliable in recording the dynamics of facial expressions, which facilitates the analysis and quantification of morphological and functional distortions (Tzou et al., 2014). Still, there is insufficient information on the dynamics of muscle movements in facial palsy (Dong et al., 2018).

Sunnybrook facial grading system has been recommended as the primary system for the evaluation of facial palsy (Fattah et al., 2015). The system is convenient for regular use in the clinic, provides scoring with consideration to the evaluation of the face at rest, during voluntarily movements, and the assessment of secondary features of facial palsy.

The Sunnybrook facial grading system has a number of deficiencies, mainly the lack of distinction between the assessment of facial function and facial asymmetry. Furthermore, the system does not consider the directionality of facial dysmorphology and its severity. The mathematical accuracy of the Sunnybrook facial grading system to confirm its sensitivity and specificity has not been tested yet.

Despite the fact that the clinical evaluation of facial palsy remains the routine approach for the assessment of facial muscle movements; there is a lack of data to link the mathematical analysis of 3D dynamic facial morphology with the clinical assessments.

Aim of Study

The aim of this study was the assessment of distorted facial muscles movements in unilateral facial palsy based on a mathematically validated subjective clinical grading systems.

Primary Objectives

- ◊ Quantify the degree of facial asymmetry at rest and during a set of facial expressions using 4D stereophotogrammetry.
- ◊ Identify the main regions affected by facial dysmorphology.
- ◊ Obtain a reproducible clinical grading system to evaluate the distorted facial movements related to unilateral facial palsy.
- ◊ Explore the correlation between the subjective grading of the asymmetric facial expressions and the mathematical calculation of the distorted facial muscle movements.

Hypotheses

- ◊ It is not possible to mathematically quantify the abnormalities of the dynamics of facial expressions in patients suffer from unilateral facial palsy using an advanced geometric morphometric approach.
- ◊ The clinical grading of facial palsy is non-reproducible.
- ◊ No correlation between the clinical grading of facial palsy and the mathematical measurements.

Rationale of the Study and Potential Impact

The clinical grading of the distorted facial expressions based on mathematical validation would allow the reliable monitoring of the applied treatments and detect preliminary signs of relapse.

Adjoining the clinical and the mathematical perspectives in the development of a reliable objective facial grading system is strenuous. An integrated approach that incorporates the clinical expertise with the mathematical precision for the development of subjective index validated mathematically and the development of objective index with clinical validity.

The objective quantification of distorted facial dysmorphology at the anatomical sites where distortion in expression is noted would facilitate the identification of the essential clinical parameters used in the clinical assessments.

Methodology

Introduction

The study design was a cross-sectional controlled trial. Two-cohorts were recruited; a group of patients who suffered from unilateral facial palsy and a control group. This chapter is subdivided into the following sections:

Section A: Recruitments of Participants

Section B: Capture of Facial Movements

Section C: Processing of the 4D Videos

Section D: The Mathematical Analysis of Facial Dynamics using Geometric Morphometrics

Section E: The Clinical Grading of Facial Palsy

Section F: The Correlation Between the Mathematical Measurements and Clinical Gradings of Facial Palsy

Section A: Recruitments of Participants

Ethical Approval

Ethical approval was obtained from the South-Central Berkshire Research Ethics Committee (Reference 17/SC/0541) and the Research and Development National Health Services Greater Glasgow and Clyde Health Board (Reference GN17OD401).

Sample Size Calculation

The sample size for this study was calculated by applying the following formula

$$Sample\ size\ (n) = Numerator\ \times \left(\frac{Standard\ deviation}{Effect\ size}\right)^2$$

For sample size estimation, the significance level, the power of the test, the effect size, and the variance of data were identified. The assessment of the effect size and variance of data were based on the recommendations of (D. J. Johnston et al., 2003). On 30 volunteers, the mean difference in overall landmark positions was 0.49 mm (Effect size) and the dispersion of landmark data was 1 Standard Deviation (SD) of the mean.

The Numerator for sample size formula can be calculated for the different values of Type I and Type II errors. For this study, a numerator value of 11 was indicated (Van Belle, 2011). Therefore, at 90% power and significance level p=0.05, 44 subjects per group were required to detect 0.5mm difference between similar expressions.

Taking into consideration that some of the captured data may not be utilised for the analysis due to unwanted head-movement during facial expressions, the study was carried out on 50 cases in each group. A total number of 100 individuals were recruited for the study, 50 unilateral facial palsy and 50 controls.

The Study Groups

Unilateral Facial Palsy Group

Patients were recruited from an outpatient consultant clinic dedicated for the diagnosis and management of facial paralysis at Glasgow Royal Infirmary. The following criteria were considered for the selection of the 50 cases of the study group:

Inclusion Criteria:

- ◊ Clinical diagnosis of unilateral facial paralysis
- ◊ Age 16 – 70 years
- ◊ Able to give an informed consent

Exclusion Criteria:

- ◊ Patients suffering from motor neuron disease, neuromuscular disease, and muscular dystrophy
- ◊ Patients with congenital or syndromic facial abnormalities
- ◊ Patients with special communication needs

Control Group

The 50 healthy volunteers who satisfied the selection criteria were recruited for the study. To facilitate the recruitment process, posters and flyers were displayed at the University of Glasgow to encourage the interested volunteers to contact the study chief investigator, who forwarded the participant information sheet to the participants by email. Capturing session was arranged for those who agreed to take part in the study. A minimum of 24 hours was given for participants to consider joining the study. The participants in the control group fulfilled the following criteria:

- ◊ Healthy individuals
- ◊ Age and sex matched to facial palsy group
- ◊ Able to give informed written consent

Section B: Capture of Facial Movements

Discussion and Consent

Data collection took place at Glasgow Dental Hospital and School. The investigator discussed the aims and the process of the study to make sure participants have a satisfactory understanding of their involvement. Participants were shown a PowerPoint presentation demonstrating how their data would be utilised for the analysis of facial symmetry and the assessment of muscle movements. Healthy volunteers were asked to confirm the eligibility criteria. Informed written consents were obtained.

Coding and Demographics

Every participant was assigned a special computer-based code to facilitate the organisation of data, ensure confidentiality of participants, and conceal the participants' identity. Data linking participants' identifiable information to computer files were stored in an especially designated database and kept anonymous during data analysis.

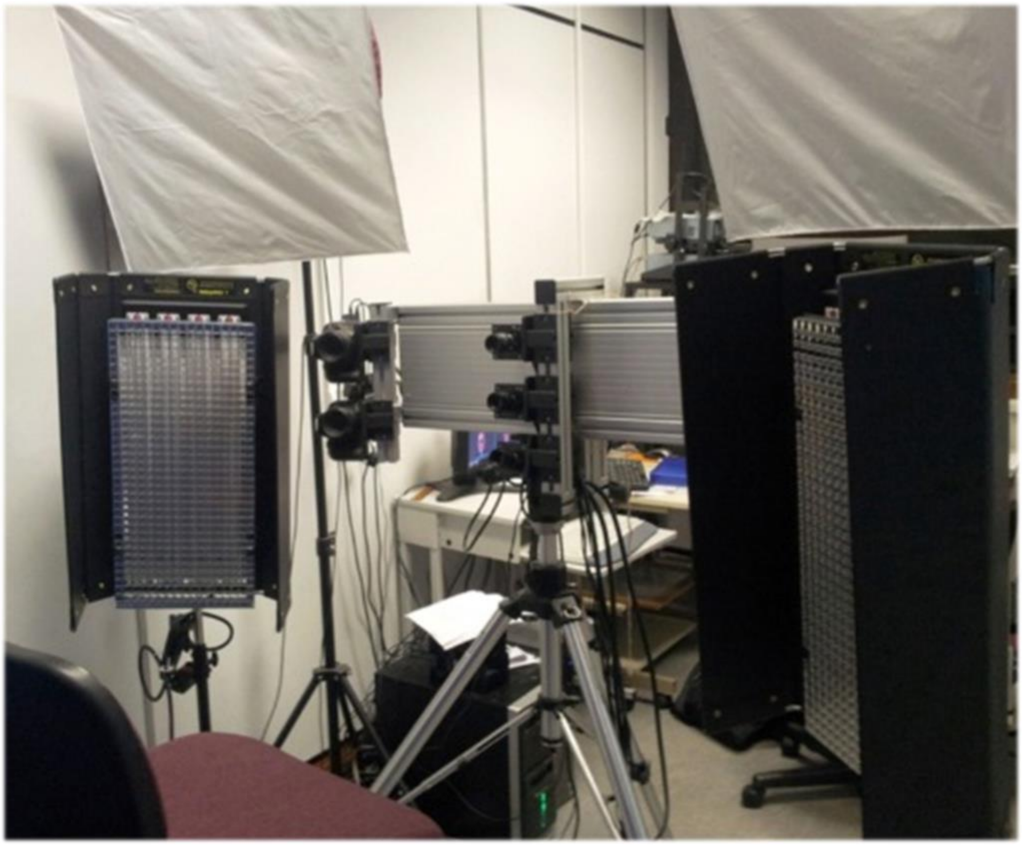
Participants were asked to complete the demographic information sheet to provide information on their date of birth, gender, and ethnicity.

The Imaging System for Recording Facial Expressions

Di4D Facial Performance Capture System, developed by Dimensional Imaging Limited, Hillington, Scotland, UK, was employed to record facial movements. The technology is based on passive stereo photogrammetry that constructs the 3D facial morphology using a stereo pair of cameras.

The system consists of two grey-scale cameras (model avA 1600–65 km/kc, resolution 1600 _ 1200 pixels), a sensor (model KAI-02050; ON Semiconductor, Phoenix, AZ, USA), a colour camera (Kodak sensor model KAI-02050, Basler, Germany), and a lighting system (model DIV-401 Diva Lite; Kino Flo Corporation, Burbank, CA, USA) (Figure 22).

Figure 22: Di4D Facial Performance Capture System



The outer grey-scale cameras capture the 3D image sequence of a video at a rate of 60 3D facial frames per second, and the central colour camera captures the surface colour and texture (Figure 23). The system was connected to a desktop computer to build the sequence of the 3D facial images for each facial expression.

Figure 23: Di4D Stereophotogrammetry Cameras

Imaging Protocol

System Calibration

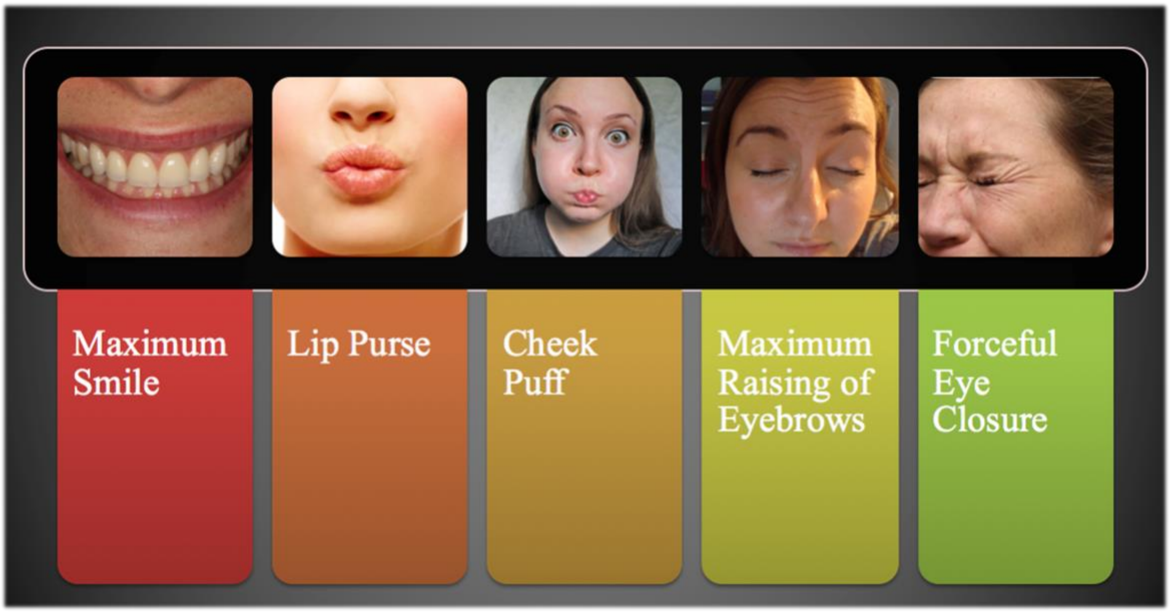
At the beginning of each imaging session, the system was calibrated according to the manufacturer's instructions. This was conducted using a calibration object of contrasting circles of known diameters; it was centred in front of the imaging system at a distance of 95cm from the camera measured using a measuring tape. The camera view on the computer screen displayed the calibration object, which was captured by the operator in 9 different positions. The imaging system utilised these parameters to automatically calibrate the camera settings including the focal depth to extract the third dimension of the captured images. The process was considered successful if the calibration errors were less than 0.4 pixels.

Instructions and Training

The participants were instructed to sit on a chair directly facing the imaging system in an upright position at a standard distance of 95cm from the video camera which was ascertained using a measuring tape.

They were shown photographic cue cards, which illustrated the five facial expressions (Figure 24). The operator provided a full demonstration for each individual participant.

Figure 24: Photographic Cue Cards of Facial Expressions



Before the recording of the expressions, each participant was trained on performing each of the facial movements starting from the rest position to reach the maximum stretch of the muscles then a gradual relaxation to the rest position. The instructions were as the following:

- ◊ Rest position: achieve complete facial relaxation, keep teeth in maximum contact, maintain gentle lip contact for competent lips or relaxed lips.
- ◊ Maximal smile: achieve maximum muscle movement during smiling and show teeth.
- ◊ Lip purse: pout lips, simulating the kissing movement.
- ◊ Cheek Puff: build up air pressure inside mouth, against cheeks, as much as possible.

The rationale of the controlled facial expressions is to standardise the patterns of muscle movements and eliminate the impact of emotions. Participants were trained to coordinate their facial movements with the operator as he counted from 1 to 4:

1. No movement; the face at rest position.
2. Start movement to reach maximum expression.
3. Hold the movements of the facial muscles at maximum expression.
4. The face returns to rest position.

For the facial expression of forceful eye closure: the instructions were as the following:

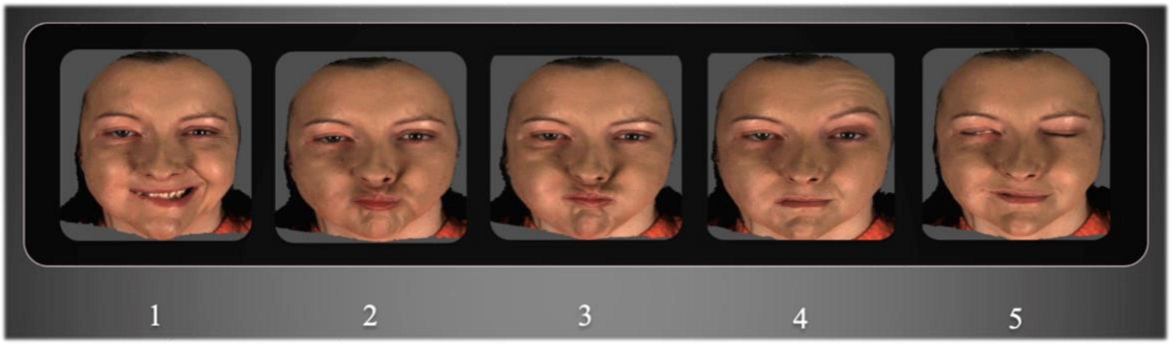
1. No movement; the face at rest position.
2. Start movement to achieve gentle eye closure as in sleep.
3. Perform forceful eye closure, squeeze the eyes together.
4. The face returns to rest position.

Recorded Facial Expressions

In addition to the facial expression at rest, five facial expressions were recorded (Figure 25) in real time using the Di4D imaging system:

1. Maximal smile
2. Lip purse
3. Cheek puff
4. Maximum raising of eyebrows
5. Forceful eye closure

Figure 25: Demonstration of Recorded Expressions in Facial Palsy



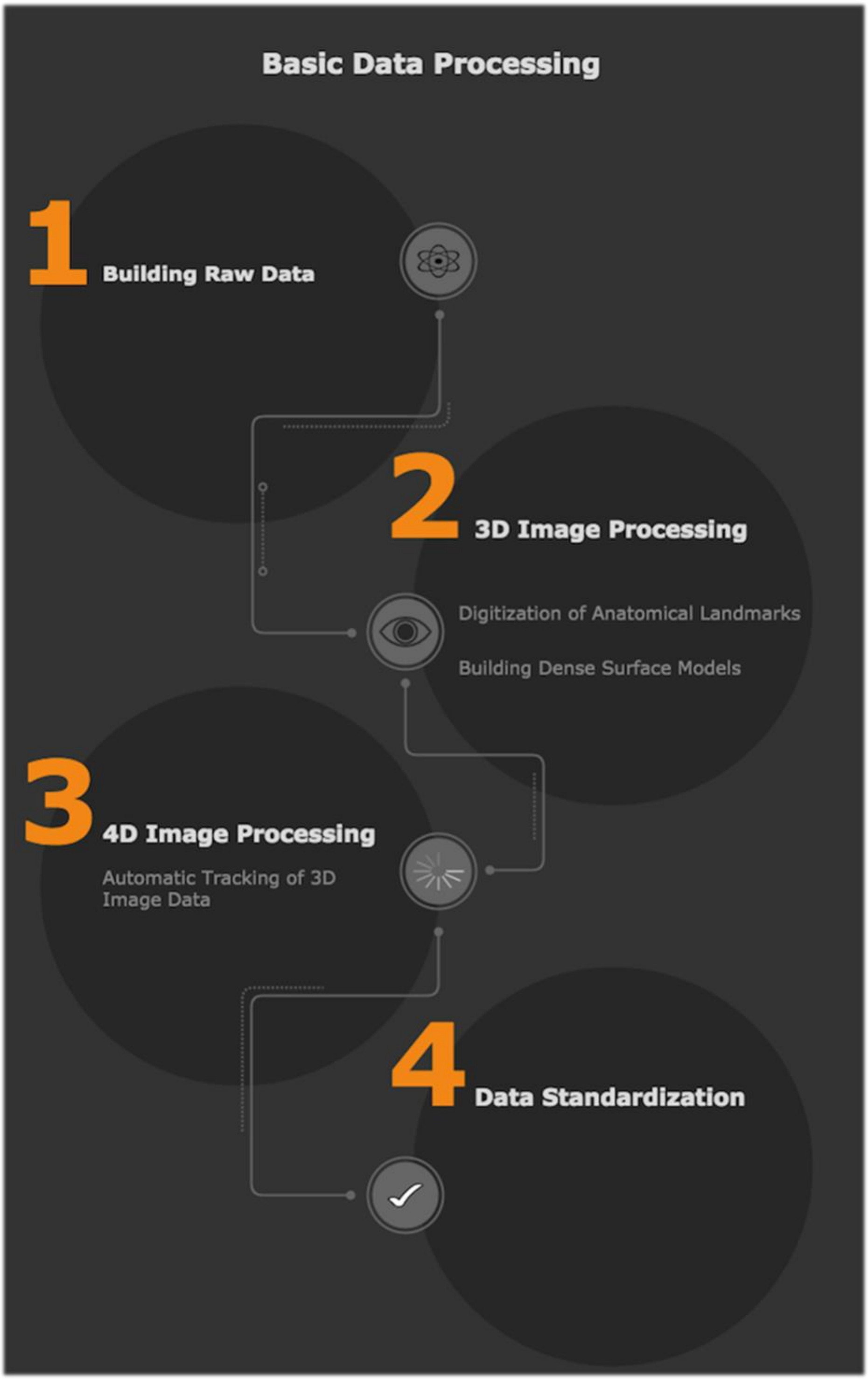
Each facial expression was recorded over 3-6 seconds. This created a minimum of 180 3D facial frames per expression per individual (60 frames per second x 3 seconds = 180 frames). The operator reviewed the generated sequence of each expression immediately after capturing to ensure the accurate recording of the muscle movements. For each case, the imaging session took around 20 minutes.

The data were stored in a password-protected University computer that is specially designed for capturing facial movements in 3 and 4 dimensions and then transferred to specially allocated University server for storage. Data were made accessible to the research team.

Section C: Processing of the 4D Videos

The real time recording of the 3D sequence of facial expressions using the Di4D imaging system generated four-dimensional videos for analysis. Each video contained a 3D image sequence captured at a rate of 60-3D facial frames per second. The aim of this section is to describe the processing of the generated data.

Figure 26: Steps of 4D Image Processing



Building Raw Video Data

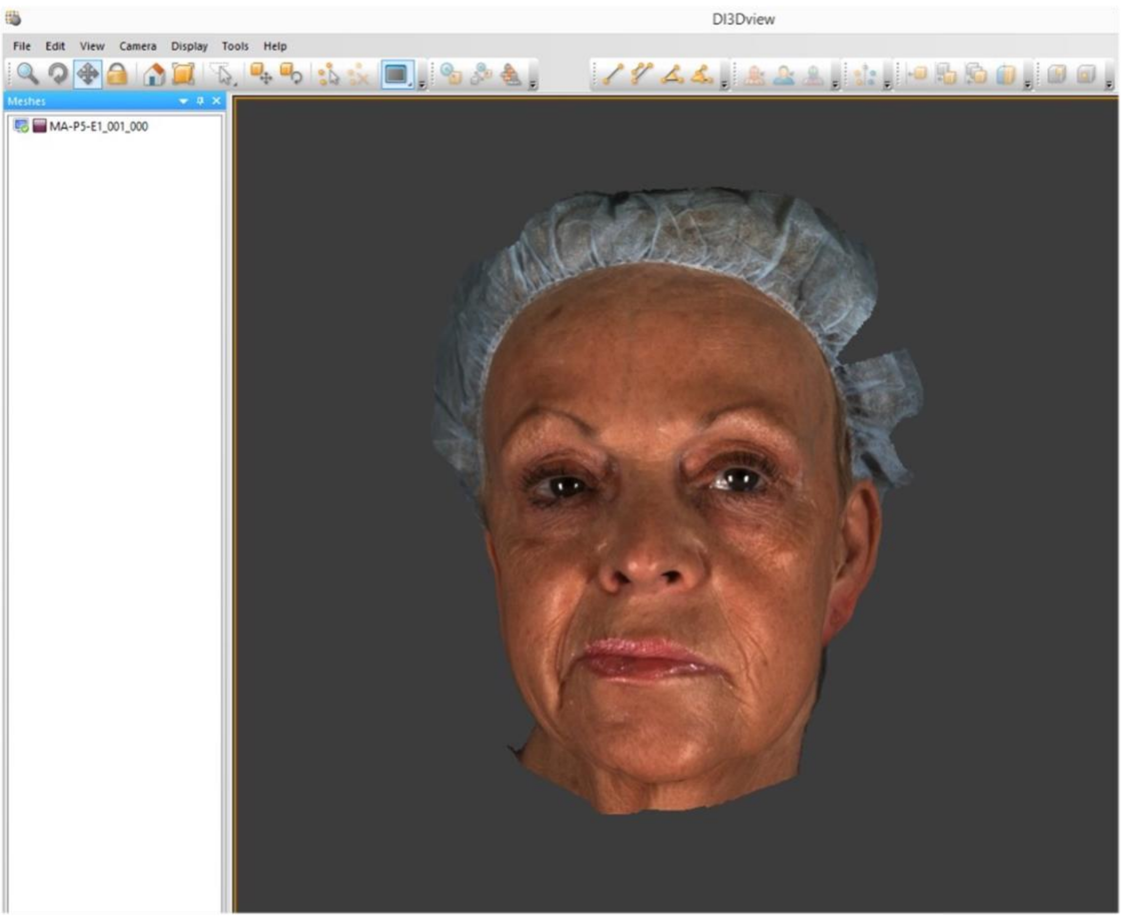
The Di4D-Capture software generated "raw" video data of the recorded facial expressions in compressed format. The operator verified the quality of the recorded video by clicking on *play* option which displayed the 3D image sequence in slow motion (Raw data).

Video capture was considered accurate if there was no blurring or distortion. To build raw data, the operator clicked on *convert from raw* option. This process is automated and took around one hour per expression. For each built video, the system created a folder that contained the 4D video of the recorded facial expression and the 3D image sequence of the recorded expression in obj format.

3D Image Processing

The first frame of the 3D image sequence of each facial expression was imported into the Di3D-View software (Figure 27). Three-dimensional image processing involved the identification and manual digitisation of facial anatomical landmarks and the building of Dense Surface Model (DSM).

Figure 27: Di3D-View Software

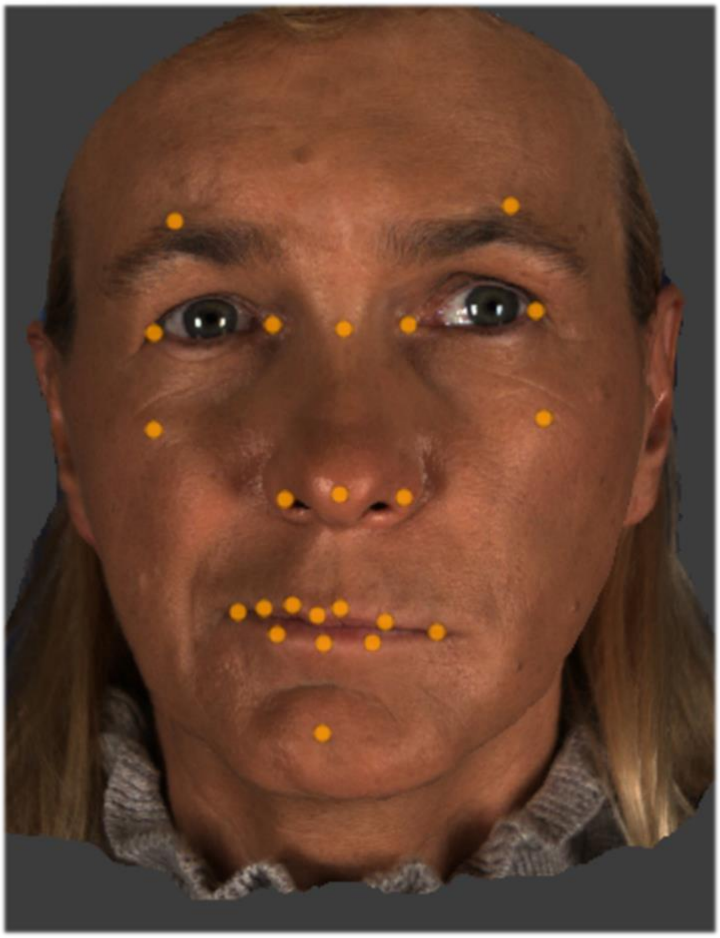


Manual Digitization of Anatomical Landmarks

The operator viewed and manipulated the captured 3D facial image in three dimensions to facilitate accurate identification of facial landmarks. A set of 23 anatomical landmarks were manually digitised on the 3D facial frame (Figure 28) according to established criteria (Gwilliam et al., 2006). Landmarking reproducibility of the selected landmarks was investigated and validated in a previous study (Alagha et al., 2017).

The anatomical landmarks provided scarce facial representation of facial morphology; hence, they were not used for the assessment of facial symmetry nor for the analysis of dynamics of facial movements. Data of landmarks' positions in the three dimensions of space (X, Y, Z) were saved in "dilm" file format. These were utilised to clone a generic facial template into the individual facial morphology.

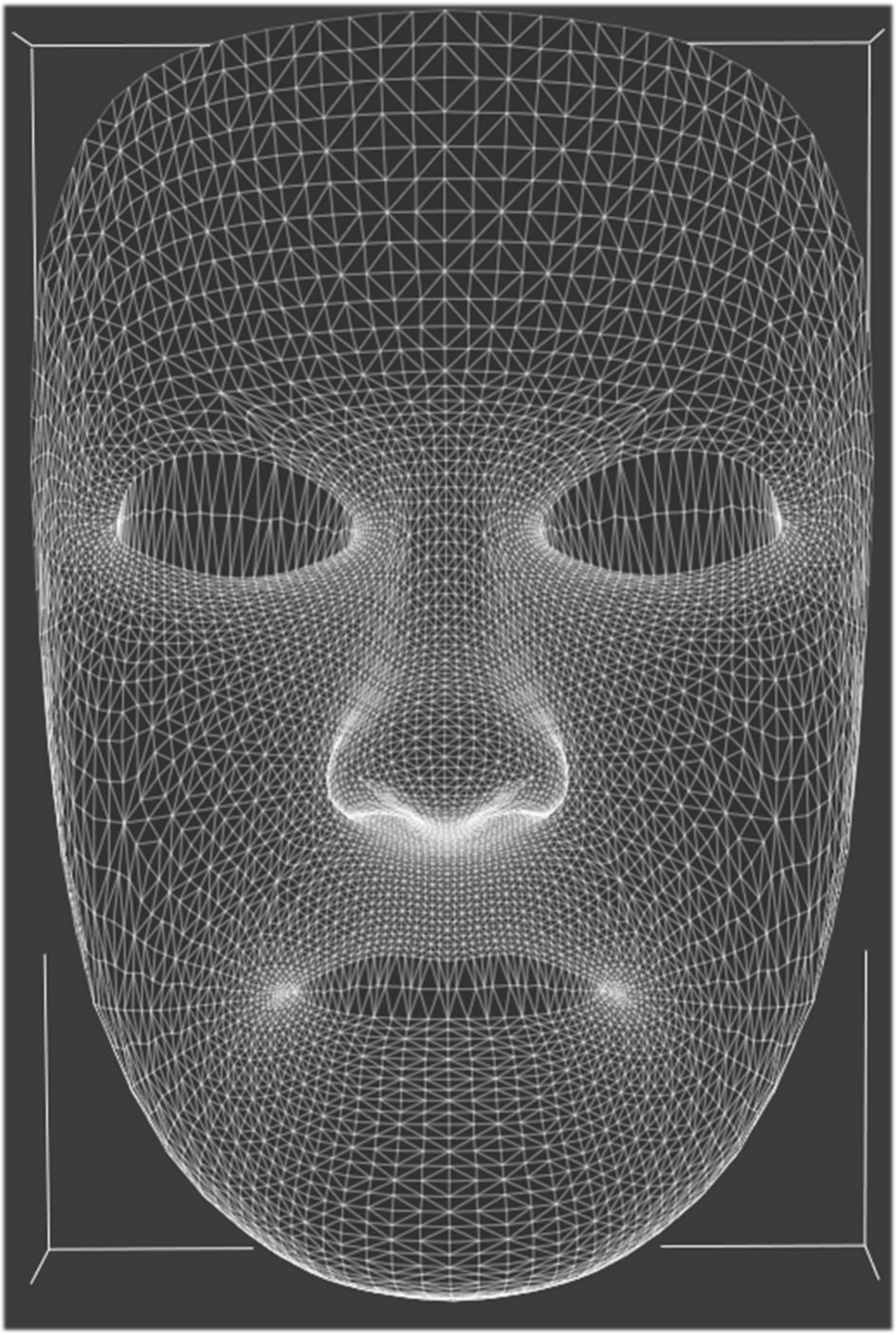
Figure 28: Anatomical Landmarks



Building Dense Surface Models (DSM)

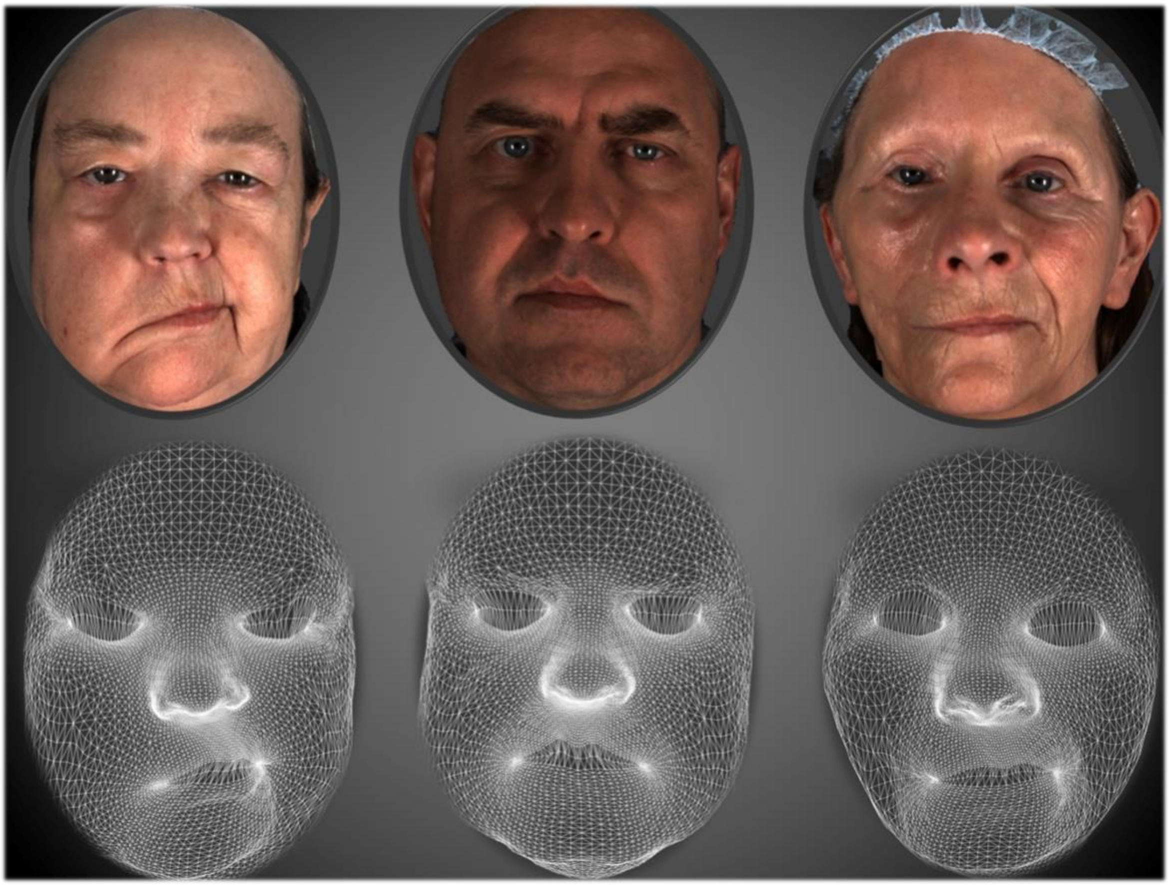
A generic facial template (Figure 29), a mathematical mesh composed of 7K symmetrical and uniformly distributed quasi-landmarks, the 3D spatial positions of which were indexed, was used to build dense correspondence on the first frame of the 3D image sequence.

Figure 29: Generic Facial Mesh



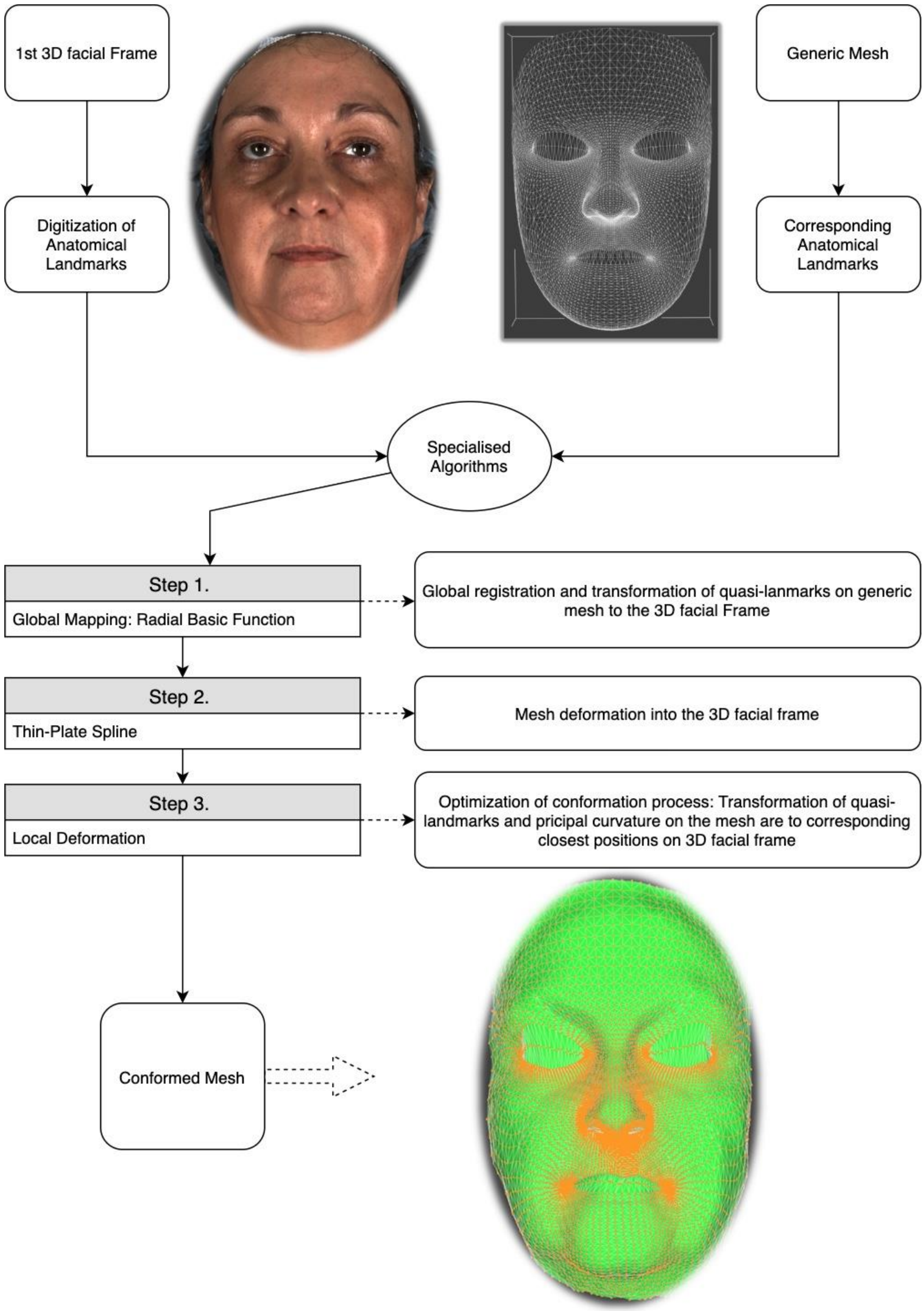
Based on advanced geometric morphometric approach, the generic mesh was mathematically adapted into the individual's facial geometry to portray surface morphology for the custom representation of each facial expression, Figure 30.

Figure 30: Conformed Mesh



The conformation process was automated and based on specialised algorithms, detailed in (Mao et al., 2006) and presented in Figure 31.

Figure 31: The Mesh Conformation Process



Four-Dimensional Image Processing

The conformed mesh provided a comprehensive full-face facial representation (Figure 30); thus, Dense Surface Model was built.

Four-dimensional image processing was achieved using the Di4D-View software to track the changes over time of 3D facial morphology throughout each facial expression according to the following steps:

1. The 4D video of facial expression was imported into the Di4D-View software.
2. The first facial frame of the 3D image sequence was selected as the anchor frame.
3. The corresponding dense surface model, conformed mesh, was imported.
4. The 7K quasi landmarks of the conformed mesh were automatically tracked throughout the full 3D image sequence for each facial expression.
5. The 3D configurations of tracked conformed mesh throughout the full 3D image sequence were exported in pc2 file format.

Data Standardization

The final step of basic image processing was data standardization. This involved a cleaning process to remove peripheral data of the captured sequence of the capture 3D image, which caused noise in the analysis. This included the neck region, ears, and hairline. DSMs were trimmed using VR-mesh software. The trimming process was universal, based on the same vertex count of the conformed meshes.

To standardize the analysis, all the 3D facial images of right facial paralysis were reflected. This kept the facial paralysis on the left side in all the 3D sequence of the captured images of all the cases.

Output Data

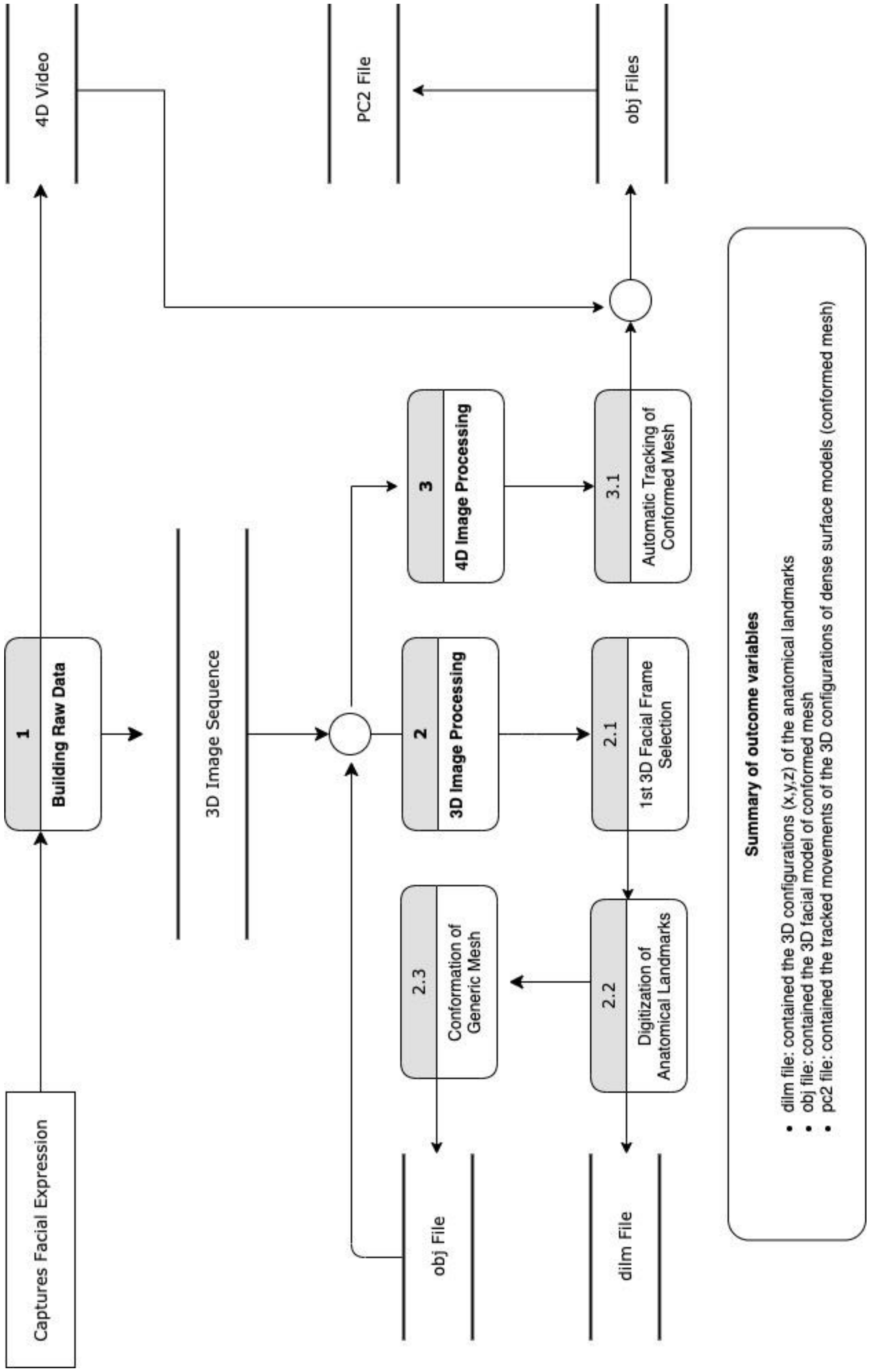
Summary of output file types, obtained from data processing, are provided in Figure 32. These include:

◊ dilm files: contained the 3D configurations (X, Y, Z) of the anatomical landmarks.

◊ obj files: contained the 3D facial model of conformed mesh.

◊ pc2 files: contained the tracked movements of the 3D configurations of dense surface models throughout the full 3D image sequence per expression (conformed mesh).

Figure 32: Summary of Output Data



Section D: The Mathematical Analysis of Facial Dynamics using Geometric Morphometrics

Introduction

- ◊ The objective of the mathematical analysis was the quantification of individual facial asymmetry at rest and during each of the five facial expressions.
- ◊ This allowed the statistical modeling of the patterns of static and dynamic facial asymmetry.

The control group involved 44 healthy volunteers, age and sex matched to the 44 unilateral facial palsy patients.

Facial expressions were recorded at rest, maximal smile, lip purse, cheek puff, eyebrow raising, and eye closure. The processed 4D videos of facial expressions contained the 3D image sequence of Dense Surface Models.

Quantification of Facial Asymmetry

Dense Surface Models (DSMs) were processed to measure facial asymmetry at rest and during facial movements. In essence, each DSM was compared to its own reflected image, Figure 33.

Figure 33: Quantification of Facial Asymmetry

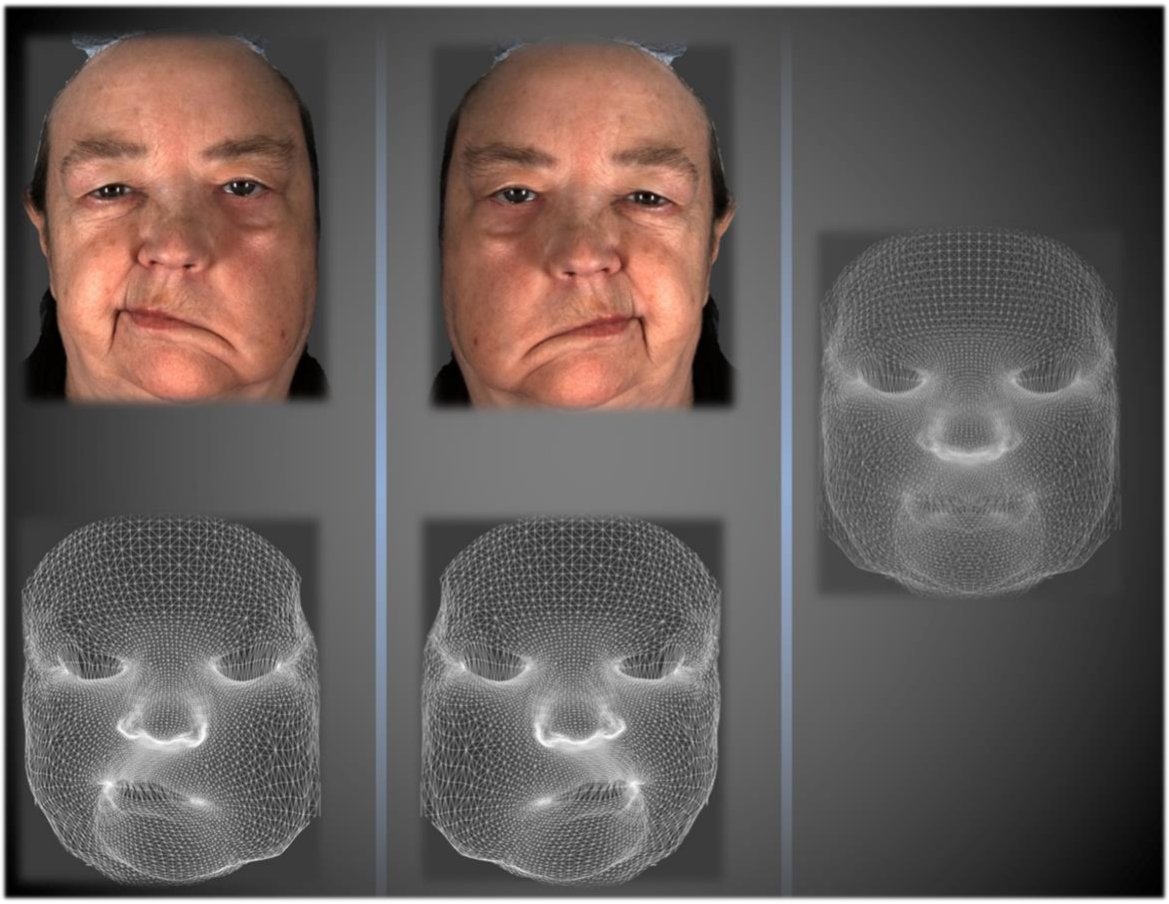


Figure 33 provides visual representation of the analysis of facial asymmetry. DSM and its mirrored replica were aligned by Partial Procrustes Analysis to measure shape difference.

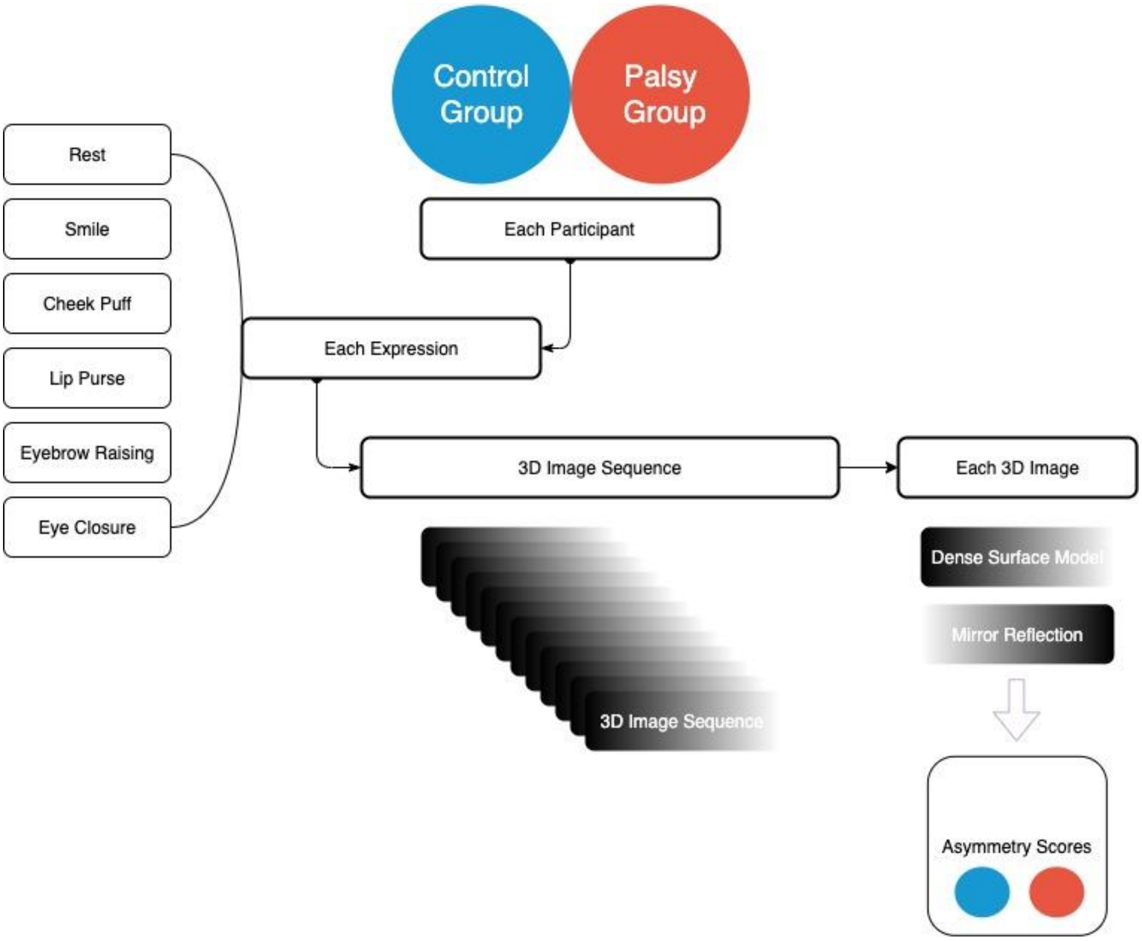
Facial Asymmetry Scores

To measure the facial asymmetry scores for each expression per participant, the steps below were followed:

1. Dense Surface Models for each frame of the 3D image sequence per expression were aligned to the generic facial mesh, which was the facial template used for 4D tracking (Figure 29), with General Procrustes Analysis (scaled to the size of the generic mesh).
2. Dense Surface Models were reflected around an arbitrary plane to create a mirror image of each 3D facial image.
3. Each of the DSMs was aligned on its own mirror image configurations using Partial Procrustes Analysis.
4. The asymmetry score was calculated based on the average Euclidean distance of the corresponding vertices between the DSM and its aligned mirror copy. The average of the root mean square distances between the 7k vertices of the conformed mesh of the 3D facial image and the corresponding vertices of the mirror copy provided a measure of the asymmetry score. In perfect symmetry, the Procrustes distance between the original and mirrored DSMs equals zero.
5. The asymmetries of the 3D image sequence of each facial expression were calculated.

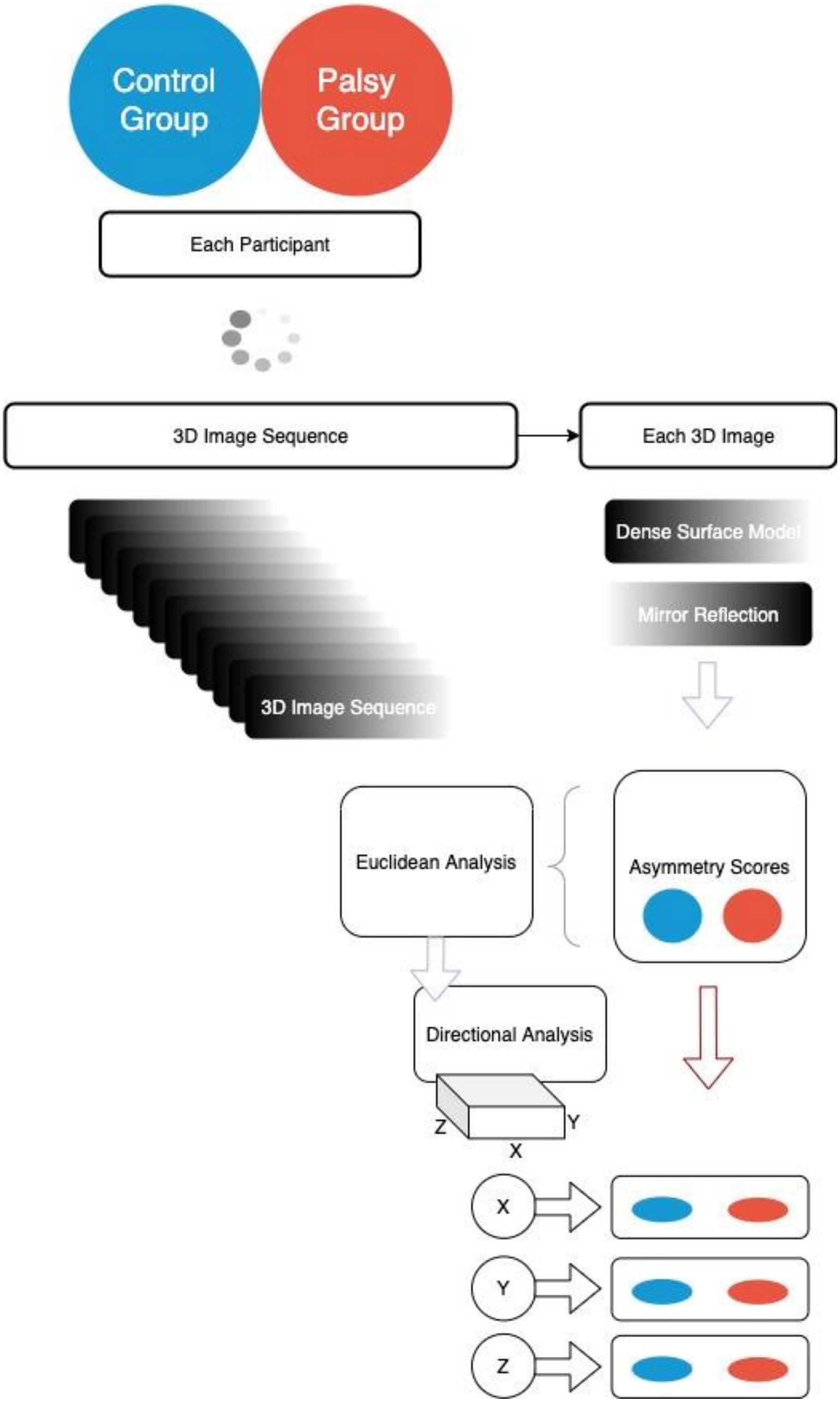
Figure 34 provides a schematic representation of 3D image processing for the calculation of asymmetry scores.

Figure 34: Asymmetry Scores - Schematic Representation



Furthermore, the directionality of the asymmetry scores were measured for each of the three dimensions X, Y, Z. This quantified and stratified facial asymmetry in the 3 directions of space: mediolateral, vertical, and anteroposterior directions, respectively, Figure 35.

Figure 35: Directional Asymmetry Scores - Schematic Representation



Regional Asymmetry Scores

Using a mesh-cutting software, VRmesh, the Dense Surface Model was subdivided into anatomical regions. The reason of mesh segmentation was to look at the neural and muscular deficit and taking into consideration how the mathematical asymmetry scores at segmented regions would correlate to the clinical assessments.

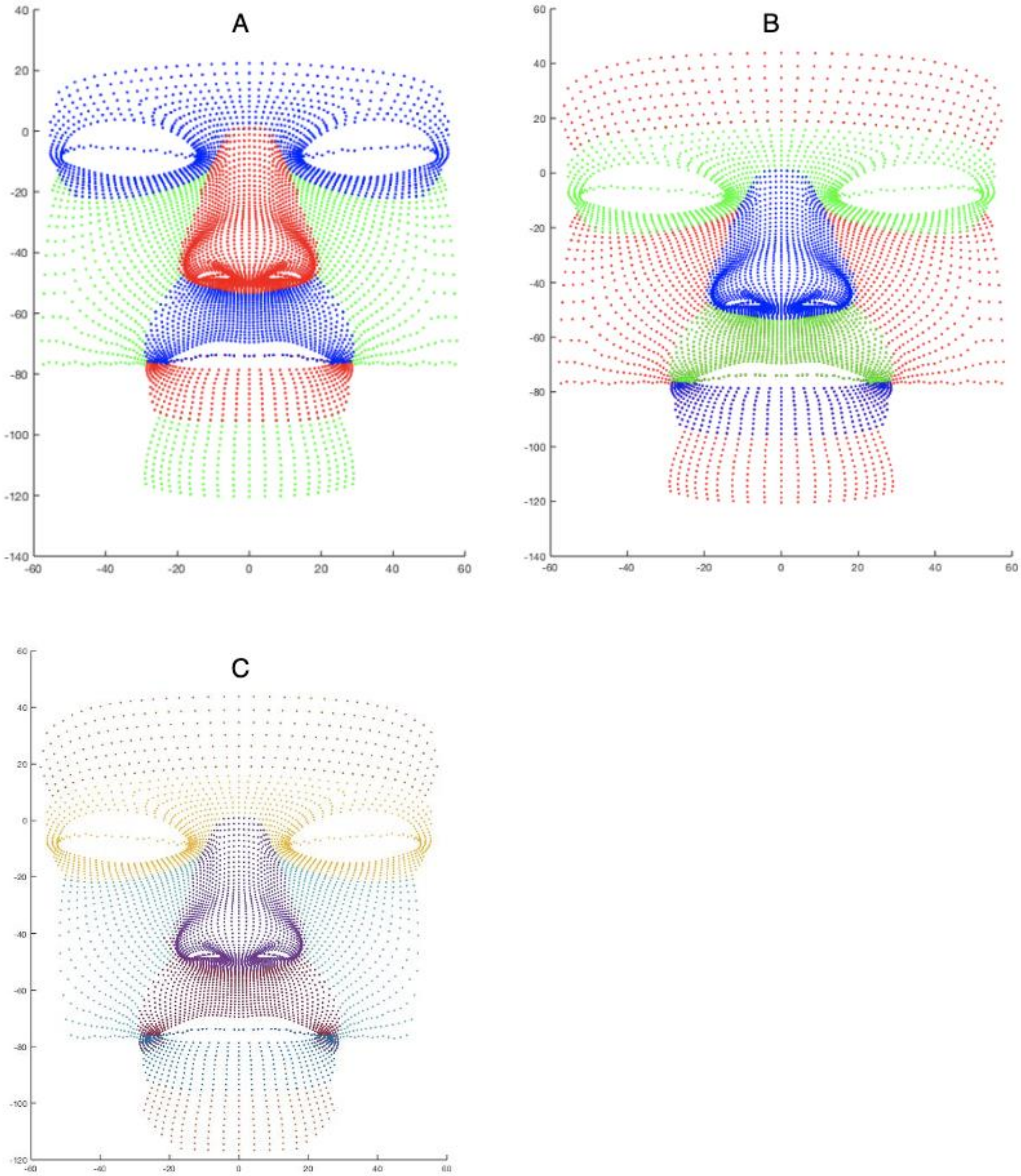
Selection of Segmented Facial Regions

The selection of segmented regions was enhanced over three trials, Figure 36. Initially, the division of the face into regions was based on our established methods of 3D and 4D assessments of facial morphology in patients who suffer from cleft lip and palate (Dhelal Al-Rudainy et al., 2018; Gattani et al., 2020). The facial regions were segmented into 6 facial regions: eyes, nose, cheek, upper lip, lower lip, and chin (Figure 36.A).

This was then adjusted to satisfy the clinical objectives of the unilateral facial palsy assessment. The segmentation of the facial regions considered the forehead region distinct from the eyes and, the nasolabial region (nose + upper lip) as a new measure (Figure 36.B).

The facial regions were refined by removing a few points in the cheek and chin, which were close to the boundary of the face and not reliable to represent the true facial shape. A new region was defined as the corner of mouth, where its points consisted of part of points from upper lip, lower lip, and cheek (Figure 36.C).

Figure 36: Selection of Segmented Regions



The Segmented Facial Regions

Figure 37 demonstrates the divided generic mesh utilised for the measurement of local asymmetry scores. Regional asymmetries were analysed at 10 facial regions are identified in Table 4.

Figure 37: Segmented Facial Regions

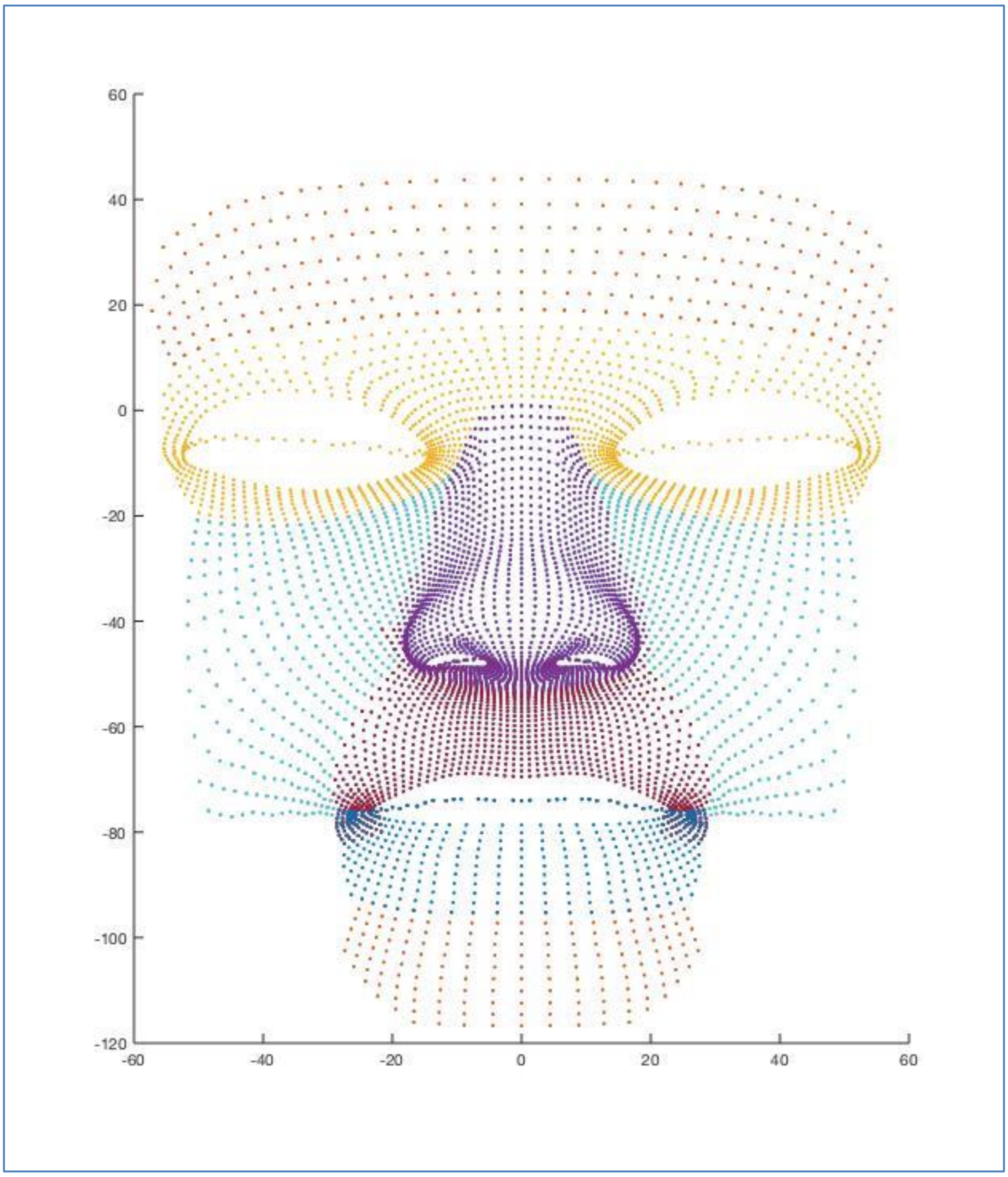


Table 4: Segmented Facial Regions

	Segmented Facial Regions (10 Regions)
1	Full face (All regions as one)
2	Forehead
3	Eyes
4	Nose
5	Cheek
6	Nasolabial (Nose and upper lip combined)
7	Upper lip
8	Lower lip
9	Chin
10	Corner of mouth (Consisted of part of points from upper lip, lower lip and cheek)

Dynamic Asymmetry Scores

Dynamic asymmetry scores at each expression per individual were calculated. The minimal, mean, median, and maximum asymmetry values were measured for each of the 10 individual regions (full face, forehead, eyes, nose, cheek, nasolabial, upper lip, lower lip, chin, and corner of mouth).

Colour Coded Facial Maps

Colour-mapping technique (Almukhtar et al., 2016) was applied to visualize the resting and dynamic patterns of facial dysmorphology. The average inter-surface distances between the 3D facial DSMs and their mirror copies were colour-coded on a scale ranging from blue to red colour to indicate the degree of average asymmetry.

To visualise the average distance patterns (Euclidian distance), the blue colour indicated perfect symmetry with a minimal difference in the mean absolute distance between the vertices of the 3D images and their corresponding reflections. The changing colour from blue to red indicated an increase in the magnitude of facial asymmetry.

To visualise the difference patterns at the mediolateral, vertical, and anteroposterior directions, Right Hand Coordinate System was implemented in which, the red colour indicated an increase in facial asymmetry on the left, upward, and away from the operator directions whereas the blue colour indicated an increase in the magnitude of facial asymmetry on the right, downward and toward the operator directions.

Section E: The Clinical Grading of Facial Palsy

Introduction

The clinical assessment of facial palsy was based on two clinical grading indices this study introduced; the Modified Sunnybrook Index and the Glasgow Index of Facial Paralysis.

The two clinical grading indices were used by a panel of assessors to evaluate facial dysmorphology and distorted facial movements in unilateral facial palsy patients.

Facial expressions were recorded at rest, maximal smile, lip purse, cheek puff, eyebrow raising, and eye closure (Section B: Recorded Facial Expressions).

The clinical assessors were shown the 4D videos of unilateral facial palsy patients. Sixteen cases out of 44 were selected from the unilateral facial palsy group, which represented the broad spectrum of facial palsy.

The Clinical Assessors

Expert assessors who deal with the diagnosis and management of facial abnormalities were invited to take part in the subjective assessment of unilateral facial palsy. The invitation letter was sent by email along with the study information sheet. Seven expert assessors agreed to join the study, one consultant oral and maxillofacial surgeon, four consultant plastic surgeons, a consultant orthodontist specialised in cleft care, and a physiotherapist.

The Clinical Assessment

Calibration Process

The scope of the study and an overview of the literature on the available scales for grading facial palsy were presented to the panel. Two grading systems for the clinical evaluation of facial palsy were introduced; the Glasgow Index (proposed by our research group) and the modified Sunnybrook index.

A trial run for the clinical gradings was conducted on the 4D image data of facial expressions at rest, maximal smile, lip purse, cheek puff, eyebrow raise, and forceful eye closure of some pilot cases.

Rating Sessions

The clinical assessment of the 16 facial palsy cases was conducted twice, 45 days apart to minimise the memory bias on the clinical grading of unilateral facial palsy patients. The sequence of the cases was altered to avoid the impact of the severity of the cases on the grading process.

The Clinical Grading Systems of Facial Palsy

The Modified Sunnybrook Index

Sunnybrook Facial Grading System (Table 5) is currently considered the standard for the clinical evaluation of facial palsy (Fattah et al., 2015).

Table 5: Sunnybrook Facial Grading System

Parameter	Finding	Point Value
Resting symmetry score		
Eye	Normal or abnormal	0 or 1 points
Cheek (nasolabial fold)	Normal, altered, or absent	0 or 1 or 2 points
Mouth	Normal or abnormal	0 or 1 points
Voluntary movement score		
Forehead wrinkle	No movement to normal	1 to 5 points
Gentle eye closure	No movement to normal	1 to 5 points
Open mouth smile	No movement to normal	1 to 5 points
Snarl	No movement to normal	1 to 5 points
Lip pucker	No movement to normal	1 to 5 points
Synkinesis score		
Forehead wrinkle	None, mild, moderate, or severe	0 to 3 points
Gentle eye closure	None, mild, moderate, or severe	0 to 3 points
Open mouth smile	None, mild, moderate, or severe	0 to 3 points
Snarl	None, mild, moderate, or severe	0 to 3 points
Lip pucker	None, mild, moderate, or severe	0 to 3 points
Final score calculation = (sum of resting symmetry points x 5) - (sum of voluntary movement points x 4) - (sum of synkinesis points x 1)		

For the purpose of this study, only the parameters for the assessment of facial symmetry at rest and voluntary movements were considered. The grading of synkinesis was excluded.

The Modified Sunnybrook Index MSB was changed in the following aspects:

- ◊ Snarl movement was replaced with cheek puff.
- ◊ Descriptive annotations for the 5 grades of the voluntary movements were provided according to the consensus of the expert assessors.

The Glasgow Index

The Glasgow Index (GI) for the assessment of distorted facial expressions was proposed to address the following aspects in the clinical assessment:

- ◊ The global and regional dysmorphology.
- ◊ The static and dynamic facial asymmetry.
- ◊ The directionality and severity of asymmetric facial movements.
- ◊ Specific facial features.

The GI contained 29 parameters to achieve the following:

- ◊ Assessment of facial dysmorphology at rest (6 parameters).
- ◊ Assessment of smile (6 parameters).
- ◊ Assessment of lip purse (5 parameters).
- ◊ Assessment of cheek puff (4 parameters).
- ◊ Assessment of eyebrow raising (4 parameters).
- ◊ Assessment of eye closure (4 parameters).

Table 6 and Table 7 show the parameters of the modified Sunnybrook Index and the Glasgow Index used in the clinical assessment. The marking criteria of the two indices are highlighted in Appendix B: Marking Sheets.

Table 6: Clinical Parameters of the Modified Sunnybrook Index MSB

	The Modified Sunnybrook Index (8 parameters)
	Parameters assessed at rest
1	Eye
2	Cheek (nasolabial fold)
3	Mouth
	Parameters assessed at voluntary movements
4	Forehead Wrinkle
5	Eye Closure
6	Smiling
7	Cheek Puff
8	Lip Pucker

Table 7: Clinical Parameters of the Glasgow Index GI

	The Glasgow Index (29 parameters)
	Parameters assessed at rest
1	Total facial asymmetry
2	Forehead wrinkles and eyebrow
3	Eyes
4	Nose and nasolabial fold
5	Cheeks
6	Corner of mouth and chin
	Parameters assessed at maximum Smile
7	Total dynamic asymmetry
8	Magnitude of smiling
9	Magnitude of lower lip
10	Dynamic asymmetry of Nasolabial fold
11	Direction of asymmetry
12	Severity of asymmetric direction
	Parameters assessed at lip Purse
13	Total dynamic asymmetry
14	Magnitude of lip movement
15	Magnitude of lower lip
16	Direction of asymmetry
17	Severity of asymmetric direction
	Parameters assessed at cheek Puff
18	Total dynamic asymmetry
19	Magnitude of cheek movement
20	Direction of asymmetry
21	Severity of asymmetric direction
	Parameters assessed at maximum raising of eyebrow
22	Total dynamic asymmetry
23	Magnitude of eyebrow movement
24	Direction of asymmetry
25	Severity of asymmetric direction
	Parameters assessed at forceful eye closure
26	Total dynamic asymmetry
27	Magnitude of eye closure
28	Direction of asymmetry
29	Severity of asymmetric direction

The Assessment Protocol

Rater's Calibration

Training was provided at the beginning of the assessment session in the form of a PowerPoint presentation to help familiarise the assessors with the assessment criteria. This took 10-15 minutes. The PowerPoint slides presented the 4D images of unilateral facial palsy to provide examples of the assessment criteria.

Settings of the Clinical Assessment

The grading of facial palsy cases took place in a dim-light, medium-sized room. The raters sat on comfortable chairs in front of a table and the grading sheets were made available. Four-dimensional image data of the clinical cases were displayed on a wall-mounted widescreen located 2 meters away from the assessors.

Presentation of Unilateral Facial Palsy Cases

Each clinical case was shown in PowerPoint using 12 slides (size 16:9). The slideshow was automated; upon opening the program the show starts with the first slide displaying the facial expression at rest and then transitions to a countdown slide before displaying the next facial expression (Figure 38). To standardise the assessment the transition time between slides was configured at 60 seconds per expression followed by 20 seconds for marking (countdown slide). The assessment of each case took 8 minutes.

The PowerPoint slide displaying facial movements contained the video and expression title. Each 4D video demonstrated the facial expression starting from rest to maximal animation and back to rest. The video aspect ratio was configured for all cases. The video showed the full face of the subject and displayed facial movements in the frontal view and then a repeat in the anteroposterior view (the recorded video rotated 45 degrees around the horizontal line). The duration of videos ranged from 10 to 12 seconds. The video was set on auto-repeat until the PowerPoint slide transitioned to the next slide.

Figure 38: Demonstration of PowerPoint Slides

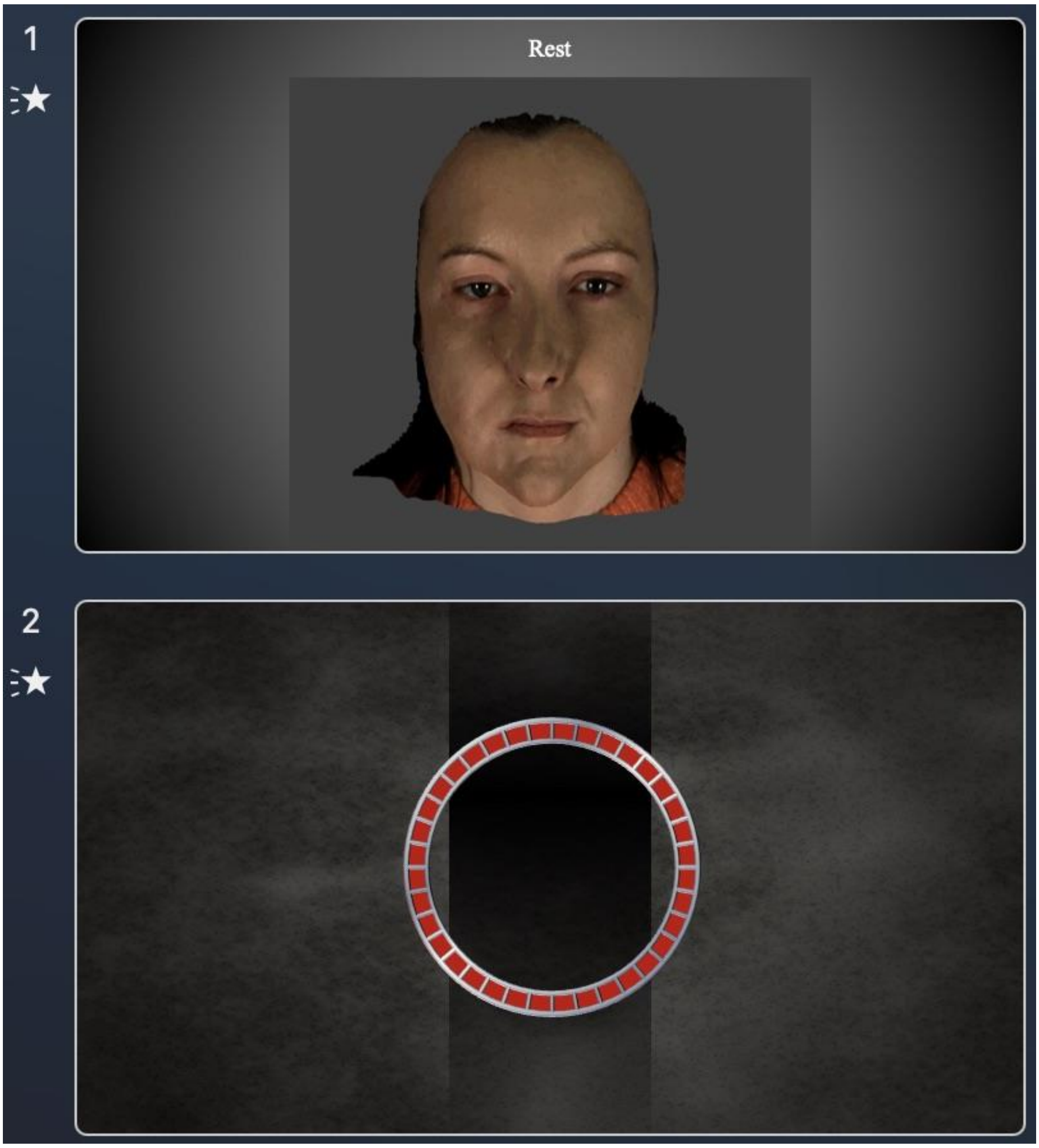


Figure 38 shows the first two PowerPoint slides and demonstrates the slide displaying a facial expression at rest and the countdown slide.

The Clinical Grading of Unilateral Facial Palsy Cases

For each clinical case, 6 marking sheets were provided, one sheet per expression. On each sheet, relevant expression questions from both indices were included. To eliminate grading bias, two forms of marking sheets were provided where the ordering of indices questions alternated from case to case.

The Reliability Assessment of the Clinical Grading of Facial Palsy

The consistency of results was investigated by measuring the repeatability and the reproducibility of the clinical gradings.

- ◊ The Repeatability (intra-observer consistency) assessed the variations due to the repeated assessment of the same variables under identical conditions (same assessor).
- ◊ The Reproducibility (inter-observer consistency) assessed the variations due to the different conditions when grading the images (different assessors and different grading systems).

Test-Retest reliability Analysis of the Grading Parameters

Wilcoxon signed rank test was applied to evaluate reproducibility of the grading of the individual parameters between the first and second sessions for each of the modified Sunnybrook index and the Glasgow index.

Reproducibility of Assessors

Intraclass Correlations Analysis (ICC) was applied to assess the reproducibility of the clinical gradings of the 7 assessors using the modified Sunnybrook index and the Glasgow Index. The ICC is used to determine the reproducibility of measurements (observations) that are organised into groups (Liljequist et al., 2019). In this study the results were reported and interpreted according to (Koo & Li, 2016); the following ICC characteristics were indicated:

- ◊ **Model**: two-way random-effect model.
- ◊ **Type**: mean of K raters.
- ◊ **Definition**: rater’s consistency.

The interpretation of the ICC values:

- ◊ **Poor reliability**: ICC<0.5
- ◊ **Moderate reliability**: ICC 0.5 to 0.75
- ◊ **Good reliability**: ICC 0.75 to 0.9
- ◊ **Excellent reliability**: ICC>0.9

Pearson correlation analysis investigated the reproducibility of the clinical gradings among the 7 expert assessors at the two rating sessions. The consistency of the clinical gradings between the first and second rating sessions was measured for the 7 expert assessors. The interpretation of the correlation coefficient was according to (Overholser & Sowinski, 2008; Schober et al., 2018), Figure 39.

Figure 39: Interpretation of the Correlation Coefficient

Absolute Magnitude of the Observed Correlation Coefficient	Interpretation
0.00–0.10	Negligible correlation
0.10–0.39	Weak correlation
0.40–0.69	Moderate correlation
0.70–0.89	Strong correlation
0.90–1.00	Very strong correlation

Several stratifications (with different cutoff points) have been previously published.

Figure 39 presents the interpretation of the correlation coefficient (Schober et al., 2018), utilised in this study.

Statistical Analysis of the Indexing Methods

Linear mixed effects model analysis of the indexing methods was applied to assess the effect of fixed and random variables on the statistical analysis of the data. This included the impact of the repeated gradings and the parameters of the clinical scales on the reproducibility.

Section F: The Correlation Between the Mathematical Measurements and Clinical Gradings of Facial Palsy

This section aims to explore the relationship between the objective and subjective assessment of altered facial expressions. Specifically, to:

- ◊ Investigate the correlation between the mathematical measurements of facial asymmetry and the subjective assessments of the Glasgow Index and the modified Sunnybrook Index.
- ◊ Assess the similarities and differences between the two clinical indices to the mathematical measurements.
- ◊ Compare and identify the aspects of dissimilarity between the parameters from the two clinical indices.

The mathematical asymmetry of the facial palsy cases was quantified in Section D. The following steps were followed:

1. The average distances between the vertices of the 3D image and that of its reflection were calculated for the 10 regions – All regions as one and its 9 segment regions.
2. For 44 controls, the mean asymmetry scores (mean) and its standard derivations (std) were calculated for six expressions, including the rest expression at 10 regions.
3. For 16 assessed patient cases, the mean asymmetry scores (pts) at 10 regions of six expressions were calculated.
4. For 16 assessed patient cases, Z scores were calculated for 10 regions of six expressions based on the equation:

$$Z = (\text{pts} - \text{mean})/\text{std}$$

$$Z = 0.0 \text{ if } (\text{pts} - \text{mean})/\text{std} < 0$$

5. Z scores, mean distances and mean absolute X, Y, Z differences of 16 patient cases at 10 facial regions of six expression were compared with the Sunnybrook index and the Glasgow index.

The clinical grading of facial palsy by the 7 assessors (measured twice) of each of the 8 parameters for the modified Sunnybrook Index and 29 parameters for the Glasgow Index generated the data for the correlation analysis.

Pearson's correlation analysis was applied to identify the aspects of correlation between the subjective and objective assessments. The correlation coefficients were calculated between the mathematical values of asymmetry at the segmented facial regions (the minimum, mean, median, maximum, range, and SD) and the clinical grades of each parameter of the two grading indices. The statistical significance of correlations was tested. The level of significance at the rate 0.05.

Results

The clinical Grading of Facial Palsy

The clinical assessment of the 16 unilateral facial palsy patients was performed by 7 expert assessors on two different occasions, 6 weeks apart. For each clinical case, the assessors observed the 4D images of 6 facial expressions. The grading of facial dysmorphology and dysfunction was achieved using the modified Sunnybrook index and the Glasgow index.

The Modified Sunnybrook Index

Grading Reproducibility for the 8 Parameters Assessed in the Modified Sunnybrook Index

Wilcoxon Sign Rank test was applied to investigate the reproducibility for the modified Sunnybrook index parameters between the two rating sessions. The results presented in Table 8 are based on 7 assessors who assessed 8 parameters of 16 patients.

Table 8: Grading Reproducibility for the 8 Parameters Assessed in the Modified Sunnybrook Index

MSB Parameters	*P-values*	*Mean difference*	*Median difference*	*SD*
1-Eye	0.05	-0.09	0	0.53
2-Cheek (nasolabial fold)	0.33	-0.05	0	0.58
3-Mouth	0.12	0.07	0	0.49
4-Forehead wrinkle	0.39	-0.08	0	0.87
5-Eye closure	0.84	-0.00	0	0.47
6-Smiling	0.86	0.01	0	0.78
7-Cheek puff	0.17	0.10	0	0.82
8-Lip pucker	0.35	0.05	0	0.61

The findings show no statistically significant difference in the reproducibility of the subjective grading of the MSB parameters among the 7 assessors. The assessment of the eye at rest was the least reproducible as indicated by the marginally significant p-value. The mean differences in the grading scores per parameter between the two sessions were less than one point and less than 1 standard deviation among the seven assessors.

Consistency Between the 7 Expert Assessor Using the Modified Sunnybrook Index

Intraclass correlations analysis was applied to assess the reproducibility of the clinical gradings of the 7 assessors using the modified Sunnybrook index. Results are presented in Table 9 and were reported and interpreted according to (Koo & Li, 2016).

Table 9: Consistency Between the 7 Expert Assessor Using the Modified Sunnybrook Index

MSB Parameters	*Intraclass Correlations ICCs*	*P-values*
1-Eye	0.45	<0.01
2-Cheek (nasolabial fold)	0.58	<0.01
3-Mouth	0.56	<0.01
4-Forehead wrinkle	0.83	<0.01
5-Eye closure	0.82	<0.01
6-Smiling	0.75	<0.01
7-Cheek puff	0.44	<0.01
8-Lip pucker	0.74	<0.01

Table 9 shows the inter-rater reliability measures of the 8 MSB parameters reported by the ICC values. It demonstrates the variation between the 7 expert assessors in the clinical grading scores of the Modified Sunnybrook index. At the 95% confidence interval of the ICC estimate, MSB parameters number 1 and 7 showed the lowest correlation (ICC value less than 0.5), MSB parameter 2, 3, 8 showed moderate correlation (ICC values between 0.5 and 0.75); MSB parameter 4, 5, 6 showed strong correlation (ICC values between 0.75 and 0.9). The correlations were statistically significant.

Inter Observer Reproducibility of the Modified Sunnybrook Index

The reproducibility of the clinical gradings between the 7 expert assessors were measured at the first and second rating sessions, Table 10, Table 11, respectively.

Table 10: Correlations Between the Modified Sunnybrook Index Scores Among the 7 Assessors at the First Grading Session

1St grading session	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	**1.00**	0.63	0.47	0.46	0.64	0.35	0.55
Rater 2	0.63	**1.00**	0.53	0.59	0.62	0.35	0.50
Rater 3	0.47	0.53	**1.00**	0.45	0.55	0.20	0.47
Rater 4	0.46	0.59	0.45	**1.00**	0.44	0.48	0.48
Rater 5	0.64	0.62	0.55	0.44	**1.00**	0.18	0.57
Rater 6	0.35	0.35	0.20	0.48	0.18	**1.00**	0.44
Rater 7	0.55	0.50	0.47	0.48	0.57	0.44	**1.00**
P-values	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 3	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
Rater 4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 5	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	<0.01
Rater 6	<0.01	<0.01	0.02	<0.01	0.04	<0.01	<0.01
Rater 7	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 10 shows no statistically significant difference among assessors in the clinical gradings of the 16 facial palsy patients at the first rating session. The agreements of the average grading between different assessors were moderate (Correlation Coefficient ranged between 0.44 - 0.64), except for the sixth assessor.

Table 11: Correlations Between the Modified Sunnybrook Index Scores Among the 7 Assessors at the Second Grading Session

2nd grading session	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	**1.00**	0.63	0.54	0.54	0.65	0.40	0.63
Rater 2	0.63	**1.00**	0.62	0.61	0.60	0.40	0.56
Rater 3	0.54	0.62	**1.00**	0.60	0.60	0.23	0.49
Rater 4	0.54	0.61	0.60	**1.00**	0.51	0.48	0.55
Rater 5	0.65	0.60	0.60	0.51	**1.00**	0.21	0.58
Rater 6	0.40	0.40	0.23	0.48	0.21	**1.00**	0.58
Rater 7	0.63	0.56	0.49	0.55	0.58	0.58	**1.00**
P-values	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 5	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Rater 6	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Rater 7	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 11 shows no statistically significant difference among assessors in the clinical grading of 16 facial palsy patients at the second rating session. The agreement of grading between the assessors were moderate (Coefficient ranged between 0.49 - 0.65), except for the sixth assessor; the agreement of the grading with the rest ranged from weak to moderate (Correlation Coefficients ranged from 0.21 to 0.58).

Intra Observer Reproducibility of the Modified Sunnybrook Index

The consistency of the clinical gradings between the first and second rating sessions was measured for the 7 expert assessors Table 12.

Table 12: Correlations Between the Modified Sunnybrook Index Scores Among the 7 Assessors Between the First and Second Grading Sessions

Session 1st / 2nd	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	**0.82**	0.56	0.49	0.50	0.65	0.38	0.66
Rater 2	0.63	**0.84**	0.59	0.58	0.61	0.40	0.58
Rater 3	0.43	0.56	**0.80**	0.52	0.63	0.22	0.48
Rater 4	0.52	0.62	0.58	**0.86**	0.45	0.48	0.54
Rater 5	0.68	0.59	0.56	0.51	**0.87**	0.22	0.63
Rater 6	0.38	0.35	0.23	0.45	0.17	**0.94**	0.52
Rater 7	0.52	0.53	0.44	0.50	0.55	0.49	**0.84**
P-values	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 3	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Rater 4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 5	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
Rater 6	<0.01	<0.01	<0.01	<0.01	0.04	<0.01	<0.01
Rater 7	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 12 shows no statistically significant difference between the first and second session of grading of facial dysmorphology and dysfunction among assessors using the modified Sunnybrook index scores. The correlations between the repeated scores were strong for all assessors (Correlation Coefficient ranged between 0.82 – 0.94). The reproducibility of grading among the assessors was moderate (Coefficient between 0.4 - 0.68), except for the sixth assessor; the reproducibility of gradings in comparison with the rest ranged from weak to moderate (Correlation Coefficients ranged from 0.17, 0.49).

Linear Mixed-Effect Model Analysis of The Modified Sunnybrook Indexing Methods

Linear mixed-effects model was applied on the grades of the modified Sunnybrook index, in the model, the fixed effects of the raters and the repeated assessment were tested against the random effects of the graded parameters and of the patients.

No significant effects were detected between the grades of the repeated assessments ($p = 1$; estimated coefficient 0.005); there is a significant effect of raters on the grades ($p = 0.032$; estimated coefficient -0.018).

The results indicate that the modified Sunnybrook indexing method is repeatable but there are differences in between raters, although the differences are small (coefficient = -0.018).

The Glasgow Index

Grading Reproducibility of Glasgow Index Scores at Individual Facial Expressions

ANOVA test for 6 expressions of Glasgow index scores showed that there was no statistically significant difference of the repeated subjective assessments among the group of assessors on the first and second rating sessions, Figure 40.

Figure 40: Boxplot of the First and Second Gradings Difference of The Glasgow Index at 6 Expressions

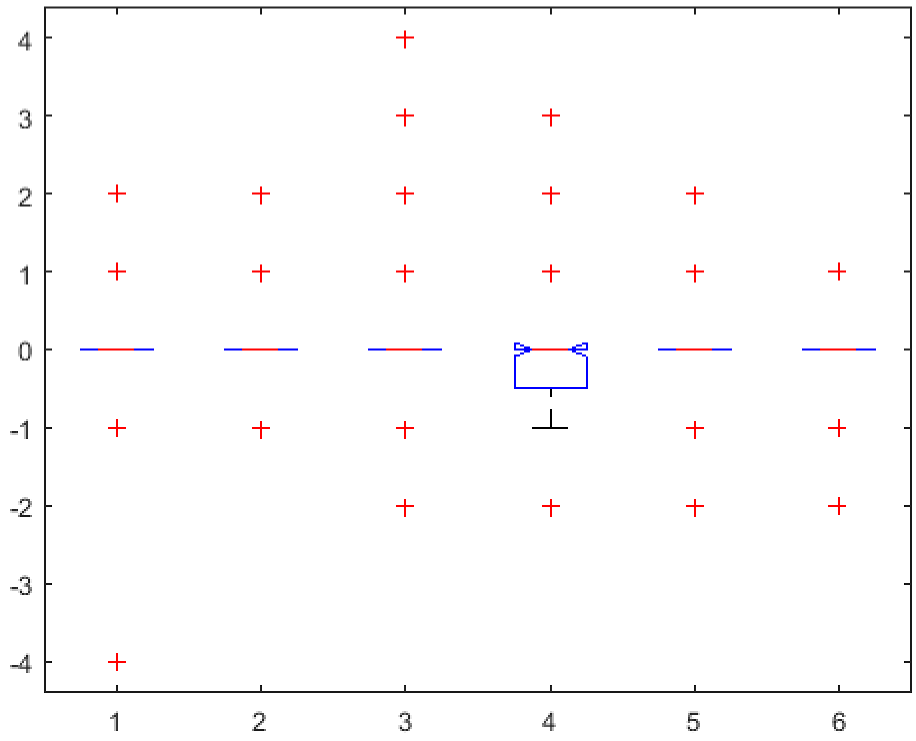


Figure 40 shows the ANOVA test of the grading reproducibility of 6 expressions using the Glasgow index. The X-axis is for the 6 facial expressions (1-rest, 2-smile, 3-lip purse, 4-cheek puff, 5-eyebrow raise, 6-eye closure). The Y-axis indicates the mean difference between the first and second gradings per expression. The cheek puff is the least reproducible

Grading Reproducibility for the 29 Parameters Assessed in the Glasgow Index

Wilcoxon Sign Rank test was applied to investigate the reproducibility of 7 assessors in grading the 16 patients using the Glasgow index parameters. Results are presented in Table 13.

Table 13: Grading Reproducibility for the 29 Parameters Assessed in the Glasgow Index

GI Parameters	*P-value*	*Mean difference*	*Median difference*	*SD*
1	0.39	0.05	0	0.59
2	0.63	-0.02	0	0.59
3	0.75	-0.00	0	0.63
4	0.38	-0.05	0	0.65
5	0.58	-0.03	0	0.70
6	0.61	0.07	0	0.82
7	0.06	0.11	0	0.65
8	0.03	0.13	0	0.67
9	0.34	-0.03	0	0.40
10	0.07	-0.07	0	0.41
11	0.22	-0.10	0	0.91
12	0.01	0.13	0	0.56
13	0.64	0.02	0	0.60
14	0.20	0.07	0	0.59
15	0.34	-0.03	0	0.40
16	0.21	0.14	0	1.17
17	0.03	0.11	0	0.65
18	<0.01	0.15	0	0.52
19	0.18	0.07	0	0.56
20	0.85	0.01	0	1.12
21	<0.01	0.17	0	0.61
22	0.26	0.06	0	0.58
23	0.66	-0.01	0	0.46
24	0.86	0.00	0	1.06
25	0.33	0.08	0	0.85
26	0.01	0.14	0	0.62
27	0.16	0.08	0	0.60
28	0.77	-0.02	0	0.79
29	0.05	0.11	0	0.76

No statistically significant differences were detected of the repeated grading of 23 parameters of the Glasgow index. Statistically significant differences were detected in six parameters; GI 8, 12, 17, 18, 21, 26. Three of the parameters were related to the severity of the dynamic asymmetry of the lip during smile (parameter 12), the dynamic asymmetry of lip purse (parameter 17) and the dynamic asymmetry of cheek puff (parameter 21). Parameters 18 and 26 assessed the total facial dynamic asymmetry at the maximum cheek puff and forceful eye closure, respectively. Parameter 8 was related to the magnitude of smiling. Across all parameters, the mean differences in the grading scores for each parameter between the two sessions was less than one grading point difference among the seven assessors. The clinical scores differences between the two sessions per parameter were around 1 standard deviation of the mean value. The median difference between the two rating sessions was 0 for each parameter which indicates the similarity in the grading rank.

Consistency Between the 7 Expert Assessor Using the Glasgow Index

Intraclass correlations analysis was applied for the clinical gradings of the 7 assessors using the Glasgow index. Results are presented in Table 14.

Table 14: Consistency Between the 7 Expert Assessor Using the Glasgow Index

GI Parameters	*Intraclass Correlations ICCs*	*P-values*
1	0.74	<0.01
2	0.63	<0.01
3	0.67	<0.01
4	0.67	<0.01
5	0.65	<0.01
6	0.58	<0.01
7	0.72	<0.01
8	0.71	<0.01
9	0.53	<0.01
10	0.71	<0.01
11	0.50	<0.01
12	0.78	<0.01
13	0.72	<0.01
14	0.72	<0.01
15	0.54	<0.01
16	0.43	<0.01
17	0.65	<0.01
18	0.76	<0.01
19	0.74	<0.01
20	0.45	<0.01
21	0.67	<0.01
22	0.86	<0.01
23	0.79	<0.01
24	0.51	<0.01
25	0.68	<0.01
26	0.65	<0.01
27	0.73	<0.01
28	0.56	<0.01
29	0.54	<0.01

Table 14 shows the interrater reliability measures of the 29 GI parameters reported by the ICC values. It demonstrates the variation between the 7 expert assessors in the clinical grading scores of the Glasgow index. At 95% confidence interval most of the parameters were moderately reproducibility. The correlations were statistically significant.

Inter Observer Reproducibility of the Glasgow Index

The reproducibility of the clinical gradings among the 7 expert assessors were measured at the first and second rating sessions, Table 15, Table 16, respectively.

Table 15: Correlations Between Glasgow Index Scores Among the 7 Assessors at the First Grading Session

1st grading session	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	**1.00**	0.37	0.03	0.09	0.19	0.05	0.02
Rater 2	0.37	**1.00**	0.17	0.13	0.23	0.12	0.08
Rater 3	0.03	0.17	**1.00**	0.26	0.13	0.22	0.16
Rater 4	0.09	0.13	0.26	**1.00**	0.34	0.22	0.22
Rater 5	0.19	0.23	0.13	0.34	**1.00**	0.22	0.22
Rater 6	0.05	0.12	0.22	0.22	0.22	**1.00**	0.35
Rater 7	0.02	0.08	0.16	0.22	0.22	0.35	**1.00**
P-values	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	<0.01	<0.01	0.45	0.05	<0.01	0.32	0.63
Rater 2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.08
Rater 3	0.45	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 4	0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 6	0.32	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 7	0.63	0.08	<0.01	<0.01	<0.01	<0.01	<0.01

The Pearson correlation coefficient showed the clinical gradings of 16 facial palsy patients at the first rating session were not uniformly correlated and were generally weak (Correlation Coefficient less than 0.39).

Table 16: Correlations Between Glasgow Index Scores Among the 7 Assessors at the Second Grading Session

2nd grading session	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	**1.00**	0.38	0.02	0.10	0.16	0.08	0.06
Rater 2	0.38	**1.00**	0.21	0.15	0.18	0.15	0.03
Rater 3	0.02	0.21	**1.00**	0.28	0.14	0.16	0.11
Rater 4	0.10	0.15	0.28	**1.00**	0.35	0.22	0.26
Rater 5	0.16	0.18	0.14	0.35	**1.00**	0.26	0.18
Rater 6	0.08	0.15	0.16	0.22	0.26	**1.00**	0.39
Rater 7	0.06	0.03	0.11	0.26	0.18	0.39	**1.00**
P-values	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	<0.01	<0.01	0.62	0.03	<0.01	0.10	0.21
Rater 2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.56
Rater 3	0.62	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
Rater 4	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 6	0.10	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 7	0.21	0.56	0.01	<0.01	<0.01	<0.01	<0.01

The Pearson correlation coefficient showed the clinical gradings of 16 facial palsy patients at the second rating session were not uniformly reproducible. The reproducibility of grading between different assessors was generally weak (Correlation Coefficient less than 0.39).

Intra Observer Reproducibility of the Glasgow Index

The consistency of the clinical gradings between the first and second rating sessions was measured for the 7 expert assessors Table 17.

Table 17: Correlations Between the Glasgow Index Scores Among the 7 Assessors Between the First and Second Grading Sessions

Session 1st \ 2nd	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	**0.82**	0.35	0.02	0.13	0.18	0.05	0.05
Rater 2	0.41	**0.80**	0.17	0.17	0.22	0.12	0.04
Rater 3	0.04	0.21	**0.74**	0.23	0.11	0.20	0.11
Rater 4	0.09	0.13	0.30	**0.77**	0.29	0.18	0.24
Rater 5	0.13	0.18	0.17	0.37	**0.69**	0.24	0.17
Rater 6	0.06	0.15	0.21	0.26	0.27	**0.73**	0.38
Rater 7	-0.01	0.07	0.15	0.23	0.19	0.38	**0.72**
P-values	Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	Rater 6	Rater 7
Rater 1	<0.01	<0.01	0.64	<0.01	<0.01	0.28	0.28
Rater 2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.44
Rater 3	0.35	<0.01	<0.01	<0.01	0.02	<0.01	0.01
Rater 4	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 6	0.18	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Rater 7	0.86	0.14	<0.01	<0.01	<0.01	<0.01	<0.01

The Pearson correlation coefficient showed there was no statistically significant difference in the intra observer repeatability between the first and second round of grading of facial dysmorphology and dysfunction among assessors using the Glasgow index scores. The correlations between the repeated scores among assessors were strong (Correlation Coefficients ranged from 0.69 to 0.82).

Linear Mixed Effects Model Analysis of the Glasgow Indexing Methods

Glasgow Indexing Test 1

Linear mixed-effects model was applied on the grades of the Glasgow Index, in the model, the raters and repeated assessments were the fixed effects, and grading parameters and patients were considered the random effects.

The results show that there is a significant effect of repeated times on the grades ($p < 0.01$; estimated coefficient 0.047); there is a significant effect of raters on the grades ($p < 0.01$; estimated coefficient 0.014).

The results indicated that the Glasgow Index in its totality was not reproducible, although the effect is small (coefficient = 0.047); there were differences in between raters, although the differences were small (coefficient = 0.014).

Effects of Individual Parameters of 29 Glasgow Index Data

Linear mixed-effects model was applied on the individual grades (29 parameters) of the Glasgow index method, in the model, the raters and repeated times were fixed effects; and patients were random effects, results are in Table 18.

Table 18: Effects of Individual Parameters of 29 Glasgow Index Data

GI Parameters	*Repeated times P-value*	*Raters P-value*
1	0.44	0.70
2	0.71	0.15
3	0.90	0.03
4	0.44	0.16
5	0.59	0.11
6	0.39	0.02
7	0.10	0.48
8	0.07	0.09
9	0.38	0.66
10	0.14	0.01
11	0.29	0.11
12	0.05	0.64
13	0.69	0.47
14	0.27	0.30
15	0.39	<0.01
16	0.24	<0.01
17	0.12	0.47
18	0.02	0.42
19	0.30	0.47
20	0.88	<0.01
21	0.01	0.76
22	0.38	0.13
23	0.69	0.19
24	0.92	<0.01
25	0.35	0.60
26	0.02	0.19
27	0.21	0.03
28	0.76	<0.01
29	0.15	0.95

Table 18, shows the p-values of the coefficients of the repeated times and raters. Three parameters showed poor reproducibility. Parameter 18 and 21 assessed cheek puff expression to evaluate total dynamic asymmetry and the severity of asymmetry, respectively. Parameter 26 assessed at forceful eye closure expression to evaluate total dynamic asymmetry. Differences in between raters are found for nine parameters; two of which are assessed at rest to evaluate eye and corner of the mouth-chin asymmetry (parameters 3, 6 respectively). The remaining 7 parameters are related to the dynamics of various facial expressions, namely the dynamic asymmetry at lip purse, cheek puff, eyebrow raise, eye closure expressions (parameters 16, 20, 24, 28 respectively). Parameters number 10, 15, 27 were related to the asymmetry of the nasolabial fold with smiling, the magnitude of lower lip at lip purse, and the magnitude of eye closure, respectively.

Glasgow Indexing Test 2

After removing unrepeatable parameters (18^{th}, 21^{st}, and 26^{th} parameters), the linear mixed-effects model was applied on the grades of the Glasgow index, the raters and repeated times were the fixed effects; and grading parameters and patients were random effects.

The results show that there is no significant effect of repeated grading ($p = 0.056$; estimated coefficient 0.034); there is a significant effect of raters on the grades ($p < 0.01$; estimated coefficient 0.015).

The results indicate that the Glasgow indexing method is repeatable apart from the parameters 18, 21, and 26 due to the significant differences in between raters, although the differences are small (coefficient = 0.015).

Summary of the Results of the Subjective Assessments

The modified Sunnybrook index was reproducible for grading the dysmorphology and dysfunction of unilateral facial paralysis

1. The gradings of each of the 8 MSB parameters were reproducible among assessors.
2. Raters were reproducible in their gradings between the first and second rating sessions.
3. The assessors agreed on the grading of unilateral facial paralysis cases.

The Glasgow Index proved reproducible after excluding three parameters of poor reproducibility

1. The gradings of each of the 26 GI parameters were reproducible among assessors.
2. Raters were reproducible in their gradings between the first and second rating sessions.
3. Small differences in between raters remained on the grading of the dynamics of facial expressions.

The Correlation Between the Clinical Grading and the Mathematical Measurements of Facial Palsy

The Facial asymmetry of the six facial expressions of 16 unilateral facial palsy patients was quantified using an advanced geometric morphometric approach. Facial asymmetry was calculated by measuring the shape difference between the 3D facial model and its reflected shape. The face was segmented into the regions of forehead, eyes, nose, cheek, nasolabial region, upper lip, lower lip, chin, and corner of the mouth, Figure 37. The minimal, mean, and median values of the regional asymmetries (Table 4) were calculated from the 3D image sequence of facial expressions.

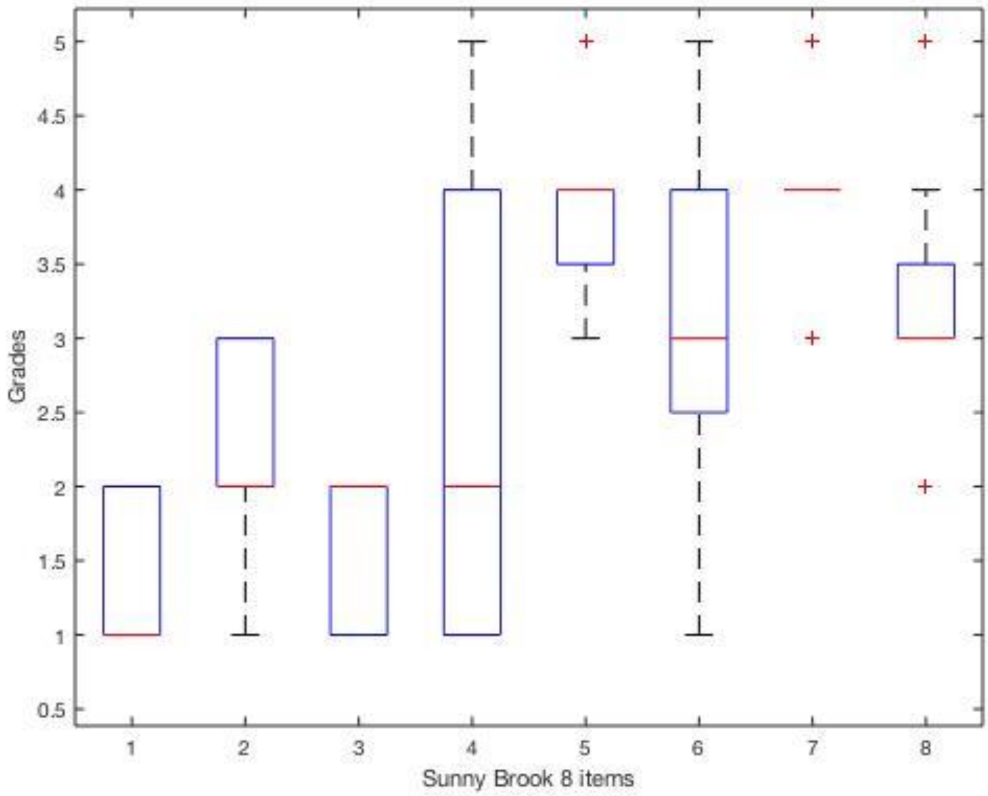
The correlations were investigated between the mathematical measurements of the asymmetry at the segmented facial regions and the subjective assessments of the Glasgow Index and the modified Sunnybrook Index.

For the modified Sunnybrook Grades, 7 assessors graded (twice) 8 parameters for each of the 16 unilateral facial paralysis patients. The mode of 14 grades of each parameter was obtained as the modified Sunnybrook grade for the correlation analysis, Table 19.

Table 19: Mode of the Scores of Assessors in Repeated Assessments of the Modified Sunnybrook Index Grades

MSB Parameters	Grades of 16 patients for the correlation analysis															
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1 Eye	1	1	1	2	2	1	2	1	2	1	2	1	2	1	1	1
2 Cheek	2	2	3	3	3	1	3	2	2	2	3	2	3	3	2	2
3 Mouth	1	1	2	2	2	1	2	2	2	1	2	1	2	2	2	1
4 Forehead Wrinkling	1	1	1	1	4	1	5	3	1	3	5	4	4	3	1	1
5 Eye Closure	3	3	4	4	4	3	5	4	4	4	5	4	4	5	3	4
6 Smile	2	3	2	4	4	1	5	3	3	3	4	2	4	3	3	4
7 Cheek Puff	4	4	4	4	4	4	5	4	4	3	5	4	4	4	4	4
8 Lip Pucker	3	3	3	3	3	3	5	3	3	3	4	3	4	3	4	2

Figure 41: Boxplot of the MSB Parameters of 16 Patients



The X-axis is for the parameters assessed in the Modified Sunnybrook index. The first three parameters were related to the symmetry at the rest pose and the remaining five parameters (items 4-8) evaluated the symmetry of the dynamics of facial movements of five expressions. The Y-axis displays the distribution of the range of the clinical grades of 16 unilateral facial palsy patients.

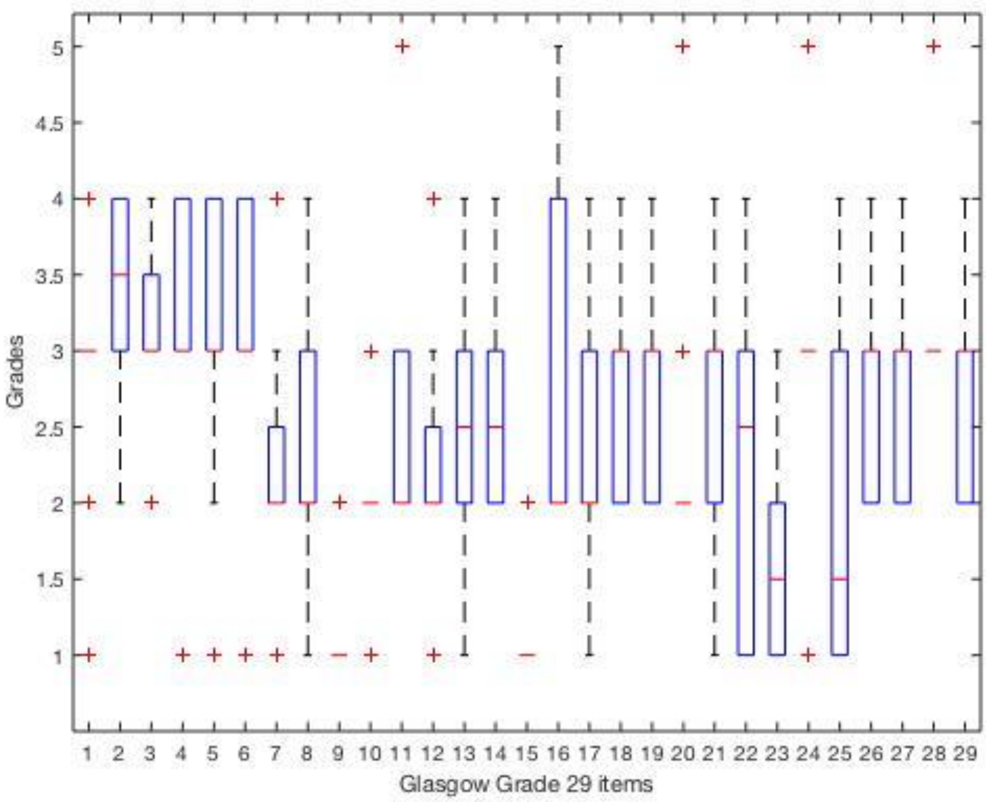
Boxplot showed that the data were not evenly distributed where the grades were constrained by the number of patients and their symptoms. Parameter 4 and 6 for the assessment of forehead wrinkling and smiling showed the largest range of variation.

For the Glasgow Index, 7 assessors graded (twice) 29 parameters for each of the 16 unilateral facial paralysis patients. The mode of 14 grades of each parameter was obtained as the Glasgow index grade for the correlation analysis, Table 20, Table 19.

Table 20: Mode of the Scores of Assessors in Repeated Assessments of Glasgow Index Grades

GI Parameters	**Grades of 16 patients for the correlation analysis**															
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Rest																
1	2	2	3	3	3	1	4	3	3	3	4	3	3	3	3	3
2	3	3	3	4	4	2	4	4	4	3	4	3	4	3	3	4
3	2	3	3	4	3	2	4	3	3	3	4	3	4	3	2	3
4	3	3	4	4	4	1	4	3	3	3	4	3	4	4	3	3
5	3	2	4	4	4	1	4	3	3	3	4	3	4	4	3	3
6	3	3	4	3	4	1	4	3	3	3	4	3	4	4	4	3
Smile																
7	2	2	2	2	3	1	4	2	2	2	4	2	3	2	2	2
8	1	2	2	3	3	1	4	2	2	2	3	2	3	2	2	2
9	1	1	1	1	1	1	2	1	1	1	2	1	1	1	1	1
10	2	2	2	2	2	1	3	2	2	2	3	2	2	2	2	2
11	2	2	2	2	3	2	3	2	2	2	3	3	2	3	2	2
12	1	2	2	2	3	1	3	2	2	2	3	2	3	2	2	2
Lip Purse																
13	2	3	2	3	3	1	4	2	2	2	3	2	3	3	3	2
14	2	3	2	3	3	2	4	2	2	2	3	2	3	3	3	2
15	1	1	1	1	1	1	2	1	1	1	2	1	1	1	1	1
16	2	2	2	4	4	2	3	2	2	2	2	2	4	2	2	2
17	2	3	2	2	3	2	3	2	2	2	3	2	3	2	3	1
Cheek Puff																
18	2	3	2	2	3	2	4	2	3	3	4	2	3	3	3	3
19	2	3	2	2	3	2	4	3	3	3	4	2	3	3	3	3
20	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2
21	1	3	2	2	3	2	3	3	2	3	3	2	3	3	3	2
Eyebrow Raise																
22	1	1	3	1	3	1	4	3	1	2	4	3	3	2	1	4
23	1	1	1	1	2	1	3	2	1	2	3	2	2	2	1	1
24	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1
25	1	1	1	1	2	1	1	2	1	1	3	3	3	2	1	3
Eye Closure																
26	2	2	3	2	3	2	4	3	3	2	4	3	3	3	2	3
27	2	2	3	2	3	2	4	3	3	2	4	3	3	3	2	3
28	3	3	3	3	3	3	4	3	3	3	3	3	3	3	3	3
29	2	2	3	2	3	2	1	3	3	2	3	3	3	3	2	3

Figure 42: Boxplot of the GI Parameters of 16 Patients



The X-axis is for the parameters assessed in the Glasgow index. The first 6 parameters were related to the symmetry at rest and the remaining 23 parameters (items 7-29) assessed the symmetry during facial movements. The Y-axis indicates the distribution of the clinical grades of 16 unilateral facial palsy patients.

Boxplot showed that the clinical grades were not evenly distributed, and this reflects the heterogenicity of the cohort of unilateral facial palsy patients; that is the different disease aetiologies and various degrees of disease involvement. Parameter 16 and 22, 25 for the assessment of asymmetric direction at lip purse, total dynamic asymmetry, and severity at eyebrow raise showed the largest range of variation.

The correlations of the mean, median and minimum values of the asymmetries in the regions to the subjective assessments were evaluated:

- The correlations between the minimum value of the mathematical asymmetries at regions related to the Glasgow index and the modified Sunnybrook index at rest are presented in Table 22.
- The correlations between the mean and median values of the mathematical asymmetries at regions related to the Glasgow index and the modified Sunnybrook index at dynamic facial expressions are presented in Table 24 smile, Table 27 lip purse, Table 30 cheek puff, Table 33 eyebrow raise, Table 36 eye closure.

The Glasgow Index considered the directionality of dynamic facial asymmetry. Absolute values of differences between the 3D model and its reflection in X, Y, Z directions were calculated to identify the directionality of the asymmetry.

The relationships between the mean and median absolute values of directional asymmetries of the facial anatomical regions of the 3D image sequence of facial expressions and the relevant GI parameters were evaluated (at smile Table 25, lip purse Table 28, cheek puff Table 31, eyebrow raise Table 34, eye closure Table 37).

The tables are colour coded and present the correlations between the mathematical measurements of asymmetry at 10 facial regions (blue colour) and the Glasgow index GI (white rows) and to the modified Sunnybrook index MSB (grey rows). The following section presents the correlation results at individual facial expressions.

Rest Expression

Table 21: The Parameters Assessed at Rest for each of the Glasgow Index and the Modified Sunnybrook Index

Glasgow Index GI	***Modified Sunnybrook Index MSB***
Parameters assessed at rest ***1- Total facial asymmetry*** *Likert scale (4 points)* ***2- Forehead wrinkles and eyebrows*** *Likert scale (4 points)* ***3- Eye*** *Likert scale (4 points)* ***4- Nose and nasolabial fold*** *Likert scale (4 points)* ***5- Cheek contour/tone*** *Likert scale (4 points)* ***6-Corner of the mouth and chin*** *Likert scale (4 points)*	*Parameters assessed at rest* ***1- Eye*** *Normal or abnormal (narrow, wide, eyelid surgery)* ***2- Cheek (nasolabial fold)*** *Normal, altered, absent* ***3- Mouth*** *Normal or abnormal (corner drooped, pulled up/out)*

Table 22: Correlations Between the Minimum Values of the Mathematical Asymmetry Scores in the Segmented Facial Regions and both the GI and MSB Parameters at Rest Expression

Facial Regions	Index parameter	Correlation to Minimum value of mean asymmetries in expression	P-value
Full face	MSB 1	-0.45	0.07
	MSB 2	-0.74	<0.01
	MSB 3	-0.60	0.01
	GI 1	-0.81	<0.01
Forehead	MSB 1	-0.48	0.05
	GI 2	-0.72	<0.01
Eyes	MSB 1	-0.42	0.10
	GI 3	-0.49	0.05
Nose	GI 4	-0.69	<0.01
Cheek	MSB 2	-0.76	<0.01
	GI 5	-0.84	<0.01
Nasolabial	MSB 2	-0.76	<0.01
	GI 4	-0.85	<0.01
Upper lip	MSB 3	-0.69	<0.01
Lower lip	MSB 3	-0.47	0.06
Chin	MSB 3	-0.47	0.06
	GI 6	-0.76	<0.01
Corner of Mouth	MSB 3	-0.60	0.01
	GI 6	-0.79	<0.01

In Table 22, the Glasgow index GI shows stronger correlations with the objective assessment compared to the modified Sunnybrook index MSB. The stronger correlations were noted between the GI parameters and the mathematical measurements across the facial regions and were statistically significant.

Smile Expression

Table 23: The Parameters Assessed at Smile for each of the Glasgow Index and the Modified Sunnybrook Index

Glasgow Index GI	***Modified Sunnybrook Index MSB***
Parameters assessed at smile expression	Parameters assessed
7- Total dynamic facial asymmetry	***6- Smiling***
Likert scale (4 points)	*Likert scale (5 points)*
8- Magnitude of smiling	
Likert scale (4 points)	
9- Lower lip movement	
Normal or abnormal	
10- Dynamic asymmetry of nasolabial fold	
Normal, alters with movement, no change from rest	
11- Asymmetric direction of movement	
Categorical (4 points)	
12-Severity of 12	
Likert scale (3 points)	

Table 24: Correlations of the Mean and Median Values of the Mathematical Asymmetry Scores in the Segmented Facial Regions to GI and MSB Parameters at Smile Expression

Facial Regions	Index parameter	Correlation to Mean	P-value	Correlation to Median	P-value
Full face	MSB 6	-0.66	<0.01	-0.66	<0.01
	GI 7	-0.59	0.01	-0.58	0.01
Cheek	MSB 6	-0.67	<0.01	-0.67	<0.01
	GI 8	-0.73	<0.01	-0.73	<0.01
	GI 9	-0.30	0.25	-0.28	0.29
Nasolabial	MSB 6	-0.64	<0.01	-0.64	<0.01
	GI 8	-0.67	<0.01	-0.70	<0.01
	GI 9	-0.31	0.25	-0.30	0.26
	GI 10	-0.60	0.01	-0.55	0.02
Upper lip	MSB 6	-0.66	<0.01	-0.67	<0.01
	GI 8	-0.65	<0.01	-0.65	<0.01
	GI 9	-0.35	0.18	-0.33	0.20
Lower lip	MSB 6	-0.61	0.01	-0.61	0.01
	GI 8	-0.58	0.01	-0.58	0.01
	GI 9	-0.27	0.31	-0.25	0.34
Chin	MSB 6	-0.59	0.01	-0.59	0.01
Corner of Mouth	MSB 6	-0.60	0.01	-0.61	0.01
	GI 8	-0.53	0.03	-0.52	0.03

In Table 24, the Glasgow index GI and the modified Sunnybrook index MSB a show similar level of correlations with the objective assessment. The MSB6 parameter was comparable to the GI parameters GI7, GI8, GI10. The correlations were statistically significant. The correlations to the mean and the median values of asymmetry scores at the segmented facial regions were similar in strength.

The correlations between GI9 to the mean and median values of the asymmetry scores at the relevant facial regions were not statistically significant. Hence the coefficients of correlations were weak.

Table 25: Correlations of the Mean and Median Absolute Values of the Mathematical Directional Asymmetry Scores in the Segmented Facial Regions to GI Parameters 11 "Directional Asymmetry" and 12 "Severity of Asymmetry" at Smile Expression

Facial Regions	Agreement of direction	Severity correlated to Mean Absolute Value (Directional)	P-value	Severity correlated to Median Absolute Value (Directional)	P-value
Cheek	68.75%	-0.53	0.03	-0.53	0.03
Nasolabial	68.75%	-0.61	0.01	-0.63	<0.01
Upper lip	68.75%	-0.62	0.01	-0.62	0.01
Lower lip	68.75%	-0.57	0.02	-0.56	0.02
Corner of mouth	37.5%	-0.55	0.02	-0.54	0.02

Table 25 shows 68.75% agreement between the clinical grading of GI11 for the assessment of directional asymmetry at smile expression and the mathematical asymmetry scores of the cheek, nasolabial region, upper and lower lip regions, and 37.5% agreement at the corner of the mouth. The clinical grading of the severity of asymmetry at the smile (GI12) showed significant correlations with the mathematical measures at the cheek, nasolabial region, upper and lower lip, corner of the mouth.

Lip Purse Expression

Table 26: The Parameters Assessed at Lip Purse for each of the Glasgow Index and the Modified Sunnybrook Index

Glasgow Index GI	***Modified Sunnybrook Index MSB***
Parameters assessed at lip Purse expression ***13- Total dynamic facial asymmetry*** *Likert scale (4 points)* ***14- Magnitude of lip movement*** *Likert scale (4 points)* ***15- Lower lip movement*** *Normal or abnormal* ***16- Asymmetric direction of movement*** *Categorical (4 points)* ***17-Severity of 16*** *Likert scale (3 points)*	*Parameters assessed* ***8- Lip Puckering*** *Likert scale (5 points)*

Table 27: Correlations of the Mean and Median Values of the Mathematical Asymmetry Scores in the Segmented Facial Regions to GI and MSB Parameters at Lip Purse Expression

Facial Regions	Index parameter	Correlation to Mean	P-value	Correlation to Median	P-value
Full face	MSB 8	-0.52	0.03	-0.50	0.04
	GI 13	-0.74	<0.01	-0.71	<0.01
Cheek	MSB 8	-0.52	0.04	-0.49	0.05
Nasolabial	MSB 8	-0.45	0.07	-0.43	0.09
Upper lip	MSB 8	-0.65	<0.01	-0.61	0.01
	GI 14	-0.61	0.01	-0.59	0.01
	GI 15	-0.61	0.01	-0.65	<0.01
Lower lip	MSB 8	-0.62	0.01	-0.60	0.01
	GI 14	-0.62	0.01	-0.60	0.01
	GI 15	-0.53	0.03	-0.54	0.03
Chin	MSB 8	-0.43	0.09	-0.46	0.07
Corner of Mouth	MSB 8	-0.62	0.01	-0.60	0.01
	GI 14	-0.63	<0.01	-0.61	0.01
	GI 15	-0.55	0.02	-0.56	0.02

In Table 27, the Glasgow index GI and the modified Sunnybrook index MSB showed a similar level of correlations with the objective assessment of the upper lip, lower lip, and corner of the mouth. The MSB8 parameter which assessed lip-puckering was comparable to the GI parameters GI14, GI15. The mathematical versus subjective correlations were statistically significant and there was no difference between the correlations to the mean and median values of asymmetries

MSB8 showed statistically significant correlations to the mean and median values of asymmetries at the cheek region.

GI13 showed stronger correlations with the mean and median values of asymmetries at the full-face region compared to MSB8; the coefficients of correlations were -0.74, -0.52, respectively. The correlations were statistically significant.

Table 28: Correlations of the Mean and Median Absolute Values of the Mathematical Directional Asymmetry Scores in the Segmented Facial Regions to GI Parameters 16 "Directional Asymmetry" and 17 "Severity of Asymmetry" at Lip Purse Expression

Facial Regions	Agreement of direction	Severity correlated to Mean Absolute Value (Directional)	P-value	Severity correlated to Median Absolute Value (Directional)	P-value
Cheek	75.0%	-0.22	0.41	-0.20	0.47
Nasolabial	75.0%	-0.49	0.05	-0.50	0.04
Upper lip	75.0%	-0.44	0.08	-0.45	0.07
Lower lip	75.0%	-0.66	<0.01	-0.65	<0.01
Corner of mouth	43.75%	-0.71	<0.01	-0.68	<0.01

Table 28 shows 75% agreement between the clinical grading of GI16 for the assessment of directional asymmetry at lip purse expression and the mathematical asymmetry scores of the cheek, nasolabial region, upper and lower lip regions and, 43.75% agreement at the corner of the mouth. The clinical grading of the severity of asymmetry at lip purse (GI17) showed significant correlations with the mathematical measures at the cheek, nasolabial region, lower lip, corner of the mouth. The highest level of correlation is shown at the corner of the mouth (Coefficient of correlation -0.71).

Cheek Puff Expression

Table 29: The Parameters Assessed at Cheek Puff for each of the Glasgow Index and the Modified Sunnybrook Index

Glasgow Index GI	*Modified Sunnybrook Index MSB*
Parameters assessed at cheek puff expression ***~~18- Total dynamic facial asymmetry~~*** **(Excluded)** *~~Likert scale (4 points)~~* ***19- Magnitude of cheek movement*** *Likert scale (4 points)* ***20- Asymmetric direction of movement*** *Categorical (4 points)* ***~~21-Severity of 20~~*** **(Excluded)** *~~Likert scale (3 points)~~*	*Parameters assessed* ***7- Cheek Puffing*** *Likert scale (5 points)*

Table 30: Correlations of the Mean and Median Values of the Mathematical Asymmetry Scores in the Segmented Facial Regions to GI and MSB Parameters at Cheek Puff Expression

Facial Regions	Index parameter	Correlation to Mean	P-value	Correlation to Median	P-value
Full face	MSB 7	-0.44	0.08	-0.48	0.05
	~~GI 18~~	~~-0.28~~	~~0.30~~	~~-0.20~~	~~0.46~~
Cheek	MSB 7	-0.69	<0.01	-0.67	<0.01
	GI 19	-0.30	0.24	-0.29	0.27
Nasolabial	MSB 7	-0.41	0.11	-0.46	0.07
	GI 19	-0.17	0.51	-0.17	0.51
Upper lip	MSB 7	-0.38	0.14	-0.40	0.12
	GI 19	-0.36	0.17	-0.37	0.16
Lower lip	MSB 7	-0.43	0.10	-0.48	0.05
	GI 19	-0.52	0.03	-0.53	0.03
Chin	MSB 7	-0.37	0.15	-0.36	0.17
Corner of Mouth	MSB 7	-0.52	0.03	-0.58	0.01
	GI 19	-0.52	0.03	-0.50	0.05

In Table 30, the Glasgow index GI and the modified Sunnybrook index MSB show weak to moderate correlations to the mean and to the median values of asymmetry scores in relevant regions. MSB7 at the cheek region showed the highest correlation with the objective measurement of the asymmetry and it was statistically significant.

The MSB7 parameter assessed at cheek puff was comparable to the GI19 which assessed the magnitude of cheek movement. Both parameters showed a similar level of correlations to the asymmetry scores at the corner of the mouth and at the lower lip. The correlations to the median values of asymmetries at these regions were statistically significant.

Table 31: Correlations of the Mean and Median Absolute Values of the Mathematical Directional Asymmetry Scores in the Segmented Facial Regions to GI Parameters 20 "Directional Asymmetry" and 21 "Severity of Asymmetry" at Cheek Puff Expression

Facial Regions	Agreement of direction	Severity correlated to Mean Absolute Value (Directional)	P-value	Severity correlated to Median Absolute Value (Directional)	P-value
Cheek	93.75%	~~-0.08~~	~~0.77~~	~~-0.06~~	~~0.82~~
Nasolabial	93.75%	~~-0.28~~	~~0.30~~	~~-0.30~~	~~0.26~~
Upper lip	93.75%	~~-0.33~~	~~0.21~~	~~-0.34~~	~~0.19~~
Lower lip	93.75%	~~-0.41~~	~~0.10~~	~~-0.42~~	~~0.10~~
Corner of mouth	62.50%	~~-0.51~~	~~0.04~~	~~-0.49~~	~~0.05~~

Table 31 shows 93.72% agreement between the clinical grading of GI20 for the assessment of directional asymmetry at cheek puff expression and the mathematical asymmetry scores of the cheek, nasolabial region, upper and lower lip regions, and 62.50% agreement at the corner of the mouth. The clinical grading of the severity of asymmetry at the cheek puff (GI21) showed the lack of significant correlations with the mathematical measures at all regions except the corner of the mouth (coefficient of correlation -0.51). GI21 was excluded from the Glasgow index.

Eyebrow Raise Expression

Table 32: The Parameters Assessed at Eyebrow Raising for each of the Glasgow Index and the Modified Sunnybrook Index

Glasgow Index GI	*Modified Sunnybrook Index MSB*
Parameters assessed at eyebrow raise expression ***22- Total dynamic facial asymmetry*** *Likert scale (4 points)* ***23- Magnitude of eyebrow movement*** *Likert scale (4 points)* ***24- Asymmetric direction of movement*** *Categorical (4 points)* ***25-Severity of 24*** *Likert scale (3 points)*	*Parameters assessed* ***4- Forehead Wrinkling*** *Likert scale (5 points)*

Table 33: Correlations of the Mean and Median Values of the Mathematical Asymmetry Scores in the Segmented Facial Regions to GI and MSB Parameters at Eyebrow Raise Expression

Facial Regions	Index parameter	Correlation to Mean	P-value	Correlation to Median	P-value
Full face	MSB 4	-0.40	0.12	-0.42	0.10
	GI 22	-0.39	0.13	-0.44	0.09
Forehead	MSB 4	-0.41	0.11	-0.43	0.09
	GI 23	-0.44	0.08	-0.45	0.07
Eyes	MSB 4	-0.40	0.12	-0.42	0.10
	GI 23	-0.42	0.09	-0.42	0.01

In Table 33, the Glasgow index GI and the modified Sunnybrook index MSB show a similar level of correlations with the objective assessment. The MSB4 parameter which assessed forehead wrinkling was comparable to the GI parameters GI22, GI23. Only GI13 showed statistically significant correlations to the median values of asymmetries at the eye region.

Table 34: Correlations of the Mean and Median Absolute Values of the Mathematical Directional Asymmetry Scores in the Segmented Facial Regions to GI Parameters 24 "Directional Asymmetry" and 25 "Severity of Asymmetry" at Eyebrow Raise Expression

Facial Regions	Agreement of direction	Severity correlated to Mean Absolute Value (Directional)	P-value	Severity correlated to Median Absolute Value (Directional)	P-value
Forehead	0.0%	-0.56	0.02	-0.58	0.01
Eyes	0.0%	-0.42	0.01	-0.42	0.09

Table 34 shows 0% agreement between the clinical grading of GI24 for the assessment of directional asymmetry at eyebrow raise expression and the mathematical measurements. The clinical grading of the severity of asymmetry at the eyebrow raise (GI25) showed significant correlations with the median absolute values at the forehead -0.56 and eyes -0.42.

Eye Closure Expression

Table 35: The Parameters Assessed at Eye Closure for each of the Glasgow Index and the Modified Sunnybrook Index

Glasgow Index GI	***Modified Sunnybrook Index MSB***
Parameters assessed at eye closure expression ***~~26- Total dynamic facial asymmetry~~*** **(Excluded)** *~~Likert scale (4 points)~~* ***27- Magnitude of eye movement*** *Likert scale (4 points)* ***28- Asymmetric direction of movement*** *Categorical (4 points)* ***29-Severity of 28*** *Likert scale (3 points)*	*Parameters assessed* ***5- Eye Closure*** *Likert scale (5 points)*

Table 36: Correlations of the Mean and Median Values of the Mathematical Asymmetry Scores in the Segmented Facial Regions to GI and MSB Parameters at Eye Closure Expression

Facial Regions	Index parameter	Correlation to Mean	P-value	Correlation to Median	P-value
Full face	MSB 5	-0.52	0.03	-0.51	0.04
	~~GI 26~~	~~-0.50~~	~~0.04~~	~~-0.48~~	~~0.06~~
Forehead	MSB 5	-0.67	<0.01	-0.65	<0.01
	GI 27	-0.71	<0.01	-0.67	<0.01
Eyes	MSB 5	-0.60	0.01	-0.58	0.01
	GI 27	-0.53	0.03	-0.52	0.03

In Table 36, the Glasgow index GI and the modified Sunnybrook index MSB show a similar level of correlations to the mean and to the median values of asymmetry scores in relevant regions. The correlations were statistically significant.

The MSB5 parameter which assessed eye closure was comparable to the GI27 which assessed the magnitude of eye movement. Both parameters showed a similar level of correlations to the asymmetry scores at the forehead and eye regions.

Table 37: Correlations of the Mean and Median Absolute Values of the Mathematical Directional Asymmetry Scores in the Segmented Facial Regions to GI Parameters 28 "Directional Asymmetry" and 29 "Severity of Asymmetry" at Eye Closure Expression

Facial Regions	Agreement of direction	Severity correlated to Mean Absolute Value (Directional)	P-value	Severity correlated to Median Absolute Value (Directional)	P-value
Forehead	0.0%	-0.44	<0.01	-0.48	0.05
Eyes	0.0%	-0.44	0.08	-0.44	0.08

Table 37 shows 0% agreement between the clinical grading of GI28 for the assessment of directional asymmetry at eye closure expression and the mathematical measurements. The clinical grading of the severity of asymmetry at the eye closure (GI29) showed significant correlations with the mean absolute values at the forehead region only (Correlation Coefficient -0.44).

Table 38: Summary of the Correlation Results Across Facial Expressions

Facial Regions	**Facial Expressions**				
	Rest	**Smile**	**Lip Purse**	**Cheek Puff**	**Eye Closure**
Full face	**MSB 2** r=-0.74	**MSB 6** r=-0.66			
	GI 1 r=-0.81		**GI 13** r=-0.74		
Forehead					**MSB 5** r=-0.67
	GI 2 r=-0.72				**GI 27** r=-0.71
Nose	**GI 4** r=-0.69				
Cheek	**MSB 2** r=-0.76	**MSB 6** r=-0.67		**MSB 7** r=-0.69	
	GI 5 r=-0.84	**GI 8** r=-0.73			
Nasolabial	**MSB 2** r=-0.76	**MSB 6** r=-0.64			
	GI 4 r=-0.85	**GI 8** r=-0.67			
		GI 12 r=-0.61			
Upper lip	**MSB 3** r=-0.69	**MSB 6** r=-0.66	**MSB 8** r=-0.65		
		GI 8 r=-0.65	**GI 14-15** r=-0.61		
		GI 12 r=-0.62			
Lower lip		**MSB 6** r=-0.61	**MSB 8** r=-0.62		
			GI 14 r=-0.62		
			GI 17 r=-0.66		
Chin	**GI 6** r=-0.76				
Corner of Mouth			**MSB 8** r=-0.62		
	GI 6 r=-0.79		**GI 14** r=-0.63		
			GI 17 r=-0.71		

Table 38 shows the main regions affected by facial dysmorphology which showed a correlation strength above -0.6 between the subjective and objective assessments.

Summary of the Correlation Results

1- The Glasgow index correlated reasonably well with the mathematical measurements of facial asymmetry at rest and during function. The GI gradings of dynamic facial asymmetry across the 5 facial expressions varied in the strength of correlations to the regional asymmetries of the objective assessment. The clinical grading of the smile was strongly correlated with the objective measurements, followed by lip purse, eye closure, cheek puff and eyebrow raising.

2- The modified Sunnybrook index correlated reasonably well with the objective measurements, similar to the GI.

3- The following were the main regions affected by facial dysmorphology which showed a correlation strength above -0.6 between the subjective and objective assessments:

- The full face at rest as well as the anatomical regions of the forehead, cheek, nose and nasolabial, upper lip, corner of mouth and chin regions.
- Smile expression for assessment of
  - cheek asymmetry (GI8 r=-0.73, r=-0.67 MSB6).
  - nasolabial region (GI8 r=-0.67, GI10 r=-0.60, MSB6 r=-0.64).
  - upper lip asymmetry (GI8 r=-0.65, MSB6 r=-0.66).
  - lower lip (MSB6 r=-0.61).
  - Corner of mouth asymmetry (MSB6 r=-0.60).
- Lip purse for assessment of
  - full face asymmetry (GI13 r=-0.74).
  - upper lip asymmetry (GI14-GI15 r=-0.61, MSB8 r=-0.65).
  - lower lip asymmetry (GI14, MSB8 r=-0.62 for both).
  - corner of mouth (GI14 r=-0.63, MSB8 r=-0.62).
- Cheek puff for the assessment of cheek asymmetry (MSB7 r=-0.69).
- Eye closure for the assessment of forehead asymmetry (GI27 r=-0.71, MSB5 r=-0.67).

4- At eyebrow raise expression, the coefficients of correlations between the objective and subjective assessments were less than -0.5 and were not statistically significant.

5- The clinical assessment of the directionality and severity of the dynamic facial dysmorphology correlated adequately with the objective measurements at:

- Smile expression showed 68.75% at nasolabial and upper lip regions (r=-0.61, r=-0.62, respectively).
- Lip purse showed 75% agreement at lower lip r=-0.66.

Discussion

In this study the "p" values were not adjusted despite of the multiple testing. There is a considerable debate in the literature regarding the need to adjust the p-values in clinical trials (Feise, 2002). Bonferroni correction adjusts the "p" value in multiple testing because of the increased risk of type I error leading to the false rejection of the null hypothesis. On the other hand, the adjustment of the p-values increases the risk of type II error (false negative). Therefore, Bonferroni corrections were not applied in this study. It is important to highlight that the strength of the correlation coefficients between the related variables is more meaningful in this study rather than the level of the statistical significance of these correlations which is affected by the limited sample size.

Obtaining a Reproducible Clinical Grading of the Asymmetric Facial Expressions

The main aim of the study was the development of a reliable and a mathematically valid clinical scoring index. The rationale is the improvement of the care of facial palsy by providing a sensitive tool to quantify and measure the impairment of facial muscle movements and its associated dysmorphology. This is particularly important following surgical procedures for facial reanimation.

The study also explored the mathematical measurements of the face in three dimensions that disclose morphological characteristics of unilateral facial paralysis, that may not be easily assessed clinically, therefore, could provide an insight into the pathophysiology of facial palsy. This would be valuable for research studies where it is important to quantify the dysfunction of the complex subtle facial muscle movements.

No doubt the mathematical evaluation of the distorted facial muscle movements provides the ground truth (Tzou et al., 2012). However, this requires a sophisticated 4D imaging system to capture facial expressions and the application of various software packages for the complex mathematical calculations together with statistical analyses (Tzou et al., 2014), which may limit its scalability.

Achieving a reliable subjective clinical grading index of the abnormal facial muscle movements could be widely used in clinical practice and overcomes the limitations of the non-standardised clinical approach for the evaluation of unilateral facial paralysis or any other type of the altered facial muscle movements (Niziol et al., 2015).

Section I: The Mathematical Measurement of Facial Palsy

4D Imaging of Facial Movements

The 4D imaging system captured the 3D facial morphology and muscle movements overtime at a rate of 60 frames/second. The accuracy of the automatic tracking of landmarks throughout the course of facial expressions has been validated in previous studies, with inaccuracies of less than 0.55mm (Al-Anezi et al., 2013).

Dense Surface Model was applied for the analysis of facial dysmorphology using a validated approach (Mao et al., 2006). A generic facial mesh composed of thousands of mathematical points was conformed on the 3D facial image. The conformed meshes were used for the analysis. (Cheung et al., 2016) concluded that the conformation process produced an acceptable level of accuracy that is higher in the centre of the face than peripheral regions (Euclidean difference ranged between 0.2 to 0.7mm). In our study, the periphery of the generic mesh was trimmed to minimise the errors of the analysis. To maximise the clinical relevance of the analysis the 3D facial image was divided into anatomical regions, each represented a group of muscles to monitor the distortion of facial expressions in unilateral facial palsy. This facilitated the clinical linkage between the measured asymmetry and the clinically observed and subjectively graded unilateral disparity of muscle movements due to facial palsy. The analysis of the 3D facial morphology requires the identification of the region of interest that is usually defined based on anatomical and biomechanical knowledge of facial muscle movements (van Kaick et al., 2011).

Different methods for segmentation of facial morphology have been considered. (Kim & Oh, 2020) divided the face into 3 volumetric proportions based on 4 horizontal lines passing through a set of facial landmarks (trichion, glabella, sub-nasale, menton). The software provided a volumetric measurement of the upper, middle, and lower facial thirds. This allowed the comparison between preoperative and postoperative 3D facial volumes. The main drawback of this method is that it did not consider individual anatomical regions of the face, which is crucial for the assessment of the underlying muscular abnormality. Furthermore, volumetric analysis of horizontal facial sections does not account for the dissimilarities between the right and left sides of the face.

(Codari et al., 2017) segmented the face according to the distribution of the branches of the trigeminal nerve to evaluate facial asymmetry in unilateral facial palsy in comparison with healthy volunteers. The 3D facial morphology was divided into upper, middle, and lower hemifacial thirds based on a set of facial landmarks to demarcate the surface area innervated by branches of the trigeminal nerve. The distance between the superimposed original and mirrored facial segments measured facial asymmetry. It would have been more relevant to segment the face according to the branches of the facial nerve, which is more relevant to study unilateral palsy. Furthermore, the division of the hemifacial thirds was based on 7 midline anatomical landmarks which are difficult to identify in severe facial dysmorphology (Slice, 2007).

This study attempted to address the previous limitations by evaluating the global and regional facial asymmetries. In the global approach, the 3D image of the full facial region was reflected around an arbitrary plane to create a mirror image and facial asymmetry was calculated by measuring the disparity between the original facial shape and its registered mirror replica, therefore, eliminating the bias of selecting the mid-sagittal plane. The anatomical segmentation of facial morphology provided a number of advantages. The face was divided into 10 anatomical regions which facilitated the analysis of asymmetry at the individual facial regions. This allowed the evaluation of the impact of abnormal facial nerve function on the asymmetry of facial expressions. Furthermore, it disclosed the contribution of different muscle groups to facial dysmorphology which may inform appropriate management and surgical decision.

The segmentation did not consider the lower lateral regions of the face due to the lack of the anatomical correspondence with the subjective and objective measurements of the asymmetry.

Quantification of Dynamic Facial Dysmorphology

Two main approaches have been reported for the 3D assessment of facial dynamics: the static and the dynamic methods. In the static approach facial asymmetry is recorded and measured at the maximum movement from rest. (Hallac et al., 2017) extracted the 3D facial frame at the maximum expression of the 3D image sequence of smile and pout expressions, to quantify facial asymmetry in cleft lip patients who underwent surgical lip repair. The same approach was considered for the analysis of facial palsy, (Gibelli et al., 2020) applied surface-based analysis to quantify shape-difference between the facial 3D images at rest and at maximum expressions. The main drawback of the static approach is that the quantification of asymmetry at the maximum expression does not measure the dynamics of facial muscle movements.

The dynamic approach for the analysis of facial morphology is based on the recording and the analysis of the entire sequence of the captured 3Dimages throughout the course of each expression. This is now considered the state-of-the-art for the assessment of facial muscle movements. This approach has been used in the analysis of facial muscle movements during maximum smile in unilateral cleft lip and palate patients (Gattani et al., 2020).

Despite the empowered ability of the dynamic evaluation of facial muscle movements to overcome the limitations of the static assessments, the method requires the application of sophisticated statistical shape analysis and modeling of facial dynamics. (Alagha et al., 2017) selected 5 key frames from the 180-3D image sequence recorded during each facial expression to describe the dynamic facial dysmorphology in unilateral facial palsy. This approach suffers from a number of limitations. First, it relied on the manual selection of the 5 key frames (at rest, 1st quartile of movement, at maximum expression, 3rd quartile of movement, end of movement), which is subjective and liable to selection bias. Second, the assessment of the dynamic facial asymmetry was limited to 5 frames only, therefore, the levels of asymmetry throughout the entire facial movements were not considered in the analysis. Furthermore, there was no consideration for regional analysis of dynamic facial asymmetry, which is important for the assessment of facial nerve abnormalities affecting various groups of muscles.

An alternative approach involved the statistical modeling of whole shape mean expression movements from rest to maximum animation was considered by (Trotman et al., 2010) to quantify the effects of lip revision on the circumoral movements in cleft lip and palate. Facial movements were recorded in 3D and each expression contained 240 frames. The 3D facial morphology of each frame was represented by 38 anatomical landmarks. The changes of the 3D coordinates of these landmarks were tracked over time. Principal component analysis described the main shape variations throughout a given expression; the first principal component corresponded to the main motion represented by the 3D image sequence. Unfortunately, the study was based on a limited set of landmarks which did not fully describe the complexity of the facial morphology. The principal component analysis is not sensitive to the different aspects of shape differences since it extracts the main modes of variations without quantifying the variation (Brunton et al., 2014).

To overcome these limitations, Dense Surface Model has been introduced, in which a generic facial template is conformed on the 3D facial images to provide dense correspondence with the 3D facial images which allows for comprehensive analysis of facial morphology (Mao et al., 2006).

In this study, the mathematical asymmetry scores quantified facial asymmetry at the individual 3D model by taking into consideration the three-dimensional morphology of the segmented facial regions. This was applied to the entire 3D image sequence per expression per patient. For each facial expression six values of asymmetries were calculated and included the mean, median, maximum, minimum, range, and standard deviation. The mean and median values represented the average facial asymmetry of the 180 3D frames of each facial expression. The maximum value represented the worst facial asymmetry, and the minimal value represented the best (minimum) asymmetry, the range and standard deviation represented the distribution of the symmetry throughout the course of each facial expression.

In order to evaluate the subjective grading indices, facial asymmetry has been selected because it is the most distinctive feature of facial paralysis, although the other parameters (magnitude, speed and similarity of motion trajectories etc.) related to the face shape and the facial movements can be calculated at any points or regions of the face (Al-Hiyali et al., 2015) and be used to evaluate facial paralysis as well. Asymmetry exists in both static and dynamic phases. It significantly affects patients' smiles and esthetics, and its correction is a major challenge posed to the clinician (Coyle et al., 2013). The attractiveness of average facial configurations could be solely related to symmetry. Significant facial asymmetry causes both functional as well as aesthetic problems. The perception of attractiveness increased when facial symmetry increased (Rhodes et al., 1998).

The magnitude, as well as the speed of the nonverbal expressions, were not evaluated in this study due to time constraint. The maximum excursion of facial movements is indicative of the degree of facial nerve function. This is an important measurement for the assessment of facial nerve weakness, disease progress and remission; further investigations are needed to evaluate this aspect.

In this study, the assessment of facial dysmorphology at ten facial regions, calculating the minimal asymmetry at rest and mean and median asymmetries of facial movements of various expressions, offered a robust validation of the subjective grading indices by calculating cross-correlations between the measured and the observed asymmetry. The correlation coefficients provided an overview of the mathematical ground truth to the subjective indices in relation to the defined region of interest, and sensitivity of grades indicated by the strength of correlation.

The mean and median asymmetries of facial movements described the average asymmetry of each expression throughout the entire 3D image sequence. For the first time, this provides a measure of the dynamic symmetry that took in consideration the entire sequence of the captured 3D images throughout the course of each facial expression. In addition, it allowed the comprehensive analysis of the symmetry of anatomically meaningful facial regions. The application of dense surface correspondence and tracking the conformed generic facial meshes provided the most robust approach to evaluate the distorted dynamics of facial palsy. These measurements were related to the subjective grading of the two considered indices, which is the standard approach to evaluate their validity (Katsumi et al., 2015). The maximum asymmetry represented the worst facial dysmorphology, which may only take place in a fraction of a millisecond throughout the entire sequence of the 4D capture of a facial expression. In some expressions, the movement of facial muscles may improve the symmetry and the maximum asymmetry is noted at rest before starting the expression. Therefore, it was crucial to quantify the maximum and minimum values of the asymmetry as well as the average, the range, and the standard deviation. This, in addition to the anatomic segmentation of the face, took into consideration the fact that asymmetry of various facial regions might not appear simultaneously during a particular facial expression.

This study considered the mathematical asymmetry scores of the patients in relation to the non-patient population. The mean asymmetry scores and the standard deviations of the 44 controls were calculated at the regions of interest per facial expression and the values were used to calculate Z scores of facial asymmetries for the 16 facial palsy patients at the corresponding facial regions. The Z score statistic, also known as the standard score, is an established approach to describe the measured value (asymmetry score) in relation to the mean values of a reference group, indicated by standard deviations from the population mean (Clark-Carter, 2014). In this study, the control group was matched by age and sex to the patient group to account for the typical asymmetry in the normal population.

The need for an outcome scoring system of facial reanimation surgery has been stressed and is well documented in previous studies (Niziol et al., 2015). (Dong et al., 2018) reviewed the literature to investigate the methods of functional outcome measures following dynamic facial reconstruction with free muscle flaps. Between 1989 and 2017, 37 articles were identified, and the majority of the reported outcome measures were based on the subjective grading of facial expressions and the other studies reported functional outcomes in relation to oral competence, speech, and quality of life assessment. However, and despite being the most assessed functional outcome of facial reanimation surgery, the evaluation of facial expressions is not standardised. The authors highlighted the necessity for a validated, unified assessment protocol to improve patient care.

Directionality Assessment and the Colour-Coded Maps

The true strength of geometric morphometrics analysis resides in its ability to quantify and visualize facial asymmetry in the three dimensions of space. (Al Rudainy et al., 2019) evaluated the asymmetry of facial expression in surgically managed unilateral cleft lip and palate patients. The 3D facial models were captured at rest and at the maximum smile. A Dense Surface Model was morphed on the 3D facial images to create dense correspondence. Asymmetry was quantified by measuring shape difference between the original and its aligned reflection. The asymmetry was then stratified in mediolateral, vertical and anteroposterior directions. Colour maps of the average asymmetries at rest and at maximum smile demonstrated the different patterns of facial asymmetry. The changes in facial asymmetry scores for the full face, nose and upper lip at rest and at maximum smile in X, Y, Z (mediolateral direction, vertical, and anteroposterior direction, respectively) provided new insights on the residual facial asymmetry following surgical correction. This method was applied in our study to provide an insight into the directionality of the measured and clinically observed facial asymmetry.

The assessment of the directionality of facial asymmetry is technique sensitive and prone to error in the assessment of cases including opposite direction of measured dysfunction. In which, right dysmorphology would cancel the degree of asymmetry in the pathology affecting the left side of the face. Therefore, in this study, we flipped the 3D facial images to keep all facial paralysis on the left side in all the 3D sequences of the captured images.

It is important to highlight that statistical analysis of data was not based on the average asymmetry scores of the group but on the average asymmetries of each of the 3D sequences of each expression per individual. Providing mathematical value of the average facial asymmetry for statistical analysis of the means is useful in cases where the dataset is homogenous (Hammond & Suttie, 2012). In this study, the heterogenous cohort of patients suffered from a wide range of facial nerve pathology. Therefore, the patterns of facial asymmetry provided a general view of the asymmetry, it was not the objective of this study to explore the various causes of facial paralysis nor to investigate disease progress. The colour-coding methods of displaying facial asymmetry did not discriminate if this was due to the residual dysmorphology following the surgical treatment or a primary cause. Therefore, the method is suitable for monitoring improvements after surgery.

Section II: The Clinical Grading of Facial Palsy

In this study, sixteen facial paralysis patients were assessed by 7 expert assessors, twice, using two clinical grading indices, the study introduced, for the assessment of unilateral facial palsy: the modified Sunnybrook index and the Glasgow Index.

The clinical assessors underwent a calibration process to standardise the grading of the variables of the subjective indices, a consensus was reached on a set of assessment criteria, this was followed by the calibration process. The 4D images of cases, which represented the wide range of the severity of unilateral facial palsy, were discussed among the panel of experts. This allowed the consensus agreement on how to categorise the altered symmetry of the facial expression according to the grading scales. It was noted that assessors did not agree initially of what is considered barely visible asymmetry which reflects the major deficiency of the subjective grading systems in routine clinical practice. A consensus was reached following this process regarding the scaling of the asymmetry of facial muscle movements of unilateral facial paralysis.

The validity of the subjective evaluation of facial deformity can be affected by several factors such as the assessment method, the experience of the panel of assessors, and the method of assessment including 2D photographs, 3D images, and the clinical evaluation (Al-Omari et al., 2003; Kelly Ritter et al., 2002). The limited agreement among different methods of subjective assessment of cleft related deformities is well-documented in the literature (Mosmuller et al., 2017).

The subjective assessment of facial palsy is not different. (Tan et al., 2019) investigated the consistency between two stimulus media for the assessment of facial palsy: face-to-face evaluation versus video assessment. Seven professional assessors evaluated 28 facial palsy patients using 3 clinical grading scales (the House-Brackmann scale "HB", Sydney scale, Sunnybrook Facial Grading System "SB"). The assessment was repeated using 2D digital videos that were recorded on the same day of the clinical evaluation as a part of routine patient care. The recorded videos showed the patient performing a set of facial movements, in the frontal view, including eyebrow raise, eye closure, smile, snarl, and lip pucker. The study found the assessment of facial palsy with the HB scale and SB system was similar to that of the face-to-face scores and the video-assessed scores with insufficient agreement among assessors. The reliability of the Sunnybrook scores was poor to fair for the assessment of facial asymmetry at rest (ICC correlation coefficient ranged between 0.19 to 0.49 for the parameters at the eye, cheek, mouth) and synkinesis (ICC 0.006 to 0.63 across the 5 synkinesis scores at 5 expressions). Excellent reliability was noted for the assessment of voluntary facial movements (ICC ranged between 0.69 to 0.91). Bland Altman test showed a wide range of agreement between the two modes of assessment using SB (1 for the evaluation of resting asymmetry, 0 for the assessment of voluntary movements, between 1 and 2 for the assessment of synkinesis). The study did not provide information on the calibration process of assessors and the rating protocol of the recorded videos. The video assessment was limited to the frontal view only.

(Banks et al., 2017) evaluated the facial mimetic function using the eFACE facial grading system, (Banks et al., 2015), and the consistency of the eFACE scores between in-person evaluation of facial palsy and video assessment was investigated. The assessments were conducted on 75 patients with various degrees of facial palsy by two facial reanimation surgeons. The eFACE scores were reassessed, 3 months later, via the recorded videos of facial palsy. The study found strong agreement between the two modes of assessment. The ICCs for the static subset 0.85; dynamic subset 0.96; synkinesis subset 0.90. The test-retest of the eFACE video scores was high. In a recent paper, the same research group (Greene et al., 2020) proposed a standard database of 2D images and videos representing the spectrum of facial palsy. The degree of facial palsy was measured using the eFACE scores, House-Brackmann, and Sunnybrook scales. The facial palsy photo and video standard set, available online, was recommended as a teaching and research tool to enable the comparison of current and future scales of facial palsy assessment. However, there is substantial evidence regarding the limitations of the 2D imaging for the assessment of 3D face (Anas et al., 2019; Gross et al., 1996). The assessment of facial form using two-dimensional facial imaging underestimated the true dimensions of the human face mainly in the anteroposterior direction. Furthermore, the assessment of the volumetric changes of facial soft tissues following the facial reanimation surgery would be challenging without the ability to evaluate the anteroposterior dimension of the face, which is a clinical necessity (Kleiss et al., 2015). Equally important is the assessment of the 3D face overtime for the evaluation of any disorder affecting the facial soft-tissue movement (Burt & Crewther, 2020; Trotman, 2011).

This study introduced, for the first time, the assessment of facial palsy by expert panel of assessors using 4D image data in addition to the objective quantification of dynamic facial asymmetry to explore the mathematical validity of the assessed clinical variables. The 4D videos were displayed on a 2D screen for clinical evaluation of facial dysmorphology. This is a well-established approach which we applied in our previous studies (Al-Omari et al., 2003).

The facial palsy patients were Caucasians, adults, and were recruited from one outpatient clinic in Glasgow Royal Infirmary Hospital. A larger sample size, involving children, and including subjects from different ethnicities would empower the ability to generalize our findings.

The Modified Sunnybrook Index

The modified Sunnybrook index consisted of 8 parameters, the first three parameters were assessed at rest expression and the other 5 parameters were assessed during non-verbal expressions.

The MSB index provided a specific descriptive annotation for the 5 grades at each of the individual voluntary facial expressions to describe the abnormality of movement compared to the normal state. The snarl movement of the original Sunnybrook facial grading system was replaced with the cheek puff. This was due to the nasal obstruction in facial palsy caused by the collapse of the nasal ala and the loss of the intrinsic dilator naris tone (May et al., 1977). In a systemic review of the surgical technique for the treatment of nasal valve collapse, (Spielmann et al., 2009) reviewed the literature between 1970 and 2008. The authors concluded that there is no long-term evidence of patient benefit from the surgical corrections. Most corrections are with static slings rather than dynamic. This view is in agreement with the more recent systematic review by (Goudakos et al., 2017), therefore, we did not consider this facial expression in the study.

On the other hand, cheek puff involved the activity of the peri-oral muscle group, starting with the contraction of the orbicularis oris muscle followed by the contraction of the buccinator muscle, risorius, zygomaticus major and zygomatic minor muscles which helps the cheeks to expand maximally. The effect of paralysis on these muscles resulted in a wide range of facial asymmetry and functional impairment. Therefore, cheek puff assessed the function of the buccinator, orbicularis oris, and zygomaticus muscles (Homer & Fay, 2018).

The modified Sunnybrook index assessed the facial appearance of the eye, cheek, and mouth regions in static and five facial expressions to grasp the major defects of the facial muscle activities influenced by facial paralysis. Clinically, the fewer parameters to be assessed would enable clinicians to stratify the patients effectively for further treatments (Alicandri-Ciufelli et al., 2013), but this may provide limited diagnostic and prognostic information related to the neuromuscular involvement in the facial paralysis. Therefore, the Glasgow index was developed and validated to overcome the limited parameters of assessment of the MSB.

The Glasgow Index

The Glasgow indexing consisted of 29 parameters of the face at rest and the other five parameters of nonverbal expressions. It also encompassed a specific set of parameters for each facial expression including the directions of asymmetry at specific anatomical regions. The detailed assessments of each of the six expressions provided more information regarding the pattern and magnitude of dysfunction associated with facial paralysis.

The Glasgow index considered the distinction between the assessment of facial muscle function and symmetry. The grading of voluntary movements in the Sunnybrook facial grading system is based on a 5-point Likert scale, it combines the assessment of both the nerve function and facial symmetry in one grade. The single score for each of the five voluntary movements presumes that an increased facial nerve weakness results in worsening of the facial asymmetry. This may not be true for all expressions. For example, the performance of cheek puff evaluates the patient's ability to achieve oral seal as a measure of facial nerve function whereas the evaluation of the dynamic asymmetry during cheek puff involves the assessment of asymmetry at the upper and lower lips, cheek, and nasolabial regions.

The GI considered the directionality and the severity of asymmetric facial movements. The rationale behind these measurements is the fact that the directionality of the asymmetry provides an insight into the mechanism of distorted muscle movements. (RUBIN & Rubin, 1974) described the importance of understanding the components of the dynamic of the smile in the treatment of facial palsy especially for the oro-facial reconstruction.

Figure 43: Primary Muscular Movements at the Cheek and Lips

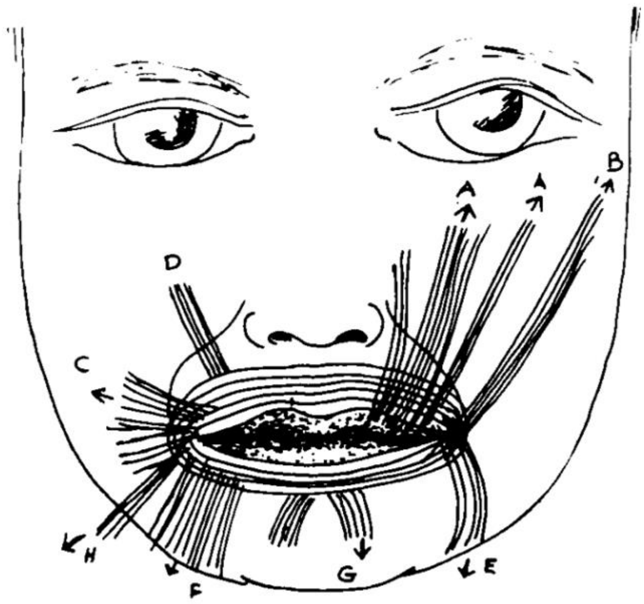


Figure 43 shows a schematic representation of the primary muscle movements of the cheek and lips: A: Levator labii superioris. B: Zygomaticus major. C: Buccinator. D: Levator Anguli Oris. E: Depressor Anguli oris. E: Depressor Labii Inferioris. G: Mentalis, H: Risorius, (RUBIN & Rubin, 1974).

Figure 44: Variations in the Smile

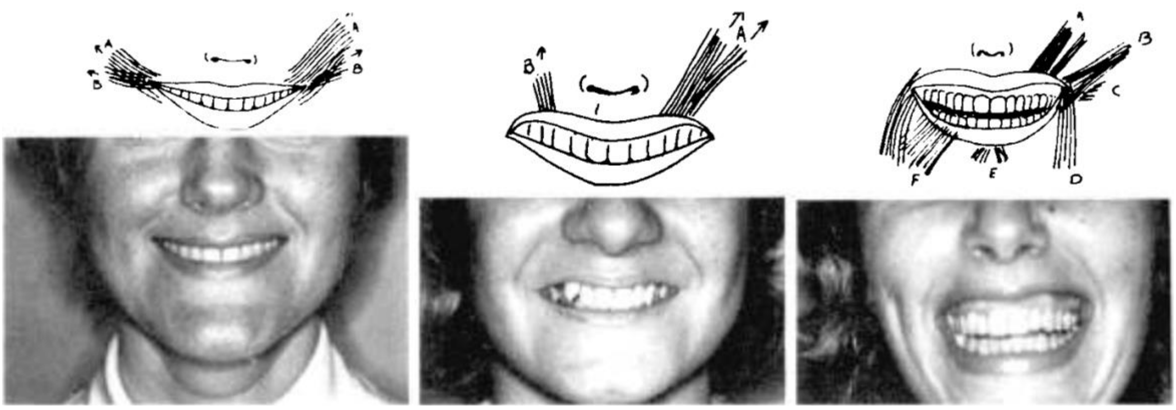


Figure 44 shows three different smiles with the schematic representation of the primary muscle movements above. On the left, the image shows the Mona Lisa smile, corner of mouth smile, represented by the dominant action of the Zygomaticus major muscle. The image in the middle shows the canine smile, the primary action of the levator labbi superioris. The image on the right shows the full denture smile in which all muscular actions are equal, (RUBIN & Rubin, 1974).

Despite its obvious importance, the direction of facial movements and its related asymmetry are not routinely assessed in facial palsy. This may be due to the lack of universal objective measurement tools for the evaluation of the dynamics of facial muscle movements. In 2019, (Roy et al., 2019) conducted a literature review and meta-analysis to investigate the effectiveness and safety of the gracilis muscle transfer for the rehabilitation of facial movements. The study found a major heterogenicity in the published research reporting the functional outcome of the smile reanimation surgery. The outcome of interest primarily involved the degree of smile excursion (magnitude of movement), asymmetry, complications, revision procedures and patient-reported outcome. The authors highlighted the critical need for universal outcome measurement tools to improve patient care. We believe the presented study is a step in the right direction to achieve this target.

Reproducibility of the Clinical Gradings

The Sunnybrook facial grading system has been recommended the standard clinical scale for the assessment of facial palsy because of its proven reproducibility (intra-observer ICC ranged from 0.83 to 0.98; interobserver ICC ranged from 0.83 to 0.99) (Fattah et al., 2015). Sunnybrook facial grading system proved reproducible in different languages (Chong et al., 2017; Mengi et al., 2020; Pavese et al., 2013). But its validity regarding its accurate measurement of distorted facial movement has not been tested yet.

In this study, the modified Sunnybrook index and the Glasgow Index were reproducible. No statistically significant differences were found in the indexing method of the modified Sunnybrook index and, the Glasgow indexing method II following the exclusion of three parameters (GI18, GI21 at cheek puff, GI26 at eye closure), Table 18.

The intra-observer reproducibility of the modified Sunnybrook index between the first and second rating sessions for the 7 assessors ranged between r=0.80 to r=0.94, Table 12. The inter-rater reliability of the 8 MSB parameters among the 7 assessors ranged between ICC 0.45 to 0.83, Table 9. We detected a higher agreement among the assessor in the evaluation of the MSB movement scores (ICC 0.83 forehead wrinkle, 0.82 eye closure, 0.75 smiling, 0.74 lip pucker, 0.44 cheek puff) in comparison to the parameters assessed at rest (ICC 0.45 eye, 0.58 nasolabial fold, 0.56 mouth droop).

The intra-observer reproducibility of the Glasgow index between the first and second rating sessions for the 7 assessors ranged from r=0.69 to r=0.82, Table 17. The inter-rater reliability of the 29 GI parameters among the 7 assessors ranged from 0.43 to 0.86, Table 14. The limited differences between raters on the grading of the dynamics of facial expressions of Glasgow indexing method II ($p<0.01$; estimated coefficient 0.015), Table 18. The results may highlight the difficulty in the clinical evaluation of these parameters. The GI parameters at rest (GI3, GI6) which assessed the eye and the corner of the mouth-chin symmetry, respectively, could be difficult to assess clinically due to the lack of explicit descriptors. The grading of facial asymmetry on an ordinal scale which ranged from no asymmetry to server asymmetry was challenging, despite the pre-study calibration and training. On the other hand, the small differences among raters on the grading of the dynamic parameters (GI 15, 16, 20, 24, 27, 28) were mainly related to the difficulty in assessing the direction of the asymmetric muscle movements, Table 18. These are discussed in the next section.

Section III: The Correlation Between the Mathematical Measurements and the Clinical Grading of Facial Palsy

The rationale of studying the correlation between the mathematical measurements and two subjective grading indices was to evaluate the validity of the subjective assessment of the distorted oro-facial muscle functions. The statistically significant correlations between the mathematical measures and the clinical scores provided the necessary validation of the subjective assessment of the asymmetric movements of the facial muscles in unilateral facial palsy.

The degree of the agreement between the mathematical measurements and the subjective assessments varied widely between the indices and the parameters of each one. Several reasons for the lack of significant correlations between the mathematical measurements and subjective assessments, mainly the limited sample size and the restricted descriptions of some of the subjective parameters.

Dissimilarities between the comparable parameters of the two clinical indices contributed to the wide range of variations in the strength of correlation between the graded variables and the measurements. This is not unexpected because the two indices have a different set of parameters that vary in number and their descriptive details. Concise descriptor (normal/abnormal) of a specific facial feature of morphological variations is a crude tool as it amalgamates a wide range of abnormalities under the same group, therefore are highly sensitive but lacks specificity. On the other hand, detailed descriptors require a comprehensive calibration of the assessors to standardize the interpretation of the variables and maximize both the inter-and intra- observer reliability and reproducibility.

Facial expressions took 4-6 seconds which may be too fast for the human eyes to coordinate with the brain to quantify the magnitude of the directional asymmetric movements of the facial muscle in facial palsy. (Kim et al., 2013) investigated the impact of timing on the detection and perception of side-to-side asymmetry of facial muscle movements. In their study, five symmetrical facial expressions were recorded using digital video camera (Canon HF200), eye blink, rapid eyebrow raising, slow eyebrow raising, smile, and lip depression. The unilateral asymmetry of muscles movement due to the time-delay of one side in comparison to the other ranged from 33 to 267 milliseconds. Fifty-eight raters viewed the facial movements and were asked to indicate the presence of asymmetry and to grade the naturalness of movement on a 5-point scale. Statistically significant differences were found among assessors in the detection of the threshold of the asymmetry of facial muscle movements. It has been reported that at 100ms of delay, almost all expressions were detected as asymmetric. Strong inverse correlation was found (R=0.82) between the time delay and the grading of naturalness.

This also raises an intriguing question of what are the facial features that attract the assessor's attention during the assessment of facial muscle movements. The possibility that certain features of facial asymmetry predominate the decision-making process of grading the asymmetry of muscle movements cannot be ruled out. On the other hand, minor subtle asymmetries which are readily measurable mathematically may not be noticed during routine subjective assessments of facial muscle movements. (Wang et al., 2017) investigated the perception of facial deformity in the medical literature published between 1946-2015 to ascertain the discriminative thresholds in facial asymmetry across facial subunits to guide surgical intervention. They reported that different facial aesthetic units possess a unique threshold of perception that was defined by an abrupt statistically significant increase in detection. The human eye is more sensitive to the asymmetry at the eyelid, brow, and corner of the mouth than the asymmetry at the tip of the nose and chin.

Assessment of Resting Facial Asymmetry in Unilateral Facial Palsy

In this study facial disfigurement, caused by the loss or impairment of the motor function of facial muscles, manifests clinically by the loss of muscular tonicity and the sagging corner of the mouth on the paralyzed side of the face. This was highlighted by the correlation between the mathematical asymmetry and the clinical grading of the full-face, forehead, eyes, nose, cheek, nasolabial, upper lip, corner of the mouth, and the chin regions Table 22.

The three MSB parameters were readily comparable with the six parameters of the Glasgow index for the assessment of the eye, nasolabial fold, and the corner of the mouth.

Assessment of the Eye at Rest (MSB 1, GI 3)

The clinical evaluation of the eye using the MSB index focused on whether the eye on the affected side is normal or abnormal. The GI graded asymmetry of the eye on the paralyzed side in comparison to the non-affected side on an ordinal scale ranging from severe asymmetry to no asymmetry. Severe asymmetry included the presence of ectropion and eyelid droop hampering vision.

Mathematical asymmetry scores at the eye region were correlated to the clinical gradings of the MSB parameter 1 and the GI parameter 3. The MSB1 and GI3 showed similar degree of moderate correlations with the measurements, (Coefficients of correlation, -0.42, $p<0.05$; -0.49, $p<0.05$, respectively) Table 22.

The mathematical colour-coded facial maps of the distance patterns of resting facial asymmetry in unilateral facial palsy reflected a minimal degree of disparity between the right and left sides of the face at the eye region (Figure 45, Figure 46). This may explain the moderate correlations between the clinical indices and the mathematical measures. On the other hand, the colour maps showed an increase of facial asymmetry in the vertical direction (Figure 47), as well as in the anteroposterior direction at rest, Figure 48. The vertical asymmetry is due to the lower position of the orbicularis oculi muscle fibers of the affected side which spreads laterally from its origin, the nasal part of the frontal bone, to the circumference of the orbit in the eyebrow region and extends over the temple. In the anteroposterior direction, the asymmetry was clear between the affected and the non-affected side, the latter was at a more forward position. Therefore, it is essential to consider the mathematical measurements for the assessment of the directionality of facial asymmetry, especially in cases where facial paralysis affects the palpebrae superiors' muscle or orbicularis oculi.

Figure 45: Case Demonstration - Resting Facial Asymmetry

Figure 45 provides case demonstration of resting facial asymmetry in unilateral facial palsy patient affecting the left side of the face.

Figure 46: Patterns of Facial Asymmetry at Rest

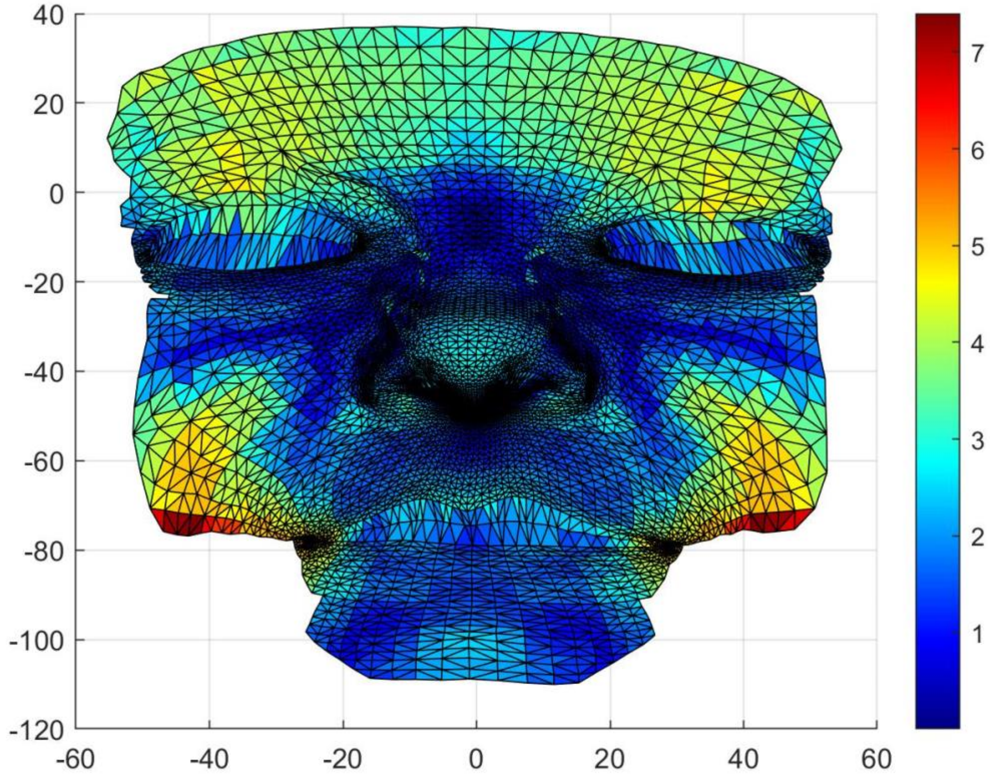


Figure 46 shows the distance patterns of the minimal facial asymmetry (global asymmetry) at rest of the unilateral facial palsy patient presented in Figure 45. The colour code ranges from blue colour (1) to red colour (7). The blue colour indicates perfect symmetry due to the minimal difference in the mean absolute distance between the vertices of the 3D images and its corresponding reflections. The changing colour from deep blue to red indicates an increase in the magnitude of facial asymmetry.

The distance patterns of the minimal facial asymmetry show a minimal degree of disparity between the right and left sides of the face.

Figure 47: Patterns of Facial Asymmetry at Rest

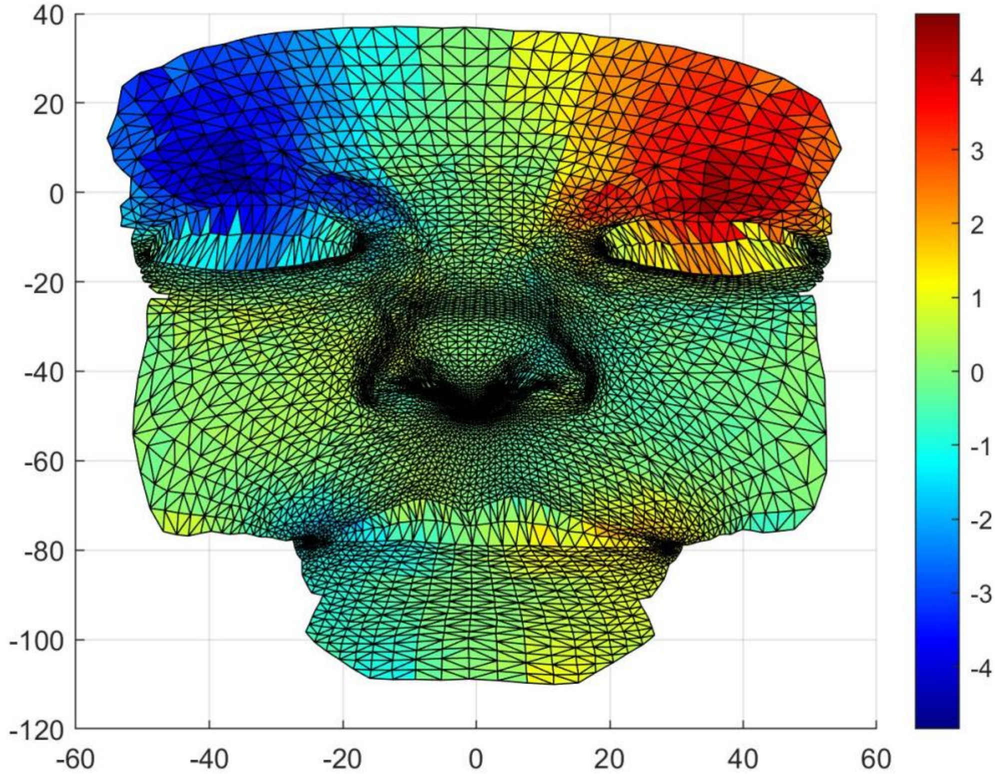


Figure 47 shows the patterns of facial asymmetry in the vertical direction at rest of the unilateral facial palsy patient presented in Figure 45. The colour code ranges from blue colour (-4) to red colour (+4). The green colour (0) indicates perfect symmetry. The changing colour from green to red indicates increased asymmetry upward. The changing colour from green to deep blue indicates increased asymmetry downward.

The pattern of the facial asymmetry in the vertical direction demonstrates the impact of unilateral facial paralysis on face droopiness.

Figure 48: Patterns of Facial Asymmetry at Rest

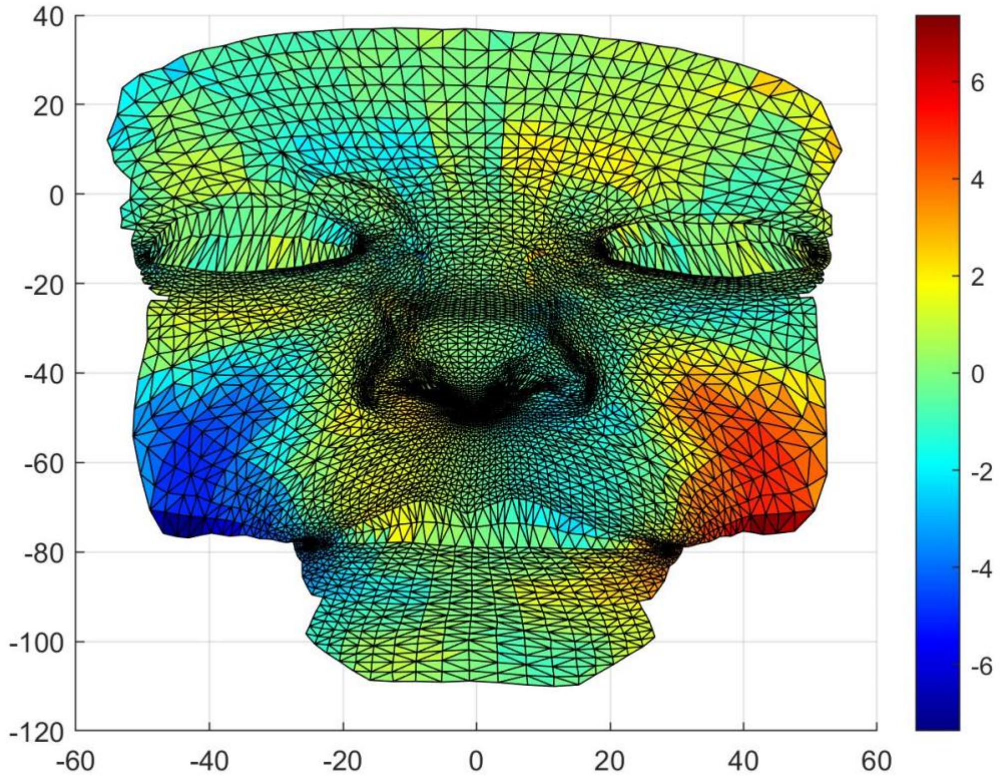


Figure 48 shows the patterns of facial asymmetry in the anteroposterior direction at rest of the unilateral facial palsy patient presented in Figure 45. The colour code ranges from blue colour (-6) to red colour (+6). The green colour (0) indicates perfect symmetry. The changing colour from green to red indicates an increased anterior asymmetry. The changing colour from green to deep blue indicates an increased posterior asymmetry.

The pattern of the facial asymmetry in the anteroposterior direction demonstrates the impact of unilateral facial paralysis on face contours, especially at the cheek region. The right cheek showed an increased degree of facial asymmetry in the anterior direction (red colour). This pattern was reversed in the left cheek.

Assessment of the Nose and Nasolabial Fold at Rest (MSB 2, GI 4)

The nasolabial fold is the demarcating line separating the cheeks from the upper lip and runs from the nose to the corners of the mouth. In facial paralysis, the loss of the buccal fat pad and the sagging of the cheeks may cause the nasolabial fold to be altered in length, depth, and width; thus, it may adversely impact the facial symmetry of adjacent regions. This provides an explanation of the correlation between the clinical scores of the nasolabial fold (using either MSB2 or GI4) and the mathematical asymmetry scores of the nose, cheek, nasolabial facial regions, Table 22.

The evaluation of the nasolabial fold abnormality in MSB2 considered the flattening or accentuation of the nasolabial fold. Whereas the Glasgow index parameter 4 is for the assessment of the nose and nasolabial fold at rest in addition to the evaluation of the philtrum and the nasolabial fold. Statistically significant correlations were found between the GI4 scores and the mathematical measurements of the asymmetry at the nose region (Coefficient of correlation -0.69). The Gl4 is more sensitive with a stronger correlation with the objective measurements in comparison with MSB2 for the assessment of the asymmetry of the nose and nasolabial fold (Coefficients of correlation -0.84, -0.76, respectively).

The mathematical colour-coded facial models of the patterns of resting facial asymmetry highlighted the morphological disparity of the nasolabial fold between the paralyzed and the unaffected sides of the face (Figure 46, Figure 47, Figure 48). The predominant facial asymmetry was detected mathematically in the anteroposterior direction. The patterns of facial asymmetry indicated the presence of fold abnormality, which adversely affected symmetry at the nose, cheek, and nasolabial regions. Significant strong correlations were found between GI and the objective measurements indicating the nasolabial fold to be a positive clinical indicator of resting facial asymmetry in unilateral facial paralysis.

Assessment of the Corner of Mouth and Chin at Rest (MSB 3, GI 6)

The assessment of the symmetry at rest using the MSB3 focused on the abnormality at the corner of the mouth (abnormal/normal). The GI6 graded mouth and chin asymmetry over a 4-point scale (severe asymmetry, moderate asymmetry, mild asymmetry, no asymmetry).

The mathematical asymmetry scores of the corner of mouth region were significantly correlated to the clinical gradings of the MSB parameter 3 and the GI parameter 6. The GI6 showed a stronger degree of correlation with the measurements than MSB3 (Coefficients of correlation, -0.79, -0.60, respectively), Table 22.

The clinical gradings of the two indices showed varying degrees of correlations to the asymmetry scores of the upper lip, lower lip, and chin regions. The correlations between the mathematical measurements and MSB3 of the upper lip region and for the GI6 at the chin region were strong and statistically significant (Coefficients of correlations -0.69, -0.76, respectively). In unilateral facial palsy, droopiness of the corner of the mouth along with the loss of muscular tonicity on one side results in a vertical asymmetry in the ipsilateral cheek, upper lip, corner of the mouth, and chin, Figure 49.

At rest the asymmetry of the corner of the mouth was mainly in the anteroposterior direction, followed by the asymmetry in the vertical direction. This provides new insights regarding the impact of facial palsy on resting asymmetry. The directional analysis of facial asymmetry can help and inform the surgical decision as well as the overall management of facial palsy. Especially in the surgical correction of the position of the mouth to provide static support to this anatomical region and improve resting facial asymmetry (Leckenby et al., 2014). The surgical technique involves the use of fascial slings to improve the suspension forces at the corner of the mouth. The autogenous graft is attached to the adjacent musculature with other techniques considering the bony-fixated support of the fascial slings (Lemound et al., 2015). It would be interesting to assess, subjectively and objectively, the position of the corner of the mouth in facial palsy before and after surgical corrections and investigate the correlations between the measured parameters. The design of this study did not allow this to be investigated.

Figure 49: Droopiness of the Corner of the Mouth

Figure 49 shows the corner of the mouth drooped on the affected left side of the face of one of the study cases with a clear vertical asymmetry in the ipsilateral cheek, upper lip, corner of mouth and chin.

Assessment of Cheek Contour and Tone at Rest (GI 5)

Clinically, there are no clearly defined features in the cheek region, therefore, the clinical assessment of cheek asymmetry using MSB2 relied on the adjacent features of the nasolabial fold. The GI5 graded the cheek asymmetry over a 4-point ordinal scale and took into consideration three facial features: droopiness of the corner of the mouth, cheek contour, and muscular tone in the cheek region; thereby enabling a direct clinical evaluation of cheek dysmorphology.

A stronger correlation was detected between the mathematical measurements and the assessment of cheek contour and tone using the GI5 in comparison to MSB2 (Coefficients of correlation, -0.84, -0.76, respectively), Table 22. The stronger correlation indicates the clinical grading of cheek symmetry is more sensitive when the direct evaluation of cheek appearance is incorporated in the assessment.

The mathematical colour-coded facial models of the patterns of resting facial asymmetry showed a remarkable anteroposterior cheek asymmetry followed by the asymmetry in the mediolateral direction and to a lesser extent in the vertical direction. The volumetric dysmorphology may be caused by the loss of muscular tonicity, especially in long-standing paralysis in which muscular atrophy and the loss of muscular tonicity results in the dropping of the cheek on the affected side anteriorly, medially, and downward, Figure 50, Figure 51.

Therefore, the surgical intervention in unilateral facial palsy affecting the cheek muscles is mainly aimed at functional improvement utilising free muscle flaps for facial reanimation (Roy et al., 2019). The accuracy in predicting the required volume of the muscle transfer to the facial region is limited due to the limited validity of objective measurement tools (Braig et al., 2017). The functional muscle transplant may result in excessive bulk in the cheek region, Figure 52. There is also the tendency to perform debulking surgery on the transferred muscle flaps to deal with the excessive volume of the transferred tissue.

This highlights the importance of considering the 3D assessment of facial dysmorphology in the surgical planning of facial reanimation surgery for the volume of the donor muscle flap and the direction of movement of the transplanted muscle in the facial regions. The result of this study is a step in the right direction to improving the quality of reconstructive surgery in facial palsy. The validated subjective parameters and the mathematical measurements would provide a more accurate evaluation of the tissue volume deficit of the affected side and guide the required muscle transfer.

Figure 50: Facial Palsy Patient with Dense Paralysis

Figure 50 shows cheek asymmetry in a participant suffering from long-standing unilateral facial palsy affecting the right side of the face.

Figure 51: Patterns of Facial Asymmetry at Rest

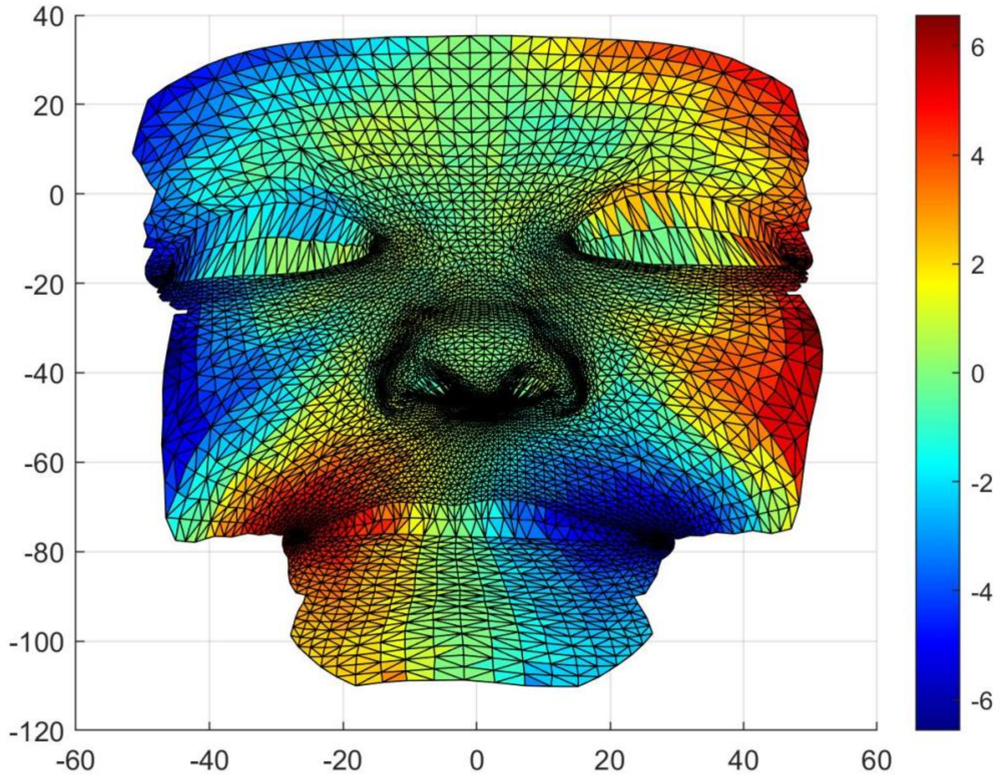


Figure 51 shows the patterns of facial asymmetry in the anteroposterior direction at rest of the unilateral facial palsy patient presented in Figure 50. The colour code ranges from blue colour (-6) to red colour (+6). The green colour (0) indicates perfect symmetry. The changing colour from green to red indicates an increased anterior asymmetry. The changing colour from green to deep blue indicates an increased posterior asymmetry.

In the anteroposterior direction, the bilateral volumetric differences of the cheek regions were due to the disparity in the underlying muscular substance. The sagging of the cheeks may have increased the tissue bulk at the corner of the mouth anteriorly.

Figure 52: Facial Palsy Patient Underwent Facial Reanimation Surgery

Figure 52 shows excessive bulk in the cheek region of a study participant due to facial reanimation surgery with free muscle transplant to the left side of the face.

Assessment of Forehead Wrinkles and Eyebrows at Rest (GI 2)

In distinction to the MSB, the GI assessed the forehead wrinkles and eyebrow (GI2) separately from the eye. The clinical grades ranged from severe asymmetry to no asymmetry. The GI parameter 2 showed stronger correlations than MSB1 with the mathematical asymmetry of the forehead, (Coefficients of correlation, -0.72, -0.48, respectively), Table 22. The GI assessment was focused on the evaluation of forehead symmetry rather than the eyes and provided more descriptors for the assessors which may have contributed to the stronger correlation with the mathematical measurements.

The mathematical colour-coded facial models of the patterns of resting facial asymmetry showed the forehead asymmetry was mainly in the vertical direction (Figure 47) followed by the anteroposterior direction (Figure 48) and to a lesser extent in the mediolateral direction. The upward asymmetry of the forehead would appear more distinct to the assessors due to the combined effect of the downward asymmetry of the cheek region on the paralyzed side.

The disclosed directional asymmetry at the forehead regions may help inform the surgical decision. The restoration of brow symmetry in facial paralysis is aimed to deal with forehead wrinkles and for the correction of eyebrow position (Leckenby et al., 2015). Treatment options of brow furrowing involve the denervation of the healthy side by Botox injection or the surgical division of the frontal branch of the unaffected side. The results of this study highlight the presence of forehead asymmetry and the correction of which may be addressed in the open approach such as the hairline lowering technique.

Assessment of Total Facial Asymmetry at Rest (GI 1)

The Glasgow index graded total facial asymmetry on a 4-points ordinal scale ranging from severe asymmetry to no asymmetry. The clinical scores showed statistically significant correlations to the mathematical asymmetry scores of the full face (coefficient of correlations -0.81), Table 22.

Whereas the MSB did not consider the clinical grading of the global facial asymmetry, nevertheless, significant correlations were found between the mathematical scores and MSB parameters for the assessment of nasolabial fold MSB2 and corner of mouth MSB3 (Coefficients of correlation -0.74, -0.60, respectively), Table 22.

The degree of mathematical facial dysmorphology varied across the different regions regarding the main direction of asymmetry. The forehead asymmetry was mainly in the vertical and anteroposterior directions. Eye asymmetry was mainly in the vertical direction. Cheek asymmetry was remarkable in the anteroposterior direction, followed by the mediolateral direction and to a lesser extent in the vertical direction. This implies that the presence of asymmetry in two or more main directions may have increased the detection threshold of facial asymmetry which resulted in a stronger level of correlations with the mathematical scores. (Coefficients of correlation at the forehead -0.72, cheek -0.84, eye -0.42), Table 22.

The assessment of full-face facial asymmetry at rest using the GI proved reliable and valid. It provides a clinical measurement for the assessment of gross facial asymmetry.

Glasgow Index for Assessment of Resting Facial Asymmetry in Unilateral Facial Paralysis

The study showed that the Glasgow index is more correlated with the objective measurements in comparison to the MSB for the assessment of resting facial dysmorphology. It is logical to consider the clinical parameters that showed the strongest correlations to the objective measurements are more meaningful and valid for the assessment of facial asymmetry.

For the assessment of resting facial asymmetry, the parameters of GI varied in their correlations with the mathematical scores at the various anatomical regions of the face. It was noticed that clinical parameters that showed a strong correlation with the mathematical regional scores, shared similar assessment criteria. For example, the descriptors of GI5 for the assessment of cheek asymmetry considered the ptosis of the corner of the mouth which has a similar diagnostic value as parameter 6 of GI for the assessment of the corner of the mouth-chin. It is interesting to note that the agreements among the assessors in the first three parameters of the modified Sunnybrook index grades are higher than the corresponding agreements in the first six parameters of the Glasgow indexing, which means that the modified Sunnybrook indexing is more reproducible. But their magnitudes of the correlations are lower, which means that the more specific Glasgow indexing leads to a higher magnitude of correlations to the 4D measurements. We would think that the modified Sunnybrook index grades are more consistent but give less specific assessments of individual parameters.

Assessment of Dynamic Bio-dysmorphology in Unilateral Facial Palsy

The assessment of facial nerve function in unilateral facial paralysis was based on the evaluation of muscle movements during smile, lip purse, cheek puff, eyebrow raise, and eye closure. The Clinical evaluation of facial dynamics using the modified Sunnybrook index was based on a 5-point Likert scale per expression. The Glasgow index considered different parameters for the assessment of each expression. The following sections discuss research results at individual facial expressions.

Assessment of the Smile (MSB 6, GI 7-12)

The clinical evaluation of the smile using the modified Sunnybrook index (MSB6) considered the mobility of the cheek and the corner of the mouth, taking into consideration the asymmetric movement of the facial muscles. The muscular action during a smile starts with the contraction of the zygomaticus major, zygomaticus minor, risorius, muscles followed by the stretching of the cheeks upward and laterally; and then extend to involve the corners of the mouth and the depressor muscles in a wide smile.

In partial unilateral facial paralysis, the same group of muscles is involved in the facial expression but to a lesser extent due to the VII cranial nerve weakness. Some muscles can become overactive or exhibit synkinesis (Placheta et al., 2014). In complete unilateral facial paralysis, the activity of the contralateral muscles on the unaffected side impacts the morphology of the nasolabial fold on the affected side. This indirect influence of the non-affected side has been considered within the Glasgow index parameter 10 for grading of the dynamic asymmetry of nasolabial fold during smile along with parameter 8 for the assessment of the magnitude of smiling.

The correlation between the objective measurements and MSB6 (r=-0.67 at Cheek) was comparable to that of GI8 (r=-0.73 at Cheek) and GI10 (r=-0.60 at Nasolabial region), Table 24. The clinical assessments showed significant correlations with the mathematical scores at the relevant regions. The asymmetry of the cheek during a smile has the highest correlation coefficients to MSB6 and GI8.

On the other hand, the parameter of the GI9 for the assessment of lower lip movement was not sensitive enough and correlated poorly with the objective measurements, Table 24. This may be due to the concise descriptor of GI9 to abnormal/normal movements which did not match the complexity of muscle movements during a smile. Another explanation may be the dominant impact of the asymmetry of the cheek and the upper lip which may have led the assessors to underestimate the lower lip asymmetry. The action of the depressor muscles of the lower lip can lead to the false impression of an abnormality on the normal side, Figure 53.

Figure 53: Case Demonstration - Maximum Smile

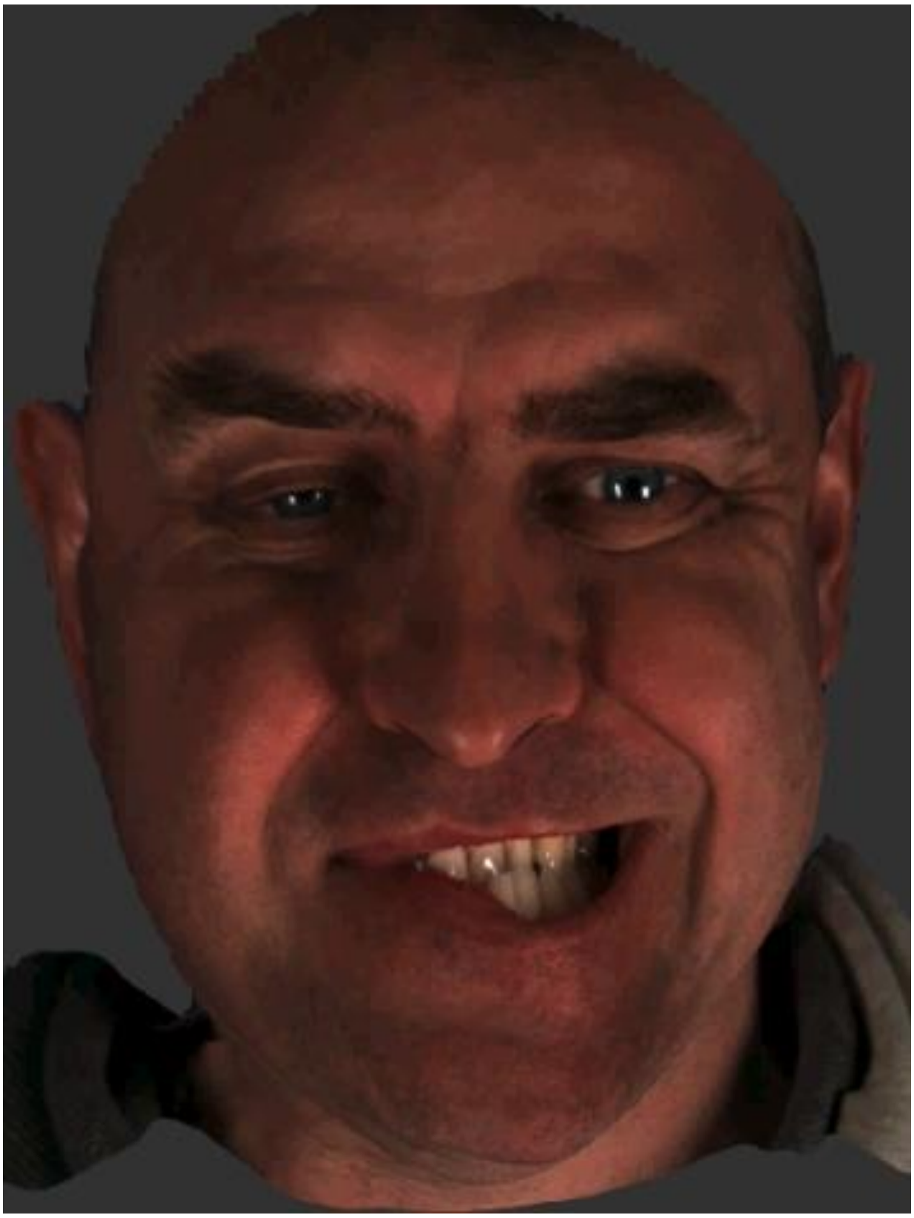


Figure 53 provides a case demonstration of unilateral facial palsy affecting the right side of the face. The face at the maximum expression of smile where the action of the depressor muscles of the lower lip on the left healthy side of the face can lead to the false impression of lower lip asymmetry.

Table 25, showed 68.75% agreement between the clinical assessment and the mathematical asymmetry of the cheek, nasolabial region, upper and lower lip. Poor agreement was detected between the clinical assessment and the mathematical measures at the corner of the mouth (37.5%). This may be explained by the fact that the dynamic movement of the corner of the mouth is affected by various groups of muscles and is a point of contact of various anatomical regions. The clinical asymmetry in any of these regions would influence the subjective grading.

The results of correlation for the direction and severity of asymmetry of the smile (Table 25) imply that the dynamic directional asymmetry during smile was at the cheek, nasolabial region, upper and lower lip regions which have influenced the clinical grading. The following figures (Figure 54, Figure 55, Figure 56, Figure 57) provide a clinical demonstration of the dynamic facial asymmetry at the smile in 4 unilateral facial palsy patients.

The parameters 7 to 12 of GI are the assessments at facial regions of the patients at smile except for parameter 9, which have moderate correlations to the objective measurements. Parameter 8 has a similar magnitude of correlation with the objective measurements as parameter 6 of the modified Sunnybrook index grades. The highest magnitude of correlation coefficient of parameter 8 of GI and the objective measurements is related to the cheek instead of in the corner of the mouth. The corner of the mouth is located in the joint between the upper lip, lower lip, and cheek, where the soft tissue movements of smiling may not be uniform across the various anatomical structures. The asymmetry measurements from the vicinity points of the corner of the mouth may not be representative of the asymmetry at the corners of the mouth, while the asymmetry measurement of the cheek is more representative of the cheek region. This may explain the higher magnitude of the correlation coefficient between the objective and subjective assessments of the cheek region.

The parameter GI9 of the lower lip showed a lack of significant correlations to the 4D asymmetry measurements. This could be because 14 out of 16 patients were graded 1 (abnormal) regarding the lower lip movement and 6 patients were graded 2 (normal), Table 20. The assessors did agree (93.8%) on the abnormality of the lower lip, but the limited descriptor of GI 9 to normal and abnormal was not suitable for calculation of correlation coefficient.

The agreement among the assessors regarding the directional abnormality of the corner of the mouth, GI11, was low (55.4%) and the agreement between the subjective assessments to the objective assessment was also poor. The diversity of smiling movement around the vicinity of the corner of the mouth may be the reason for this poor agreement. Parameter 12 of the severity of the directional asymmetry has a moderate correlation with the subjective measurement, Table 25. The assessors can make judgments on the severity but encounter difficulties to judge the direction of the asymmetry of the corner of the mouth. We would think that it is easier to observe the upper lip and the cheek instead of the corner of the mouth when assessing the smile of the patients based on the results of this study.

The clinical evaluation of the main direction of asymmetry (GI11) and the grading of the severity of asymmetry (GI12) with smile showed significant correlations with the mathematical measures of asymmetry at the cheek, nasolabial fold, upper and lower lip, Table 25. Therefore, the assessment of directionality of the asymmetry of smile at these anatomical regions should be considered in the clinical decision-making regarding the rehabilitation of the affected side of the face and this includes the static support by means of facelift or smile reanimation surgery.

Figure 54: Case Demonstration - Maximum Smile

Figure 54 demonstrates an example of a balanced smile with minimal degree of cheek asymmetry

Figure 55: Case Demonstration - Maximum Smile

Figure 55 demonstrates a maximum smile with a minimal movement of the cheek and the corner of the mouth on the affected left side of the face.

Figure 56: Case Demonstration - Maximum Smile

Figure 56 demonstrates a maximum smile where there was a movement of the cheek of the affected right side of the face without lifting of the corner of the mouth.

Figure 57: Case Demonstration - Maximum Smile

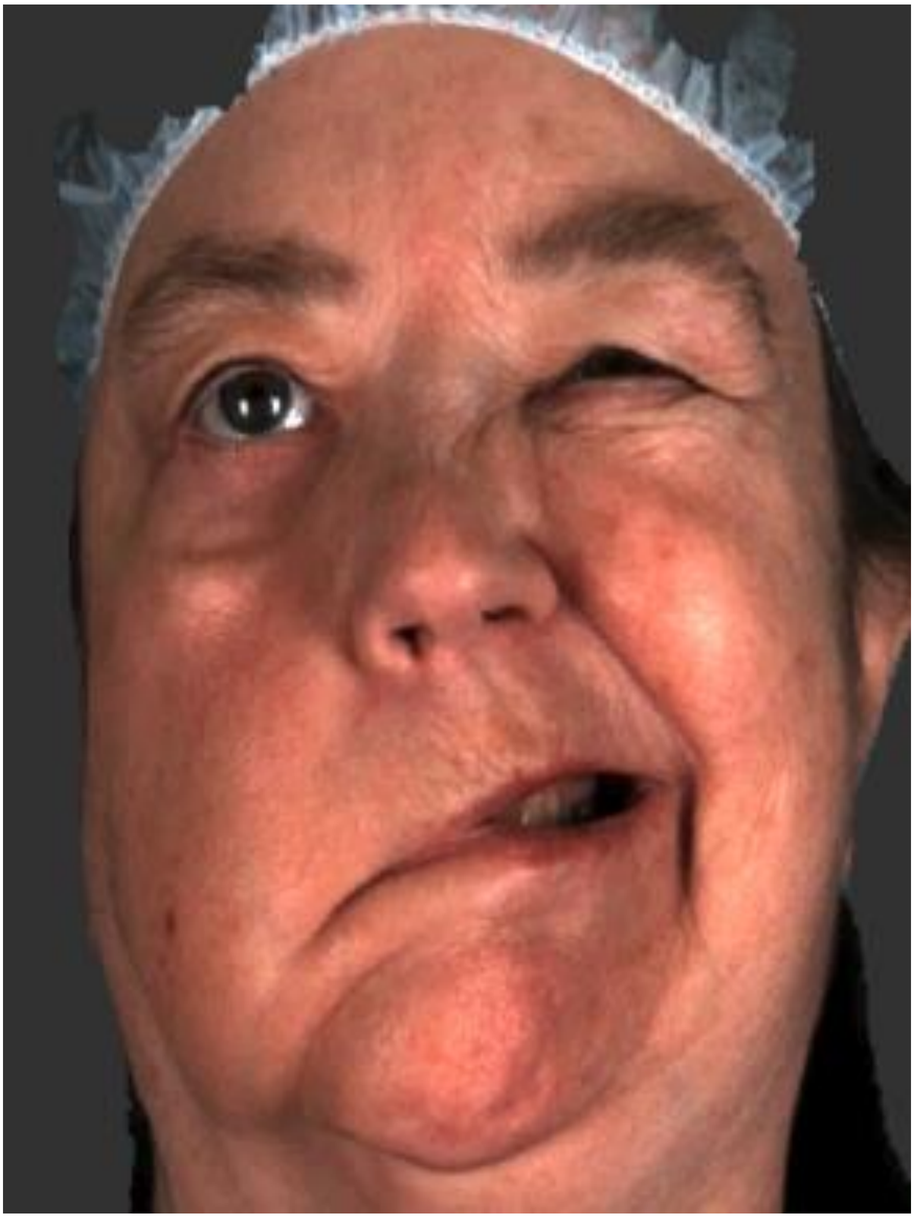


Figure 57 demonstrates a maximum smile without any movement of the paralyzed right side of the face.

Assessment of Lip Purse (MSB 8, GI 13-17)

Parameter 8 of the MSB for the clinical evaluation of lip purse evaluated the mobility of the lip with focused consideration on the dynamic symmetry of the philtrum. Parameter 15 of GI graded the dynamic asymmetry of lower lip movement during lip purse along with parameter 14 for the assessment of the magnitude of movement.

During lip purse, the orbicularis oris primarily contracts to protrude the lips. The symmetry in lip movement is dependent on the harmonious coordination between the different circumoral muscles of facial expressions, which is weak or absent in unilateral facial paralysis (Garcia et al., 2015). Lip protrusion may produce a deviation of the philtrum to the affected side, flatten the nasolabial fold on the normal side and accentuate the nasolabial fold on the affected side. The unmatched contralateral actions of muscular activity on the healthy side adversely affect facial symmetry at the cheek, nasolabial, upper lip, lower lip, corner of the mouth, and chin regions, Figure 58. Interestingly, the correlation results showed varying degrees of correlations between the clinical parameters and the mathematical scores at individual facial regions, Table 27.

Figure 58: Case Demonstration - Lip Purse

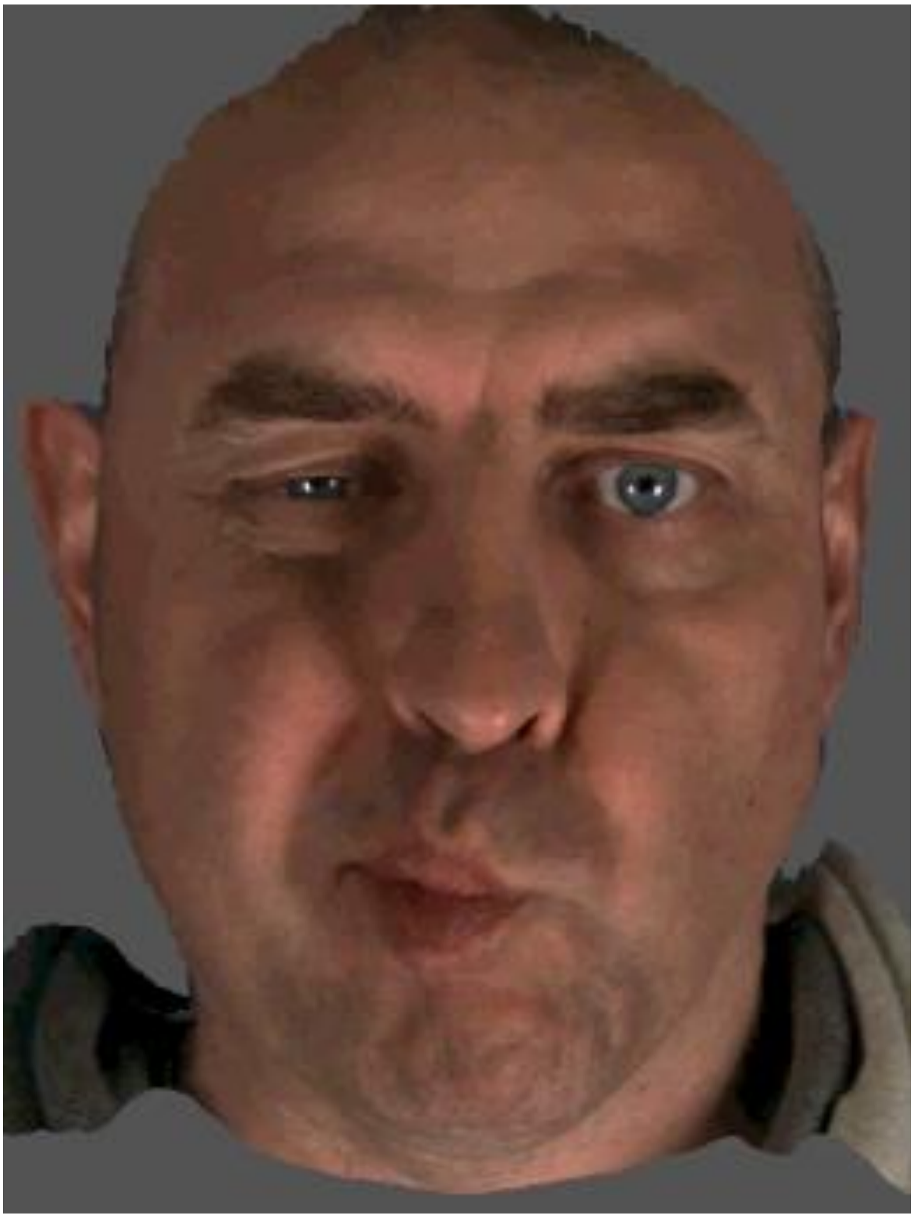


Figure 58 provides a case demonstration of unilateral facial palsy affecting the right side of the face. The face at the maximum expression of lip purse shows the deviation of the philtrum to the affected side and the flattening of the nasolabial fold on the healthy left side of the face.

The clinical assessments showed similar significant correlations with the mathematical scores at the upper lip (MSB8 r=-0.65, GI14 r=-0.61, GI15 r=-0.61), lower lip (MSB8 r=-0.62, GI14 r=-0.62, GI15 r=-0.53) and corner of mouth regions (MSB8 r=-0.62, GI14 r=-0.63, GI15 r=-0.55), Table 27. These clinical parameters were sensitive enough and correlated with the objective measurements. We would suggest observing the asymmetries of the lips and corner of the mouth when assessing the lip purse expressions of the patients.

On the other hand, parameter 8 of the MSB grading system showed moderate correlations with asymmetry scores of the cheek, nasolabial region, and chin (Coefficient of correlations -0.52, -0.45, -0.43, respectively, Table 27). This may be due to the fact the clinical grading for MSB8 was based on the evaluation of lip movements during lip purse with no consideration to the other facial regions. The detected correlations highlight the presence of dynamic asymmetry in cheek, nasolabial region, and chin regions but the magnitude of asymmetry during lip pucker was less pronounced in comparison to the lip region and corner of mouth asymmetry. The lack of statistically significant correlations may also be explained by the asymmetry in these regions which was specific to a limited number of cases. Figure 59 provides a demonstration of chin asymmetry in a severe case of unilateral facial palsy affecting the left side of the face. Paralysis and loss of muscular tonicity affecting the depressor labii inferioris and depressor anguli oris muscles produced asymmetry at the lower lip and chin regions; this is observed, upon the performance of lip-puckering, as a unilateral upward and laterally directed twist of the affected musculature in the chin region.

Figure 59: Case Demonstration - Lip Purse

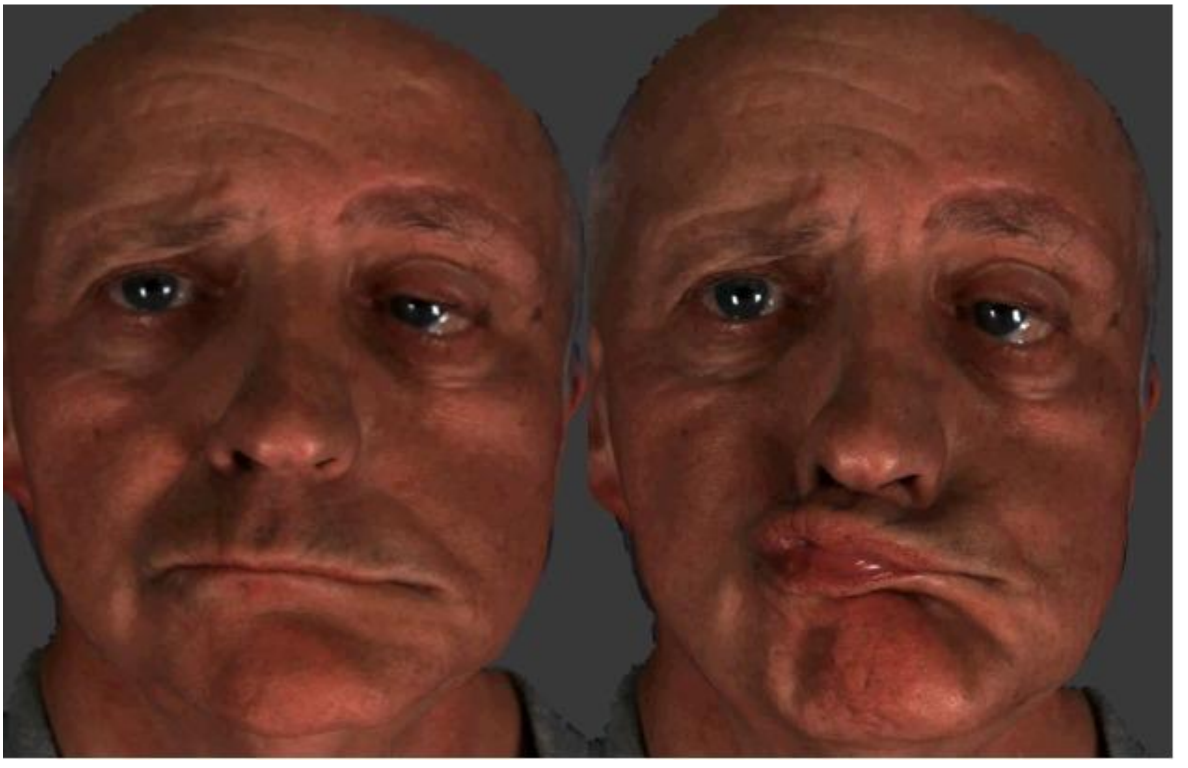


Figure 59 provides a case demonstration of unilateral facial palsy patient. L: The face at rest, R: the face at the maximum expression at lip purse.

The parameters 13 to 17 of the GI are for the assessments at facial regions of the patients at lip purse; parameters 13 (full face) and 17 (corner of the mouth) had strong correlations to the objective measurements (r=-0.74, $p<0.05$; r=-0.71, $p<0.05$, respectively), Table 27. Again, the diversity of lip pursing movements around the vicinity of the corner of the mouth affected the correlation between the subjective grades and the objective measurements at the corner of the mouth, especially the agreement of direction (GI16, 43.75%, Table 28). The grades of directional severity were highly correlated with the objective measurement. We would suggest observing the asymmetries of the lower lip and corner of the mouth when assessing the lip purse expressions of the patients.

The clinical evaluation of the direction of dynamic asymmetry during lip pure showed high agreement between assessors. Table 28 showed 75% agreement between the clinical assessment and the mathematical measurements at the cheek, nasolabial, upper lip, and lower lip regions. Moderate agreement was detected between the clinical assessment and the mathematical measures at the corner of the mouth (43.75%). The lower agreement of directionality at the corner of the mouth, similar to the smile expression, may suggest the dynamics of the corner of the mouth is not a strong indicator of the primary direction of asymmetry.

The clinical observation of facial movements during lip purse appears a sensitive clinical indicator of circumoral muscular dysmorphology of the upper lip, lower lip, and corner of mouth regions (actions of buccinators as well as the orbicularis oris muscles). The evaluation of the directionality of lip movement is important and has been shown accurate and sensitive at the lower lip (GI16 agreement 75%, GI17 severity: significant correlation between the clinical assessment and the objective r=-0.66), Table 28. Therefore, it should be considered especially in the prospect of facial reanimation surgery where the new nerve supply (cross facial nerve graft, masseter nerve, hypoglossal nerve) would empower the muscular actions in the active state, which affects the directional asymmetry (Klebuc & Shenaq, 2004).

Assessment of Cheek Puff (MSB 7, GI 18-21)

The clinical evaluation of cheek puff using the modified Sunnybrook index (MSB7) was focused on the subject’s ability to achieve oral seal. Parameter 19 of GI assessed the magnitude of cheek movement. The clinical scores MSB7, GI19 showed a general lack of statistically significant correlations with the mathematical measurements, Table 30.

The evaluation of functional impairment in cheek puff is manifested by the lack of oral seal due to the dysfunction of the Orbicularis Oris muscle, whereas movement asymmetry is observed primarily in the cheek region, at the nasolabial fold, the upper lip, the lower lip, the corner of the mouth and the chin region. This is due to the altered contraction of the buccinator muscle, risorius, zygomaticus major, and zygomatic minor muscles to achieve the maximum expansion of the cheek. The assessment criteria amalgamated both the asymmetric movement and functional distortion which confuses the grading hence the poor correlation with the mathematical measurements.

Statistically significant correlations were detected between both MSB7, GI19, and asymmetry scores at the corner of the mouth (Coefficient of correlations r=-0.52 for both), Table 30. MSB7 showed a significant correlation to asymmetry scores at the cheek region (r=-0.69). GI19 showed a significant correlation to mathematical scores at the lower lip (r=-0.52). Therefore, the clinical observation of facial movements during cheek puff is a sensitive clinical indicator of muscular dysmorphology of the cheek, corner of the mouth, and lower lip regions.

The assessment of the direction of asymmetric movement showed the highest level of agreement with the objective measurements in comparison to other facial expressions, Table 31. This was especially the case with the agreement with the mathematical scores of the cheek, nasolabial, upper lip, and lower lip (93.75%). This is due to the predominant asymmetry in the mediolateral direction. That is the maximum lateral expansion of soft tissues by air pressure during cheek puff and the inability to achieve an oral seal, Figure 60.

Figure 60: Case Demonstration - Cheek Puff

Figure 60 provides a case demonstration of unilateral facial palsy patient. L: The face at rest, R: the face at the maximum expression at cheek puff without the ability to achieve oral seal.

Interestingly, the grading of cheek puff using GI scores was the least reproducible expression, Figure 40. The GI for the assessment of the severity of facial dysmorphology during cheek puff (GI21) was excluded following the Glasgow indexing test 2, Table 18. The difficulty in the clinical evaluation of cheek puff may be further complicated by the contrasting degree of dynamic dysmorphology among the cases. We noted some improvement of facial asymmetry with cheek puff in some cases and its deterioration in others, Figure 61.

Figure 61: Case Demonstration - Cheek Puff

Figure 61 demonstrates two cases of unilateral facial palsy. The top images feature the resting facial dysmorphology. The bottom images showing facial asymmetry at the maximum expression at cheek puff. On the left side, asymmetry at cheek puff deteriorated from rest. On the right side, the performance of cheek puff improved facial symmetry from rest.

The parameter 7 of MSB evaluates the asymmetry of the cheek puff. The consistency between the 7 assessors was the lowest of the 8 parameters of this grading index (ICC=0.44), Table 9. The correlations between the MSB7 and objective assessments were high at cheek region only (r=-0.69, $p<0.05$), Table 30. This is interesting since we thought that the assessors would focus their attention on the lips when they observed the cheek puff of the patients. In fact, the oral function of achieving oral seal highly reflected the asymmetry of the cheek puff.

Parameters 18 to 21 of the Glasgow indexing are the assessments at facial regions of the patients at cheek puff; only the grades at the corner of the mouth and lower lip showed moderate correlations to the objective measurements, Table 30, Table 31. The symmetry of the cheek puff is multifactorial and depends on the harmony between the movements of various groups of muscles, muscular tonicity, as well as facial nerve function (Cattaneo & Pavesi, 2014). The cheek puff is a difficult expression to perform if the patients could not seal their lips. Observing the cheek may not grasp the severity of the asymmetry caused by the facial palsy in cheek puff. Furthermore, oral competence in cheek puff relies on other features such as dentition and lip height, not just facial nerve strength. We think that the muscle movements of individual patients who achieved the cheek puff expression were different depending on their own nerve and muscle malfunctions. We could suggest observing the corner of the mouth and lower lip.

Assessment of Eyebrow Raising (MSB 4, GI 22-25)

The raising of the eyebrow starts with the primary contraction of the frontal head of the occipitofrontalis muscles to wrinkle the forehead skin which elevates the eyebrows; the action of which extends over two facial regions, the forehead and eyes.

The MSB4 assessed the eyebrow-raising and the wrinkles of the forehead. The GI parameter 23 assessed the magnitude of eyebrow movement.

The temporal branch of the facial nerve innervates the frontal head of the occipitofrontalis muscle, weakness or paralysis of the muscle is responsible for the asymmetric movements in unilateral facial paralysis. The correlations of the modified Sunnybrook index parameter 4 to measurements of the asymmetry in the regions of the forehead (r=-0.41, $p>0.05$) and eyes (r=-0.40, $p>0.05$) were not significant, Table 33. The moderate correlation is due to a mismatch between what the assessors graded, the wrinkles on the forehead, and the mathematical measurements of forehead asymmetry. Although the wrinkles were related to the eyebrow-raising the mathematical representations of the appearance of wrinkles and the surface motions at the forehead may not be the same. The grading of the frontal wrinkling may have misled the objectives assessment of the forehead region (forehead wrinkling), this should have been focused on the clinical evaluation of the eyebrows. The asymmetric raising of the eyebrow due to unilateral facial paralysis may or may not fully reflect on the asymmetry of the wrinkles of the forehead (Figure 62 and Figure 63).

Similarly, the correlations between the subjective grading of GI23 and the measurement of the asymmetry of forehead and eyes were not significant, Table 33. There was poor agreement between the subjective grades of the directions of asymmetry and the objective measurements. Nevertheless, in forehead, there was a moderate correlation between the subjective assessment of the severity of the directional asymmetry and the corresponding mathematical measurements (GI25) of eyebrow raising (r=-0.56, $p<0.05$), Table 34. Observing the 4D movement of the peak of the eyebrow may provide a more realistic measure of the asymmetric movement of this anatomical region.

Figure 62: Case Demonstration - Eyebrow Raising

Figure 63: Case Demonstration - Eyebrow Raising

Figure 62 and Figure 63 provide case demonstration of 8 unilateral facial palsy patients. Top images: The face at rest. Bottom images: associated movements at eyebrow raising.

Figure 64: Patterns of Facial Asymmetry - Eyebrow Raise

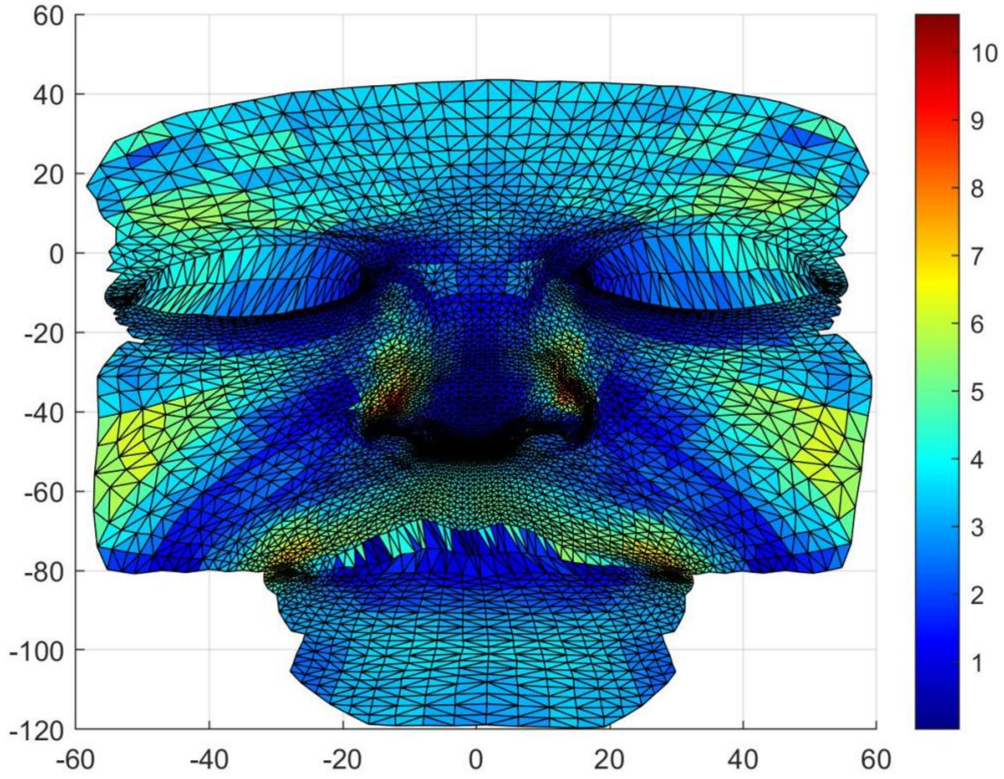


Figure 64 shows the distance patterns of the mean facial asymmetry (global asymmetry) at eyebrow raise of one of the cases of the unilateral facial palsy presented in Figure 63 (The male participant). The colour code ranges from blue colour (1) to red colour (10). The blue colour indicates perfect symmetry due to the minimal difference in the mean absolute distance between the vertices of the 3D images and its corresponding reflections. The changing colour from deep blue to yellow indicates an increase in the magnitude of facial asymmetry which was mainly at the eyebrow.

Assessment of the aesthetics of the orbital complex and brow positioning is important for the management of brow ptosis which determines the choice of brow-lifting procedure (Paskhover & Teti, 2021).

(Zandi et al., 2021) investigated the impact of upper lid blepharoplasty on the forehead and glabellar lines for cosmetic improvement in healthy subjects, Figure 65. The assessment was based on the measurements of the distance between the mid-brow to hairline (MBHLD) and the inter-brow distance (IBD) before surgery and, 3 and 6 months thereafter to assess the role of upper lid blepharoplasty on the probable reduction of forehead wrinkles. There was a significant difference in the baseline measurements in comparison to the 3- and 6-months measurements. However, the clinical assessment of the aesthetics of forehead wrinkles was subjective and based on the evaluation of the 2D clinical photographs.

Figure 65: The Clinical Assessment of Forehead and Glabellar Lines

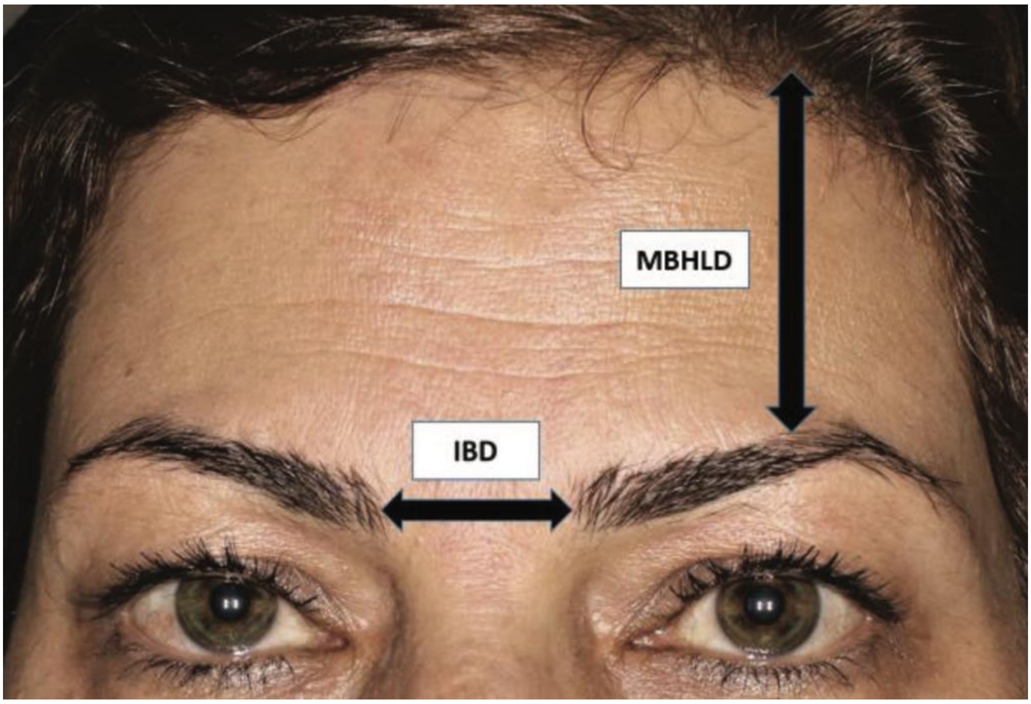


Figure 65. Assessment of forehead and glabellar lines based on the distance between the mid brow to hair line (MBHLD), and the inter-brow distance (IBD), (Zandi et al., 2021).

Stereophotogrammetry provides the current golden standard in the recording of facial morphology, however, the imaging of the eyes and the circumorbital region is challenging due to the reflective surface of the cornea and the difficulties in tracking the 4D imaging of the hair (Gibelli et al., 2019). In this study, the segmentation of the forehead region removed the hairline from the 4D captured data to standardise the assessment and minimize the imaging error.

Assessment of Eye Closure (MSB 5, GI 26-29)

Eye closure is the primary action of the orbicularis oculi muscle. The contraction of the palpebral part of the orbicularis closes the eyelid gently. Forceful eye closure involves the contraction of the orbital part of the orbicularis muscle. Different nerve branches innervate these regions, the upper part of the orbicularis muscle is innervated by the temporal branch of the facial nerve whereas the lower part is innervated with the zygomatic branch. Altered facial nerve function affects the ability to close the eye which increases the risk of corneal inflammation and ulceration. Therefore, the clinical evaluation of eye closure is primarily concerned with the ability to achieve eye closure with consideration to the muscular efforts involved (gentle vs forceful eye closure) (Homer & Fay, 2018).

The MSB5 graded patient's ability to close the eyes considering the remaining gap between the eyelids. The GI27 assessed the magnitude of eye movement on a 4-point Likert scale. The clinical assessments showed significant correlations with the mathematical scores at forehead (MSB5 r=-0.67, $p<0.05$; GI27 r=-0.71, $p<0.05$) and eyes region (MSB5 r=-0.60, $p<0.05$; GI27 r=-0.53, $p<0.05$), Table 36. A stronger correlation was detected between the asymmetry scores and the mathematical measurements of the forehead region rather than the eye region. This could be attributed to the difficulty in tracking movements due to the reflective surface of the cornea and the errors in recording eyelashes, Figure 66. In this study, 4D analysis of facial movements was based on the optical flow algorithm (Kondermann et al., 2012) that tracked the movements of the dense surface models over time. The eye closure may result in tracking errors of the DSM vertices in the eye region due to eyelash occlusion. These challenges are well recognised, these may be circumvented with segmentation and tracking of the region of interest "ROI" (Liu et al., 2020), facial contour extraction and key landmark detection (Barbosa et al., 2016). Further investigations of the details of recording eye movements are needed to improve the capture and analysis of eye movements.

Figure 66: Case Demonstration - Artifact of 4D Capture

Figure 66 provides a demonstration of the poor 3D capture quality of the eyes.

Due to the artefacts of 4D images, there was no agreement in directions of asymmetry between the subjective grades and objective measurements of eye closure. Nevertheless, there was a moderate correlation in directional severity of asymmetry of the forehead region (GI29 r=-0.44, $p<0.05$, Table 37).

The lack of significant correlations in directional severity of asymmetry between the clinical assessment and the mathematical measurement of the eye region (GI29 r=-0.44, $p>0.5$, Table 37) may be due to the complex facial muscle movements caused by involuntary contractions or by the patient's inability to coordinate the designated movement. The skin over the temple, cheek, and forehead regions are involved in the forceful eye closure. This produces significant dynamic asymmetry that predominates clinical decisions. An example is provided in Figure 67.

Figure 67: Case Demonstration - Eye Closure

Figure 67 shows a case demonstration of unilateral facial palsy patient. L: The face at rest, R: associated with movements at the temple, cheek, and forehead regions.

This is further demonstrated by the mathematical modeling of facial asymmetry at eye closure of the same patient, Figure 68.

Figure 68: Patterns of Facial Asymmetry - Eye Closure

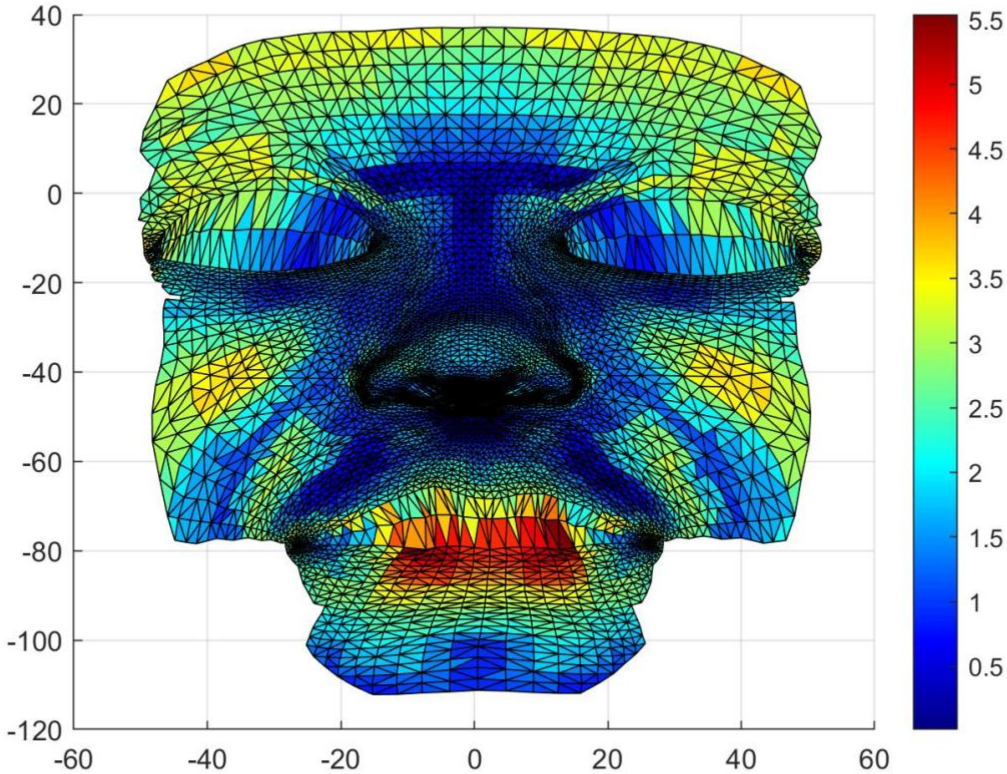


Figure 68 shows the distance patterns of the mean facial asymmetry (global asymmetry) at eye closure of the unilateral facial palsy patient presented in Figure 67. The colour code ranges from blue colour (0.5) to red colour (5.5). The blue colour indicates perfect symmetry due to the minimal difference in the mean absolute distance between the vertices of the 3D images and its corresponding reflections. The changing colour from deep blue toward red indicates an increase in the magnitude of facial asymmetry.

The assessment of eye closure is particularly important in facial palsy, in which, the facial nerve weakness extended beyond the inability of achieving complete eye closure. The priority of patient care is the preservation of eye function and that includes protecting the exposed ocular surface to maintain sight and optimal eye health, in addition to aesthetic aspects of the treatment. The lack of a universal ophthalmic grading system of facial palsy is well documented in the literature (Ziahosseini et al., 2015).

In a recent review of literature, (Zaidman et al., 2021) investigated the current assessment methods of eye closure and blink in facial palsy. Most of the reported assessment methods were based on the subjective evaluation of the eyes using the House-Brackmann Facial Nerve Grading Scale and Sunnybrook Facia Nerve Grading System. The two scales provide a general assessment of facial nerve palsy and therefore are of limited ability to accurately assess eye closure, blink, and the associated dysfunction in facial palsy, especially following surgical rehabilitation. The more specific methods included the Terzis and Burno scoring system for eye closure and blink (Table 39), the blink ratio, and the eFACE electronic clinician-graded scoring system, Figure 69. The authors recommend the eFACE scoring system as the most comprehensive available method (assessment of resting state, dynamic movements, synkinesis) to be used in conjunction with patient-reported quality of life.

Table 39: Scoring System of Eye Closure and Blink

Terzis and Burno scoring system 2002, (Terzis & Bruno, 2002)			
Group	**Grade**	**Designation**	**Description**
I	1	Poor	No blink
II	2	Fair	Minimal blink (contraction)
III	3	Moderate	Initiation of blink present but only one-third amplitude
IV	4	Good	Some coordinated blink but only two thirds amplitude
V	5	Excellent	Synchronous and complete blink present

Figure 69: The eFACE scoring system

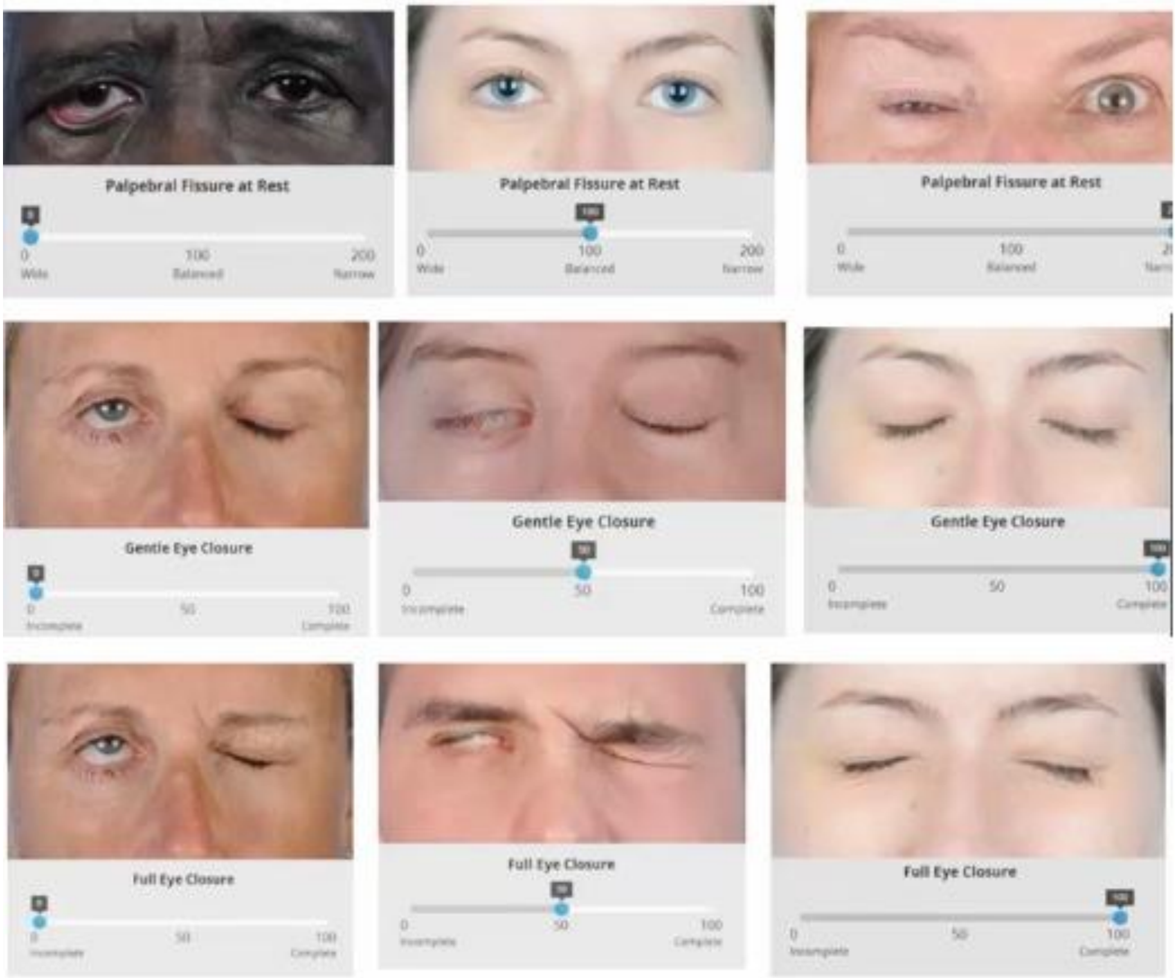


Figure 69. The clinical evaluation of the eyes using the eFACE scoring system, modified from (Banks et al., 2015). Top row: the evaluation of the palpebral fissure width at rest (eFACE scores: 0, wide; 100, balanced; 200, narrow). Middle row: the evaluation of the gentle eye closure (eFACE scores: 0, incomplete; 100, complete eye closure with minimal effort). Bottom row: the evaluation of the forceful eye closure. (eFACE scores: 0, incomplete; 100, complete eye closure with full effort).

The development of the eFACE system (16 items observer-graded analogue scale) was based on the extensive clinical experience of the research group (Banks et al., 2015), in which, a single surgeon assessed 74 subjects with unilateral facial palsy by observing 2D photographs and videos of the patients performing a standardised sets of movements. The software provided the disfigurement scores. This was followed by multiple regression analysis to find the best linear relationship between the expert-determined disfigurement and the eFACE items. Thus, the development of the eFACE considered the clinical grading as the ground truth. The mathematical accuracy of the eFACE gradings to confirm its sensitivity and specificity was not tested. The sensitivity of the eFACE scores was explored in a further study, (Greene et al., 2019), in which, the assessment of facial function in fifty-three unilateral facial palsy patients following eyelid weight placement was carried out using the eFACE system and a newly developed machine learning algorithm (Emotrics). The clinical evaluations of the eyes using eFACE, Figure 69, and the objective measurements using Emotrics (palpebral fissure at rest, with gentle eye closure, with forceful eye closure) were in agreement; both assessments identified a significant improvement in blink function following surgery. The machine learning algorithm (Guarin et al., 2018) enabled the localisation of facial landmarks and the calculation of inter-landmark measurements, Figure 70.

Figure 70: The user Interface of Emotrics

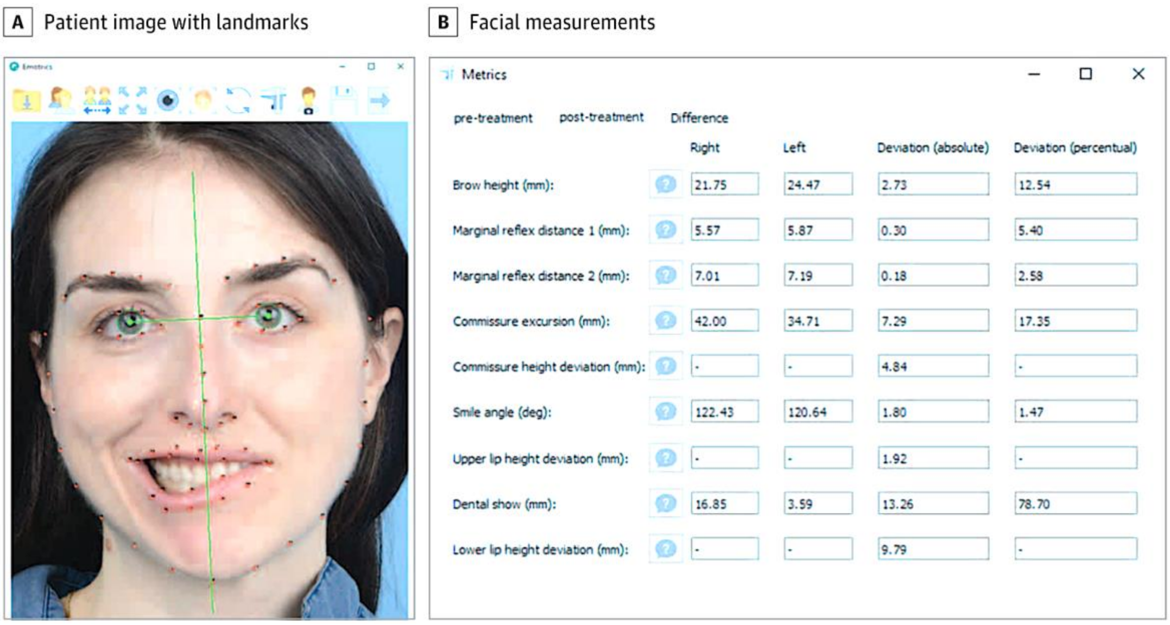


Figure 70. The user interface of Emotrics. A: patient image in the frontal view with 68 annotated landmarks. B: facial measurements provided by the machine learning alghorithm.

The computed measurements were generated from the 2D photographs in the frontal view by scaling the iris diameter to pixel width in each image. Further enhancement on the machine learning algorithms have been reported (Guarin et al., 2020; Miller et al., 2021), however, the main limitation of this approach is that the training dataset of the machine learning model and the generated measurements are based on 2D imaging of still photographs, Figure 71. The 2D measurements have been shown to underestimate the magnitude of movements by 43% (Gross et al., 1996). Furthermore, the 2D analysis could not measure the anteroposterior direction of movement in comparison to the 3D analysis (Katsumi et al., 2015).

Figure 71: Standardised Series of Facial Images in Facial Palsy

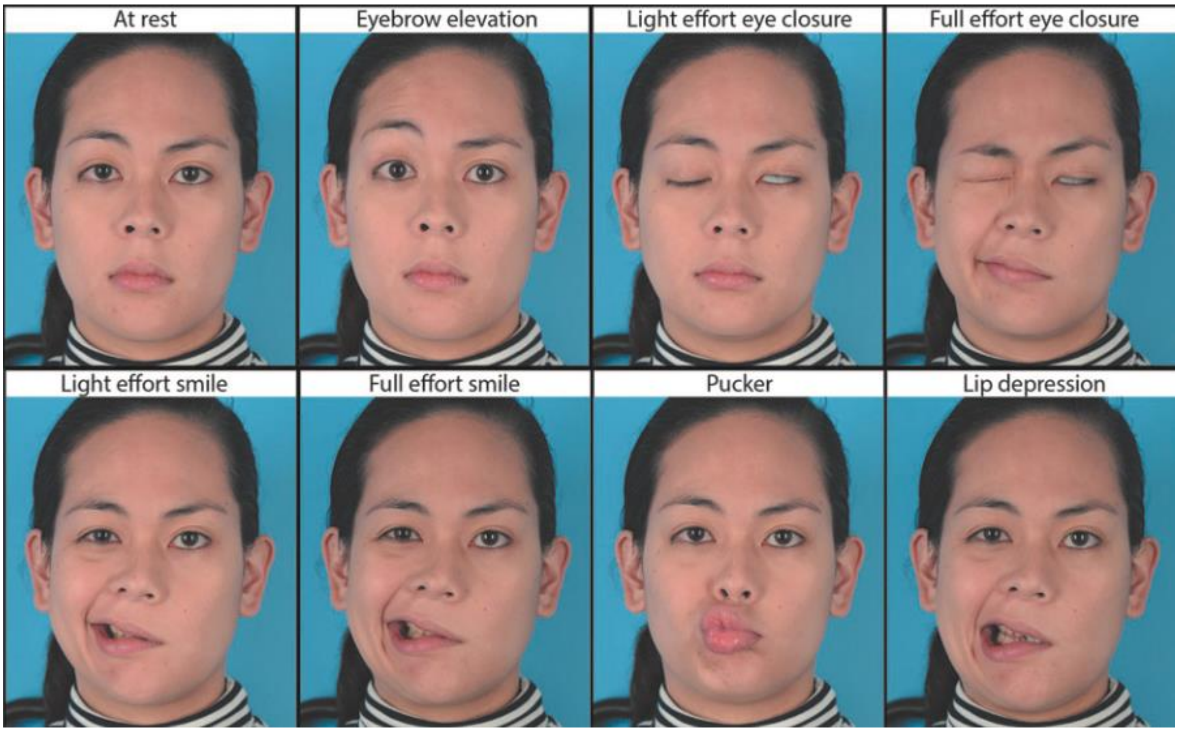


Figure 71. The standardised set of 8 facial expressions utilised to evaluate facial mimetic function.

Summary

The accuracy of the facial asymmetry calculation depends on the accuracy of point tracking and motion variations within the defined region. The accuracy of point tracking has been validated in the previous studies, which has errors less than 0.55mm. The 4D images are reliable for the recording and measurement of facial asymmetry in most facial regions. Stereophotogrammetry system has inherent limitations in capturing the shape of surfaces with repeated patterns or of reflective surfaces; the 4D images are distorted around the eyeballs and hairy regions. The correlation coefficients calculated between the subjective assessment and the mathematical measurements of the asymmetry of these areas are less reliable.

The six measured values of asymmetry were related to the subjective grades. The minimal value of the facial asymmetries of the rest expression had a higher magnitude of correlation coefficients than that of other values. The mean and median values had stronger correlation coefficients than that of the other values with the subjective grading of the other five nonverbal expressions. The reason of the minimal value of asymmetry had a higher correlation in rest is that the assessors were instructed to assess the facial asymmetries in the rest expression and the blinking of eyes and twitching of corners of the mouth were ignored but these higher asymmetry motions were recorded in 4D image sessions. The mean and median values of the mathematical calculation of asymmetries had stronger correlation coefficients with the subjective evaluations of the other non-verbal expressions. The maximum values may only represent the worst facial dysmorphology which may only exist in a fractional time of the entire expression. The maximal asymmetry of various facial regions might not appear simultaneously, further investigations are needed to confirm this assumption.

The selections of facial asymmetry at ten facial regions, and the minimal value in rest and mean and median values in motions are reliable measures to correlate with the subjective grading.

The modified Sunnybrook index consists of 8 parameters where the first three parameters were subjectively assessed in rest expression and the other 5 parameters were subjectively assessed in non-verbal expressions. The MSB index assessed the eye, cheek, and mouth regions in static and five facial motion states to grasp the major defects of the facial muscle activities influenced by facial paralysis.

Assessment of facial asymmetry at rest:

In the modified Sunnybrook index, the three parameters at rest showed high correlations at the cheek (MSB2 r=-0.76) and the upper lip (MSB3 r=-0.69) but lower correlations at the eye region (MSB1 r=-0.42).

The Glasgow indexing consists of 29 parameters, the detailed assessments in 10 key facial regions at six expressions provided more detailed information regarding facial paralysis, which would provide guidelines for clinicians to diagnose the nerve and muscle activities related to facial palsy.

The first 6 rest parameters of the Glasgow index showed high correlations at the full face (GI1 r=-0.81), forehead (GI2 r=-0.72), nose (GI4 r=-0.69), nasolabial fold (GI4 r=-0.85), cheek (GI5 r=-0.84), and at the corner of the mouth (GI6 r=-0.79) but lower correlation at the eye region (GI3 r=-0.49).

Assessment of the smile:

The correlations between the objective measurements and the clinical assessments showed significant correlations at the relevant regions (MSB6 r=-0.67 at cheek, GI8 r=-0.73 at cheek, GI10 r=-0.60 at nasolabial region). The clinical evaluation of the main direction of asymmetry (GI11) and the grading of the severity of asymmetry (GI12) at maximum smile showed significant correlations with the mathematical measures of asymmetry at the cheek, nasolabial fold, upper and lower lip.

Movement at the modiolus does not always correlate with overall facial animation, but it is commonly used as an assessment of the success of the surgery. We think that it is easier to observe the upper lip and the cheek instead of the corner of the mouth when assessing the smile of the patients based on the results of the correlations of the smile.

Assessment of lip purse:

The clinical observation of facial movements during lip purse appears a sensitive clinical indicator of circumoral muscular dysmorphology of the upper lip (MSB8 r=-0.65, GI14 r=-0.61, GI15 r=-0.61), lower lip (MSB8 r=-0.62, GI14 r=-0.62, GI15 r=-0.53), and corner of mouth regions (MSB8 r=-0.62, GI14 r=-0.63, GI15 r=-0.55). We would suggest observing the asymmetries of the lip and corner of the mouth when assessing the lip purse expressions of the patients. The evaluation of the directionality of lip movement has been shown accurate and sensitive at the lower lip.

Assessment of cheek puff:

Regarding the Glasgow Index, observing the cheek may not grasp the severity of the asymmetry caused by the facial palsy in cheek puff. We would suggest observing the corner of the mouth and lower lip in cheek puff expressions.

Assessment of eyebrow raising:

In the motion of eyebrow raising, the correlations of the clinical indices to the mathematical measurements of facial asymmetry were not statistically significant.

- We suspected that the instruction to grade the eyebrow raising might not coincide with the mathematical representation of facial asymmetry.
- The grading of face function during eyebrow wrinkling may have misled the objectives assessment to the forehead region (forehead wrinkling) rather than the eyebrow region (eyebrow-raising).

Based on the colour maps of facial asymmetry at eyebrow raising, we may suggest observing the 4D movement of the peak of the eyebrow. This requires further investigations.

Assessment of eye closure:

The clinical assessment of the eyes based on 4D image data was not ideal due to the 4D imaging defects on the reflective surface of the cornea. Further investigations of the details of eye movements captured in 4D images are needed to see if the artefacts in the eyes can be avoided in 4D images.

The parameters of GI have more descriptions to match the asymmetry measurements, therefore, it showed a stronger correlation with the mathematical measurements than that of the 8 parameters of MSB. The Glasgow indexing is more specific and descriptive to the measured asymmetry. The assessors had difficulties in assessing the directions of the asymmetry of certain expressions.

The subjective assessments of the upper lip and the cheek are less challenging than the grading of the asymmetry of the corner of the mouth.

The assessment of the directionality of the asymmetry is particularly important for the following clinical scenarios:

- The evaluation of facial contours (cheek asymmetry in the anteroposterior direction), especially in cases where facial reanimation surgery by means of free muscle flaps is indicated.
- The evaluation of face drooping (eyebrow asymmetry in the vertical direction). The static support procedures are mainly concerned with restoring symmetry at rest by means of fascia slings, eyebrow lift, and face-lift procedures.
- The evaluation of regional asymmetries. The study showed examples of facial dysmorphology at the nasolabial regions adversely affecting symmetry in the adjacent regions. This is particularly relevant to the corner of the mouth in cases where surgical repositioning may be indicated.

Conclusions and Future Work

Conclusions

1- The objective assessment of dynamic facial asymmetry in facial palsy

- ◊ The mathematical assessment of the dynamics of facial expressions in unilateral facial palsy using advanced geometric morphometrics provides a state-of-art approach for the quantification and visualization of facial dysmorphology. It allows the accurate measurement of asymmetry at individual facial regions to underpin the contribution of each group of facial muscles and the asymmetry of expressions.
- ◊ The patterns of facial asymmetry of individual facial palsy patients demonstrated the importance of applying the mathematical measurements of the 3D facial dysmorphology and the associated dynamic asymmetry to complement the clinical assessments. The stratification of facial asymmetry in the mediolateral, vertical, and anteroposterior directions provided new insights into the impact of facial palsy on facial symmetry.

2- The subjective evaluation of abnormal facial movements in facial palsy

- ◊ The introduced clinical grading indices of the asymmetric facial expressions in unilateral facial palsy were reproducible; the indexing method of the modified Sunnybrook system and, the Glasgow indexing. The clinical assessors were reasonably consistent in the grading of facial palsy.

3- The correlation between the objective and subjective assessments of facial palsy

- ◊ The significant correlations between the clinical grading of facial palsy and the mathematical calculation of the same facial muscle movements provided satisfactory evidence of objectivity to the clinical assessments.
- ◊ The correlation coefficients between the clinical assessments of facial dynamics (Five MSB parameters and 20 GI parameters) and the mathematical calculations of the same regions regarding asymmetry and directional asymmetry showed a large range of variations, especially for GI parameters assessing the directionality of asymmetry and its severity at the 5 facial expressions.
- ◊ The Glasgow indexing has higher magnitudes of correlation coefficients than that of the modified Sunnybrook index grades because the Glasgow indexing is more specific, defined, and reflects the asymmetry measurements in 4D imaging, but the assessors had difficulties in assessing directions in the Glasgow indexing.

Suggestion for Future Studies

- The multicentre validation of the clinical indices would be essential before their universal utilization to quantify and monitor the dynamic dysmorphology of facial palsy.

- The mathematical quantification of the magnitude, speed, and motion path of facial movements during facial expressions would facilitate the characterization of facial dysmorphology of individual cases. This may be employed to quantify the deviation of individual facial dysmorphology of facial palsy patients from normalcy.

- The notion of a smartphone app-based grading of facial movements is promising (Taeger et al., 2021). The availability of the true-depth smartphone camera paves the way for the 3D assessment of facial morphology. In that regard, the 4D data of facial palsy and the control group would be utilised for the development of the mathematical index of facial muscles movements. The development of a machine learning model of 4D data would allow the automatic assessment of the facial morphology of the images captured by the smartphone's true-depth camera.

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Appendices

Appendix A: Facial Palsy Subjective Clinical Grading Systems

Grading System 1: Botman and Jonkees Scale 1955

Botman and Jongkees Scale 1955	
Class	**Signification**
0	Normal facial activity
I	Light paresis: normal at rest, talking normal, the eyes can be closed, some dissymmetry in laughing and whistling
II	Moderate paresis: normal at rest; asymmetry in talking and laughing; the eyes cannot be closed
III	Severe paralysis: asymmetry at rest, dysfunction in movements
IV	Total paralysis: no tone, total loss of function. Contracture of the muscles may result in apparent improvement, and degeneration atrophy may cause a more serious defect

Grading System 2: Janssen Scale 1963

Janssen Scale 1963			
Category	**Estimation of function 0-100 %**	**Multiplied by weighting factor**	**Points**
Face at rest	%	0.3	
Forehead	%	0.1	
Eye closure	%	0.3	
Mouth	%	0.3	
			Total points %

Grading System 3: May Scale 1970

May Scale 1970				
		Normal	**Weak**	**Absent**
1	Tone	10	5	0
2	Wrinkle forehead	10	5	0
3	Close eye tightly	10	5	0
4	Blink	10	5	0
5	Wrinkle nose	10	5	0
6	Grin	10	5	0
7	Whistle	10	5	0
8	Blow out cheeks	10	5	0
9	Depress lower lip	10	5	0
10	Tense neck	10	5	0
		100%	50%	0%

Grading System 4: Adour and Swanson Scale 1971

Adour and Swanson Scale 1971					
Site	**Percentage of points assigned to each unit of recovery**				
	0	1-25%	25-50%	50-75%	75-100%
Forehead	0	+1	+1	+2	+2
Eye	0	+1	+2	+3	+4
Mouth	0	+1	+2	+3	+4

Grading System 5: Pietersen Scale 1976

Pietersen Scale 1976	
Grade	**Deficit**
0	No associated movements (no palsy – normal function of facial muscles)
I	Slight palsy and contracture less than 1 mm (just visible) without associated movements
II	Moderate palsy with clearly visible contracture and associated movements
III	Severe palsy with disfiguring contracture and associated movements
IV	Complete atonic facial palsy without contracture and associated movements

Grading System 6: Yanagihara Scale 1977

Yanagihara Scale 1977						
	Expression	**Evaluation** Full paralysis to Normal				
1	At rest	0	1	2	3	4
2	Wrinkle forehead	0	1	2	3	4
3	Blink	0	1	2	3	4
4	Closure of eye lightly	0	1	2	3	4
5	Closure of eye tightly	0	1	2	3	4
6	Closure of eye (on involved side only)	0	1	2	3	4
7	Wrinkle nose	0	1	2	3	4
8	Whistle	0	1	2	3	4
9	Grin	0	1	2	3	4
10	Depress lower lip	0	1	2	3	4

Grading System 7: Stennert Scale 1977

Stennert Scale (Facial Palsy Score) 1977		
Parameter being evaluated	**Value**	☐
Resting tone		
Difference between palpebral fissures	≥ 3mm	☐
Ectropion	Yes	☐
Loss of nasolabial sulcus	Yes	☐
Drop of angulus oris	≥ 3mm	☐
Motility		
Frowning (≤ 50% of normal side)	Not possible	☐
Incomplete lid closure		
Slight innervation (as in sleep)	Yes	☐
Maximal innervation	Yes	☐
Exposure of teeth		
Canine teeth upper and lower	Not visible	☐
2nd upper incisor (full width)	Not visible	☐
Whistling (decrease in distance between philtrum and angulus oris compared with normal side)	< 50%	☐
Facial Palsy Score =	Number of ☐ x 10	
Stennert Scale (Secondary Defect Score) 1977		
Secondary Defects	**Value**	☐
Hyperacusis	Yes	☐
Gustation impaired	Yes	☐
Synkinesis >3 areas	Forehead, eye, nasolabial sulcus, corner of mouth, chin	☐
Spasm	Present Strongly present Inconvenient	☐ ☐ ☐
Lacrimation	<30%, <30% +incomplete lid closure 0%	☐ ☐ ☐
Contracture	Present	☐
Crocodile tears	Present	☐
Secondary Defect Score =	Number of ☐ x 10	

Grading System 8: Fisch Scale 1981

Fisch Scale 1981						
Symmetry of Face			**Secondary Defects**			
	%	Points		Slight	Moderate	Sever
At rest	0	0				
	30	6	Epiphora	1	2	3
	70	14				
	100	20	Gustatory lacrimation	1	2	3
Wrinkling forehead	0	0				
	30	3	Ageusia	1	2	3
	70	7				
	100	10	Dysacusis	1	2	3
Closing eyes (slight and tight)	0	0				
	30	9	Nasal obstruction	1	2	3
	70	21				
	100	30	Pain	1	2	3
Smiling	0	0				
	30	9	Tension	1	2	3
	70	21				
	100	30	Synkinesis	1	2	3
Whistling	0	0				
	30	3	Spasm	1	2	3
	70	7				
	100	10	Contraction	1	2	3

Grading System 9: House and Brackmann 1985

House and Brackmann 1985	
Grade	**Characteristics**
I	Normal facial function in all nerve branches
II	Gross: slight weakness noticeable on close inspection; may have very slight synkinesis. At rest: normal symmetry and tone. Motion: Forehead: moderate to good function Eye: complete closure with minimum effort Mouth: slight asymmetry
III	Gross: obvious but disfiguring difference between 2 sides: noticeable but not severe synkinesis, contracture and/or hemi facial spasm. At rest: normal asymmetry and tone. Motion: Forehead: slight to moderate movement Eye: complete closure with effort Mouth: slightly weak with maximum effort
IV	Gross: obvious weakness and/or disfiguring asymmetry. At rest: normal asymmetry and tone. Motion: Forehead: none Eye: incomplete closure Mouth: asymmetric with maximum effort
V	Gross: only barely perceptible motion. At rest: asymmetry. Motion: Forehead: none Eye: incomplete closure Mouth: slight movement
VI	No movement

Grading System 10: Smith Scale 1992

Smith Scale 1992		
	Scale	**Areas to Grade**
0	No function	0 to IV Repose
I	0 to 25% function	0 to IV Forehead and wrinkle
II	25 to 50% function	0 to IV Eye
III	50 to 75% function	0 to IV Mouth
IV	75 to 100% function	

Grading System 11: Sydney Facial Grading System 1995

Sydney Facial Grading System 1995	
Facial Nerve Branch	**Voluntary Movement**
(T): Temporal	Forehead raise / frown
(Z): Zygomatic	Eye closure
(B): Buccal	Nose wrinkle, pout & smile – Upper mouth & cheek
(M): Marginal Mandibular	Lips pulled down – Chin region
(C): Cervical	Platysma
Facial Movement	**Synkinesis of the Overall Face**
Normal = 3/3	Sever = 3/3
Moderate = 2/3	Moderate = 2/3
Mild = 1/3	Mild = 1/3
No movement = 0/3	No synkinesis = 0/3
	Score 0 1 2 3
T	
Z	
B	
M	
C	
Synkinesis	

Grading System 12: Sunnybrook Facial Grading System 1996

Sunnybrook Facial Grading System 1996		
Parameter	**Finding**	**Point Value**
Resting symmetry score		
Eye	Normal or abnormal	0 or 1 points
Cheek (nasolabial fold)	Normal, altered, or absent	0 or 1 or 2 points
Mouth	Normal or abnormal	0 or 1 points
Voluntary movement score		
Forehead wrinkle	No movement to normal	1 to 5 points
Gentle eye closure	No movement to normal	1 to 5 points
Open mouth smile	No movement to normal	1 to 5 points
Snarl	No movement to normal	1 to 5 points
Lip pucker	No movement to normal	1 to 5 points
Synkinesis score		
Forehead wrinkle	None, mild, moderate, or severe	0 to 3 points
Gentle eye closure	None, mild, moderate, or severe	0 to 3 points
Open mouth smile	None, mild, moderate, or severe	0 to 3 points
Snarl	None, mild, moderate, or severe	0 to 3 points
Lip pucker	None, mild, moderate, or severe	0 to 3 points
Final score calculation = (sum of resting symmetry points x 5) - (sum of voluntary movement points x 4) - (sum of synkinesis points x 1)		

Grading System 13: FEMA Scale 1998 | Forehead, Eye, Mouth & Associated defects

FEMA Scale 1998 | Forehead, Eye, Mouth & Associated defects					
Grade	**Scale Description**	**F Scale**	**E Scale**	**M Scale**	**A Scale**
0	Normal	F0	E0	Mo	A0
I	Mild	F1	E1	M1	A1
II	Moderate	F2	E2	M1	A2
III	Severe	-	E3	M2	A3
IV	Profound	-	E4	M2	A3
V	Complete	-	E5	M3	A4
Scales Characteristics					
F (forehead) Scale					
F0	Normal function for movement				
F1	Limitation of movement				
F2	No ability of motion				
E (eyelid) Scale					
	Measurement of eye closure at maximum efforts:				
E0	Normal Movement				
E1	Strong, complete eye closure at maximum effort				
E2	Complete but weak eye closure and not wrinkled eyelid at maximum effort				
E3	Incomplete eye closure and movement over 50% at maximum effort				
E4	Incomplete eye closure and movement below 50% at maximum effort				
E5	No movement				
M (mouth) Scale					
	Measurement of lip motion at whistling or pronouncing "Woo"				
M0	Movement as same distance of normal side				
M1	50-99% of normal side				
M2	1-49% of normal side				
M3	No movement				
A (associated defect, symmetry and secondary defects) scale					
A0	Unable to make distinction from normal side				
A1	Symmetry at rest but asymmetry on motion, no secondary defect				
A2	Symmetry at rest but asymmetry on motion, synkinesis or muscle spasm				
A3	Asymmetry at rest and synkinesis or muscle spasm				
A4	Asymmetry at rest and muscle atrophy				

Grading System 14: MoReSS System 2006

MoReSS System 2006			
Movement (Mo) 0-3	**Rest (Re)** 0-2	**Secondary defects (S)** 0-6	**Subjective (S)** 0-10
0 = No disorder	0 = No asymmetry	(a) Synkinesia	0 = no complaints
1 = Mild disorder (Movement almost complete)	1 = Mild asymmetry	(b) Hemifacial spasm	10 = serious complaints
2 = Serious disorder (Slight movement)	2 = Serious asymmetry	(c) Contracture	
3 = No movement		(d) Crocodile tears	
		(e) Hyperacusis	
		(f) Dysgeusia	

Region	**Mo**	**Re**	**S (Secondary defects)**	**S (Subjective)**
(a) Forehead	0-3	0-2		
(b) Eye	0-3	0-2		
(c) Midface	0-3	0-2		
(d) Lower lip	0-3	0-2		
Total Score	0-12	0-8	0-6	0-10

Movement	The degree of movement of the four facial regions is assessed in comparison to the non-paralytic side
Forehead	(a) = Forehead raise / frowning
Eye	(b) = Complete closure
Midface / cheek /upper lip	(c) = Showing upper teeth / smiling
Lower lip / chin region	(d) = Asymmetry of the corner of the mouth / chin

Rest	Assessment of the degree of symmetry at rest comparing the non-paralytic and the paralytic side
Forehead	(a) = Wrinkles / brow
Eye	(b) = Width of eye slit
Midface /cheek / upper lip	(c) = Nasolabial fold
Lower lip / chin region	(d) = Asymmetry of the corner of the mouth / chin

Grading System 15: Facial Nerve Grading System 2.0 2009

Facial Nerve Grading System 2.0 2009				
Region				
Score	**Brow**	**Eye**	**Nasolabial Fold**	**Oral**
1	Normal	Normal	Normal	Normal
2	Slight weakness >75% of normal	Slight weakness >75% of normal. Complete closure with mild effort	Slight weakness >75% of normal	Slight weakness >75% of normal
3	Obvious weakness >50% of normal Resting symmetry	Obvious weakness >50% of normal Complete closure with maximal effort	Obvious weakness >50% of normal Resting symmetry	Obvious weakness >50% of normal Resting symmetry
4	Asymmetry at rest <50% of normal.	Asymmetry at rest <50% of normal Cannot close completely	Asymmetry at rest <50% of normal	Asymmetry at rest <50% of normal
5	Trace movement	Trace movement	Trace movement	Trace movement
6	No movement	No movement	No movement	No movement
Secondary movement (global assessment)				
Score		**Degree of movement**		
0		None		
1		Slight synkinesis; minimal contracture		
2		Obvious synkinesis; mild to moderate contracture		
3		Disfiguring synkinesis; severe contracture		
Reporting: sum scores for each region and secondary movement				
Grade		**Total score**		
I		4		
II		5-9		
III		10-14		
IV		15-19		
V		20-23		
VI		24		

Grading System 16: The Rough Grading System 2013

The Rough Grading System 2013	
Grade	Characteristics
I	Normal movement
II	Slight paralyses
III	Frank paralyses with eye closure
VI	Frank paralyses without eye closure
V	Almost complete paralyses with only slight movements
VI	Total paralyses

Appendix B: Marking Sheets

Marking Sheet 1: Facial Expression at Rest

Rest

Case No.

Grade **total facial asymmetry** compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade asymmetry of **forehead wrinkles & eyebrows** compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade asymmetry of **eyes** compared to the non-affected side

I. Severe asymmetry: ectropion, eyelid droop hamper vision
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade asymmetry of **nose & nasolabial fold** compared to the non-affected side

I. Severe asymmetry: loss of nasolabial fold, philtral deviation
II. Moderate asymmetry: flattened nasolabial fold with philtral deviation
III. Mild asymmetry: flattened nasolabial fold with no philtral deviation
IV. No asymmetry

Grade asymmetry of **cheeks contour/tone** compared to the non-affected side

I. Severe asymmetry: complete lack of tone
II. Moderate asymmetry: droop of corner of the mouth with lack of contour
III. Mild asymmetry: droop of corner of the mouth with contour
IV. No asymmetry

Grade asymmetry of **corner of mouth/chin** compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Eye resting asymmetry score compared to non-affected side

I. Abnormal: narrow / wide / eyelid surgery
II. Normal

Nasolabial fold resting asymmetry score compared to non-affected side

I. Absent
II. Altered: less or more pronounced
III. Normal

Corner of mouth resting asymmetry score compared to non-affected side

I. Abnormal: corner dropped or pulled up/out
II. Normal

Marking Sheet 2: Smile Expression

Smile

Case No.

Grade **total dynamic facial asymmetry** of the face compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade the **magnitude of smiling** at maximum expression compared to the non-affected side

I. Severe impairment of movement
II. Moderate impairment of movement
III. Mild impairment of movement
IV. Normal movement

Grade the magnitude of **lower lip movement**

I. Abnormal movement
II. Normal movement

Grade dynamic asymmetry of **nasolabial fold** compared to the non-affected side

I. No change from rest
II. Alters with movement: flattens or accentuates
III. Normal

Choose the most asymmetric **direction of movement**

I. No movement
II. Mediolateral direction
III. Vertical direction
IV. Anteroposterior direction

Grade the **severity** of most asymmetric direction of movement

I. Severe
II. Moderate
III. Mild

Grade the **degree of smile movement** compared to the non-affected side

I. No movement
II. Movement of the cheek without movement of the corner of the mouth
III. Movement of the cheek with some lifting of the corner of the mouth
IV. Movement not fully symmetrical, showing teeth on affected side
V. Normal movement

Marking Sheet 3: Lip Purse Expression

Lip Purse

Case No.

Grade **total dynamic facial asymmetry** of the face compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade the **magnitude of lip movement** at maximum expression compared to the non-affected side

I. Severe impairment of movement
II. Moderate impairment of movement
III. Mild impairment of movement
IV. Normal movement

Grade the magnitude of **lower lip movement**

I. Abnormal movement
II. Normal movement

Choose the most asymmetric **direction of movement**

I. No movement
II. Mediolateral direction
III. Vertical direction
IV. Anteroposterior direction

Grade the **severity** of most asymmetric direction of movement

I. Severe
II. Moderate
III. Mild

Grade the **degree of lip purse movement** compared to the non-affected side

I. No movement
II. Slight movement without memetic lines
III. Movement with philtral deviation
IV. Movement without philtral deviation
V. Normal movement

Marking Sheet 4: Cheek Puff Expression

Cheek Puff

Case No.

Grade **total dynamic facial asymmetry** of the face compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade **the magnitude of cheek movement** at maximum expression compared to the non-affected side

I. Severe impairment of movement
II. Moderate impairment of movement
III. Mild impairment of movement
IV. Normal movement

Choose the most asymmetric **direction of movement**

I. No movement
II. Mediolateral direction
III. Vertical direction
IV. Anteroposterior direction

Grade the **severity** of most asymmetric direction of movement

I. Severe
II. Moderate
III. Mild

Grade the **degree of cheek movement** compared to the non-affected side

I. No movement
II. Flicker of movement
III. Weak movement with incomplete oral seal
IV. Weak movement with complete oral seal
V. Normal movement

Marking Sheet 5: Eyebrow Raising Expression

Eyebrow Raising

Case No.

Grade **total dynamic facial asymmetry** of the face compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade the **magnitude of eyebrow movement** at maximum expression compared to the non-affected side

I. No movement
II. Limited movement
III. Normal movement

Choose the most asymmetric **direction of movement**

I. No movement
II. Mediolateral direction
III. Vertical direction
IV. Anteroposterior direction

Grade the **severity** of most asymmetric direction of movement

I. Severe
II. Moderate
III. Mild

Grade the **degree of eyebrow movement** compared to the non-affected side

I. No movement with no muscle activity
II. No movement with muscle activity
III. Reduced movement with minimal horizontal lines on affected side
IV. Reduced movement with horizontal lines on both sides
V. Normal movement

Marking Sheet 6: Eye Closure Expression

Eye Closure

Case No.

Grade **total dynamic facial asymmetry** of the face compared to the non-affected side

I. Severe asymmetry
II. Moderate asymmetry
III. Mild asymmetry
IV. No asymmetry

Grade the **magnitude of eye movement** at maximum expression compared to the non-affected side

I. Severe impairment of movement
II. Moderate impairment of movement
III. Mild impairment of movement
IV. Normal movement

Choose the most asymmetric **direction of movement**

I. No movement
II. Mediolateral direction
III. Vertical direction
IV. Anteroposterior direction

Grade the **severity** of most asymmetric direction of movement

I. Severe
II. Moderate
III. Mild

Grade the **degree of eye movement** compared to the non-affected side

I. No movement
II. Slight movement with significant gap
III. Moderate movement with small gap
IV. Eye-closure with forceful contracture
V. Normal movement