Application of 3D Models to Assess Natural Motion of Facial Muscles

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ABSTRACT:

The study presents a methodology for assessing the natural dynamics of facial soft tissues based on stereophotogrammetric 3D models, designed to differentiate physiological (natural) and pathological changes. In a 6-month study involving 6 subjects (20-25 years old), monthly synchronous facial survey was performed. We took pictures of the persons in two modes – static (neutral expression) and dynamic (8 facial expressions) using a 15-camera Canon EOS 550D (0.06 mm/pix resolution). Data processing included construction of triangulated 3D models at a density of 1 point/mm (RMSE = 1 mm), automatic detection of 468 key points via MediaPipe Face Mesh with asymmetry calculation, and profile analysis of orthophotos with Gaussian filtering. The results revealed an average variation of topography in the range of 0.55-0.7 mm for static models and peaks up to 5 mm for mimicry. The paper proposes a variant of automated angle measurement using orthophotos in full-face and profile, as well as a method for calculating the total angle of asymmetry as the average of the angles of eyebrows, eyes, nose and mouth.

1. INTRODUCTION

Since 3D patient modelling techniques have been introduced into the clinicians' toolkit, there have been repeated challenges in validating such systems in order to assess the accuracy of the resulting models and their suitability for medical purposes (Heike at al., 2010; Sforza at al., 2012), different survey systems were investigated (Aldridge at al., 2005, Camison at al., 2017; Gibelli at al., 2018; Kim al., 2018; Naini at al., 2017a; Skrypitsyna at al., 2023a; Ort at al., 2012; Secher at al., 2017). For example (Savoldelli at al., 2019) determined the accuracy of a model by measuring the line segments on it (as a series of equally weighted measurements) and the errors that can be introduced by different operators (Savoldelli called this as repeatability or inter-operator variability). In this case, the indicator of variability in face shape was ‘taken out of brackets’. Researchers have investigated the assessment of facial asymmetry (Hajeer at al., 2004; Hennessy at al., 2006; Shaner al., 2000) and the effects of age and gender on facial expressions (Sforza at al., 2010).

However, for accurate diagnosis and assessment of pathological changes it is necessary to know not only the threshold values of survey system capabilities, but also the basic level of natural facial non-staticity caused by physiological processes, which, in fact, should be called repeatability (variability) of natural human facial variability.

By natural facial variability we will understand non-staticity of muscles and soft tissues caused by their interaction with the nervous system. This flexibility is manifested in facial expressions, gestures and other natural movements that reflect the normal activity of facial structures.

Photogrammetry, as a highly accurate and non-invasive method, offers unique opportunities to build detailed three-dimensional facial models and monitor their changes over time. The extraction and quantification of this motion allows the creation of a reference level on the basis of which disease-induced abnormalities can be analysed. The issues related to the determination of the dynamic range threshold for the correctness of monitoring the treatment of patients with various diseases have been repeatedly raised in the work of the authors. For example, in the work (Skrypitsyna, Spiridonova, 2018) the significance of the influence of such factors as breathing, body weight distribution, inclination and rotation of the shoulders, etc.) on the construction of back reliefs and the need to take them into account when conducting photogrammetric surveys was clearly shown.

Another study (Skrypitsyna at al., 2023a) attempted to extract the variation component from 3D models of human faces. Surveys were taken by a multi-camera photogrammetric system 6 times. Non-staticity indices were determined from key points on the face and from the DEM. The RMSE was calculated from the difference between the first shooting and the other five and was 1.2 mm. This is a number obtained from a study of only one person. In addition, the face was investigated only in a relaxed state. Therefore, for a deeper assessment of facial non-staticity, a methodology was developed to capture changes in facial surface shape based on the determination of a number of indicators of natural facial variability using modern photogrammetric technologies.

2. MATERIALS AND METHODS

A group of 6 persons aged between 20 and 25 years (3 males and 3 females) without specific pathologies participated in the study. The study participants underwent photogrammetric facial scanning once a month for 12 months. Such a period was justified by the fact that in the case of neurofacial palsy treatment, monitoring of the patient's condition and major changes in the treatment process occur during a similar period of time. All survey sessions were carried out in the morning, similar to real patients, to minimise the effect on the results of muscle fatigue accumulated during the day. Three-dimensional models of the face were then generated. Based on the results of the comparison of the models of the studied patients, it is planned to obtain some average value that will be present in all patients, which in the paper we called natural non-staticity. All

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surveys were performed under the same conditions to ensure comparability of data.

The initial data for the study of facial non-staticity were 3D models and orthophotomaps (full-face and profile) obtained by photogrammetric method. To build 3D models of the face, a specialised photogrammetric installation was used, which allows to take photos synchronously from several angles. The multi-camera photography installation is a rigid frame in the half-cylinder shape with a radius of 700 mm. Fifteen Canon EOS 550D digital photographic cameras and lighting equipment are mounted on this frame. The cameras have a sensor size of 5184x3456 pixels, a focal length of f=55 mm and a physical pixel size of 0.0043 mm. The nominal pixel size is d= 0.06 mm.

The result of data processing is a triangulation model, which accurately reproduces the topography of the face. The use of triangulation models for comparison avoids erroneous measurements at the edges of the face, which inevitably occur if one uses a facial DEM for the same purpose (Skrypitsyna at al., 2023b). Additionally, full-face and profile orthophotos were constructed.

Analysing facial geometry.When developing the methodology for assessing facial variability, we took into account the fact that non-staticity should be analysed not only when the face is calm, but also in its dynamics. This condition follows from the anatomical features of the structure of facial muscles, which are paired. This means that the response to a nerve impulse (contraction) that sets the muscles in motion in a healthy face should be somewhat the same. Among other symptoms, the response to mimic exercises allows doctors to judge the presence of pathology.

So each participant took two types of photography:
1. Static: taking pictures in the natural position of the face (calm state).
2. Dynamic: taking pictures while performing facial expressions (e.g. smiling, frowning, raising eyebrows).

We extracted key parameters to evaluate the changes:
A) Distances between three-dimensional surfaces along the normals;
B) Distances between key distinct facial contours measured from full-face orthophotos;
C) Angles of reference lines on the profile of the face according to the orthophotos created in profile.

This combined approach allowed to record both natural facial variability and changes caused by active facial expressions. Studies on the extraction of reference lines in photographs have been conducted before, but their variation over time was not assessed, and geometric distortions of the optics, which may be present in the original images, were not taken into account (Alanazi at al., 2024).The use of orthophotomaps excludes the influence of distortions caused by the central projection of the original images on the result of non-staticity detection.

A) The comparison of polygonal models was carried out by calculating the distances between two surfaces along the normals drawn from the points (nodes) of the reference surface to the surface under study. As a result, a new surface is obtained, in each node of which the difference value is found. This value serves as a measure of the change in the relief of the face as a whole. Comparisons were made between sessions, by comparing models of identical mimicry tests.

For statistical evaluation, the Standard Deviation (*SD*) and Mean (*A*) were determined for all differences

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(D_i - A)^2} \quad A = \frac{1}{n}\sum_{i=1}^{n} D_i ,$$

Where D - the magnitude of the change;
n - number of measurements;
A - the arithmetic mean of all changes.

B) Extraction of well-defined contours on the orthophoto full-face was performed using the MediaPipe library developed by Google(https://www.google.com/url?=https://ai.google.dev/edge/mediapipe/solutions/guide?hl=ru). This library is a large package of modern tools for computer vision tasks, including face detection and analysis. MediaPipe Face Mesh uses neural networks to detect a face and build a three-dimensional mesh of key points. The algorithm automatically detects 468 keypoints in person face images that cover all facial regions including the contours of the eyes, eyebrows, nose, mouth and facial oval (Alanazi at al., 2024). Based on the key points, clear facial contours were constructed (Fig. 1) and then the coordinates and angles of key lines (e.g. mouth line) were calculated for these key points. The average angle of asymmetry is calculated by the formula:

$$\alpha = \frac{1}{n}\sum_{i=1}^{n} \tan^{-1}((y_{li} - y_{ri})/(x_{li} - x_{ri})) ,$$

Where ***n*** is the number of angles measured in the Figure 1, x_l, y_l are coordinates on the left side of the face, x_r, y_r – on the right side.

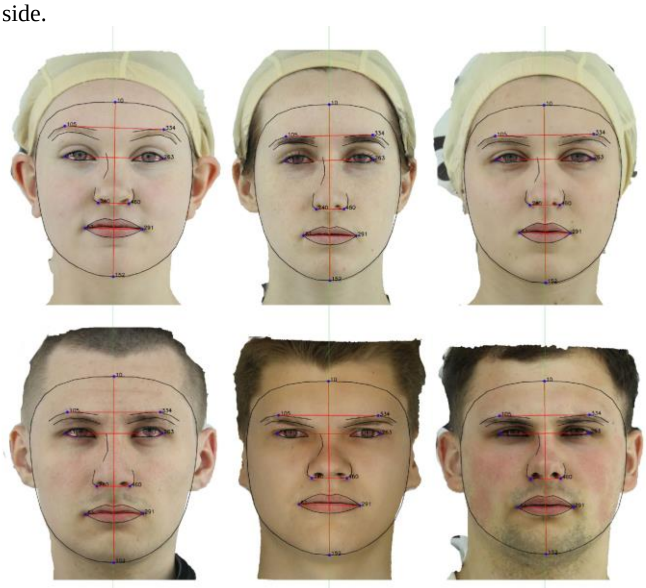

Figure 1. Selection of facial contour lines and key line segments. top row – female, bottom row – male.

C) Orthophotomaps in profile were constructed to construct reference lines and measure soft tissue parameters, which are commonly used in anthropometric investigations of maxillofacial problems (Sviridov at al., 2019).
To build the profile, threshold binarisation of the image was preliminarily performed. Then the profile was smoothed and the peaks in the right part along the x-axis were searched. Both

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positive and negative peaks were selected. The quality of finding the peaks was determined visually.

The algorithm for image processing was implemented in Python using OpenCv (cv2) library and Mediapipe. For binarisation we used the threshold function with a threshold value of 230, which provided an accurate boundary, since the background of the image has a value of 255 (however, there is noise on the boundary of the media due to compression of jpg images). For contour smoothing we used Gaussian blurring method (function gaussian_filter1d of skipy library) with standard deviation of normal distribution equal to 3 (it was chosen experimentally to reach the best result).

The function find_peaks of the skipy library was used to detect peaks, which finds all local maxima by simple comparison of neighbouring values of a one-dimensional array. For this function we set the minimum distance between peaks – 5, minimum peak significance – 1, which were selected experimentally to reach the best result.

The method has shown quite reliable results, but has errors in the case of determining parameters from orthophotos of patients with flat chins or beards (stubble). In the future, it is planned to connect a neural network to search for peaks. The points were assigned names according to common medical literature (Naini at al., 2017b, Sviridov at al., 2019), and angles were calculated from coordinate increments. This process was carried out in batch mode for the results of the survey in the calm state of all study sites for the duration of the monitoring period. The results were combined in a table (Tab.1), and can also be displayed for visual inspection on the orthophotos themselves (Fig. 2).

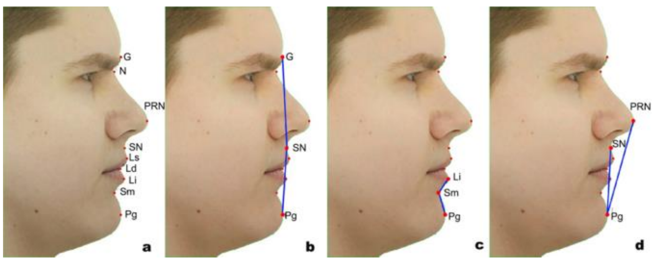

Figure 2. Measuring soft tissue parameters by profile, (a) – results of automatic determination of point coordinates on the orthophotoplane, (b) – G-SN-Pg - facial convexity angle according to Arnett and Bergmann, (c) – Li-Sm-Pg - mentolabial angle, (d) – SN-Pg-PRN - T angle according to A.M. Schwarz (Sviridov at al., 2019).

3. DISCUSSION OF RESULTS

For each study subject, 6 imaging sessions of 9 mimicry trials were performed: natural state, frowning eyebrows, pursing lips, clenched eyes, pouting cheeks, showing teeth, smiling to the right, smiling to the left, raising eyebrows. As a result of photogrammetric processing, 351 three-dimensional models were obtained, 54 models for each researcher, for which further statistical analyses were performed. The groups of models were brought into a single coordinate system, the axes of which pass through the horizontal and sagittal planes, the zero of the coordinate system is in the middle of the segment connecting the inner corners of the eyes. The 3D models have a density of 1 point/mm and a photogrammetric accuracy (RMSE) of 1 mm, as described in previous articles (Skrypitsyna at al., 2023a; Skrypitsyna at al., 2023b). The models were orientated relative to each other using 10 reference points located in the upper part of the face (corners of the eyes, ears, etc.).

Assessment of non-staticity. The resulting dataset provides a rich source of information that can be analysed to summarise the facial response to each facial expression probe across all subjects, as well as separately by gender. By using SD when comparing different datasets, the stability of the data can be assessed. Therefore, anything within the SD range is natural facial variability, while values above this range reflect dynamic facial variability.

Model Comparison. Figure 3 shows the results of the assessment of facial shape change over a period of 6 months (i.e., comparison of the 1st and 6th survey) in the form of a matrix. Each row contains a particular facial expression probe, and each column contains a different persona: columns 1-3 are males and columns 4-6 are females.

The green colour shows the value of the differences that are in the SD-range. Anything greater or less than this value describes the dynamic features of that persona. In addition to the visual picture, to the right of each model you can see a histogram that shows the distribution of the differences, as you can see that they are all close to a normal distribution.

Table 1 shows the SD values for the personas according to Figure 3. The column value is the persona number and the row number is the mimicry sample number.

person / probe	Standard Deviation, mm					
	1	**2**	**3**	**4**	**5**	**6**
1	0,7	0,7	0,6	0,5	0,6	0,6
2	0,7	0,8	0,7	0,8	0,6	0,7
3	0,9	1,4	1,0	0,6	0,6	0,9
4	0,7	1,2	0,7	1,1	1,0	0,6
5	1,0	1,1	0,8	1,2	0,6	0,7
6	0,9	1,2	0,9	0,6	0,8	0,7
7	0,9	1,2	0,7	0,6	0,7	0,7
8	1,0	1,2	0,8	0,7	0,7	0,7
9	0,8	1,5	0,7	0,6	1,0	0,7

Table 1. SD of facial shape change over a period of 6 months

Even with particularly dynamic tests (puffing up cheeks or stretching lips into a tube), the CD does not exceed 1.5 mm. From the table we can also see that girls have more stable mimicry (girls more often than boys repeat mimicry exercises in the same way time after time), and males in general and, in particular, male characters 2, have mobile mimicry. At the same time, the maximum values of facial surface changes during some mimicry trials reach +/- 5 mm. In Table 1, the samples in which the maximum values exceed +/- 5 mm are highlighted in colour.

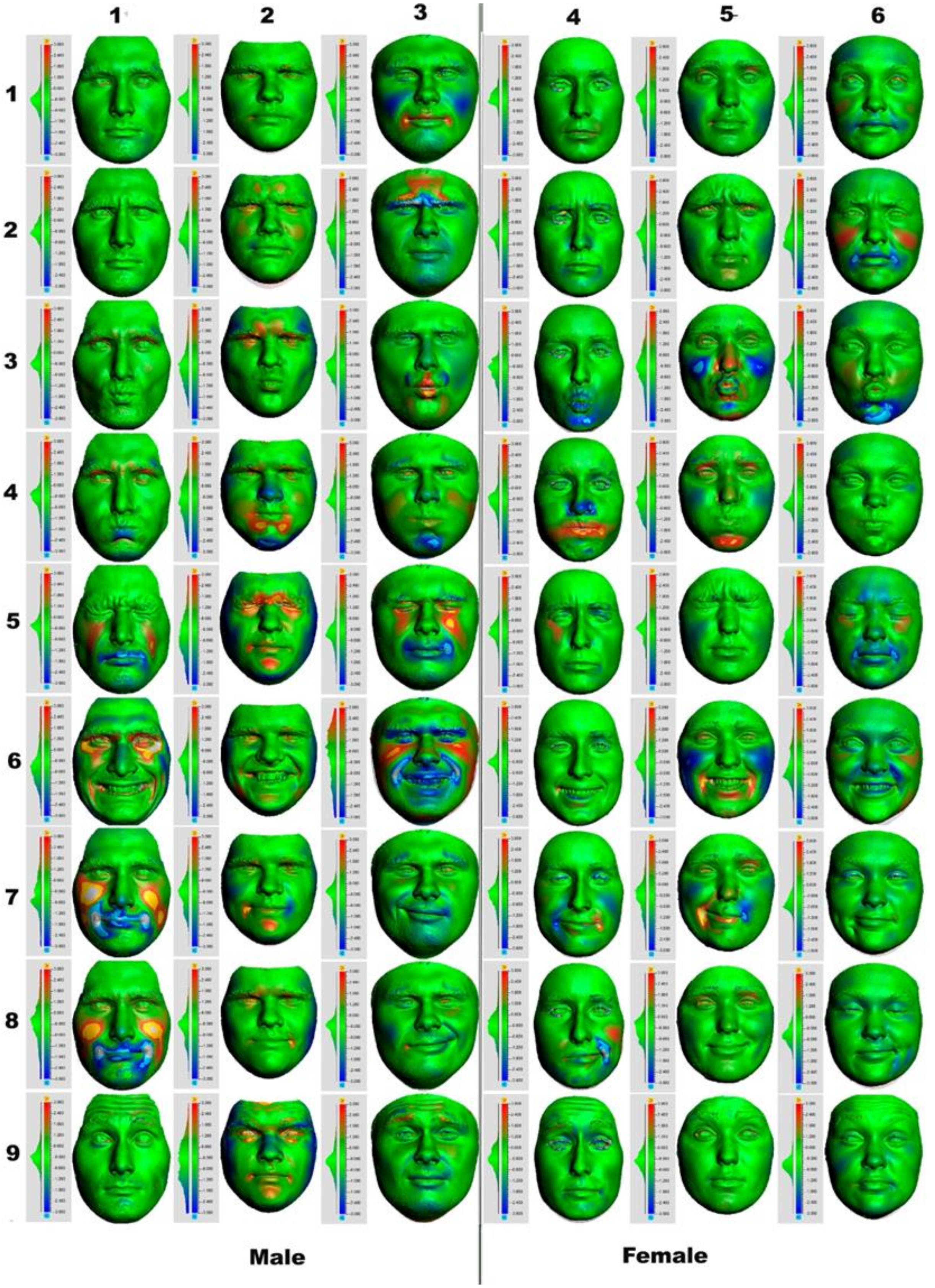

Figure 3. The results of the assessment of facial shape variation over a period of 6 months. In each line a certain mimicry according to the numbering: 1– natural state, 2– frown eyebrows, 3–pursed lips, 4–pout cheeks, 5– squeeze, 6–show teeth, 7– smile to the right,8– smile to the left, 9–raise eyebrows. The histograms show the distribution of difference values.

We analysed the data by months (Fig. 4), i.e. we obtained differences by months: 1-2, 2-3, 3-4, 4-5, 5-6. In total, we obtained 5 ranges.

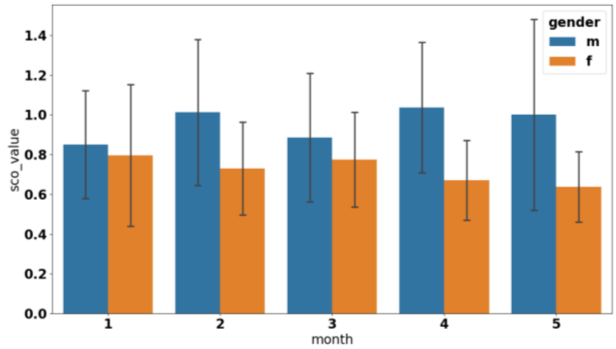

Figure 4. Average values of Standard Deviation with confidence interval, interval for each survey period.

As can be seen in Figure 4, there are no correlations of values between boys and girls: on average for all probes, the level of statins does not exceed 0.8 mm in girls, and in boys this value is slightly more than 1 mm. Despite the small fluctuations in SD during the study period (girls - 0.15m and boys-0.25mm), the value is generally smaller than when comparing month 1 and month 6. This can be explained by the fact that some of the persons had shape changes (some of the persons gained weight and some lost weight) during the six months. Therefore, when comparing month 1 and month 6, these differences affected the final result.

Figure 5 summarises the results (for all personas), showing the values of SD as a function of sample performance. This is necessary to assess the impact of facial movement (regardless of gender). For example, the variability value for the calm face condition (row 1) ranges from 0.55-0.7 2mm, whereas in the study (Skry 2023) this value was 1.2mm. This is due to the fact that young participants (20-30 years old) have higher facial statics than persons over 50 years old who have natural age-related changes.

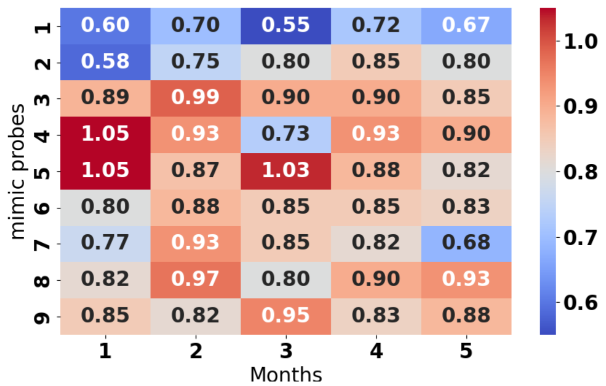

Figure 5. Summary table of the value of SD depending on the type of probe, but regardless of gender.

Each sample has its own range of staticity, which is explained by the possibility of reproducing this or that probe unambiguously. Based on the table in Figure 5, the unambiguously reproducible probes are 1,2,6-9, and the variable probes are 3-5. The range of staticity for each sample is different and we can conclude on the whole time interval about more mobile samples, such as 3,4 and 5.

Determination of the total asymmetry angle. The average variance in the total asymmetry angles (average of the angles of the mouth, nose, eyes and eyebrows) was 0.6°. At the same time, the minimum divergence falls on the calm state (0.4°) the maximum - on smiling to the side (0.9°), which is explained by the low repeatability of this mimicry probe (an example is presented in Figure 6).

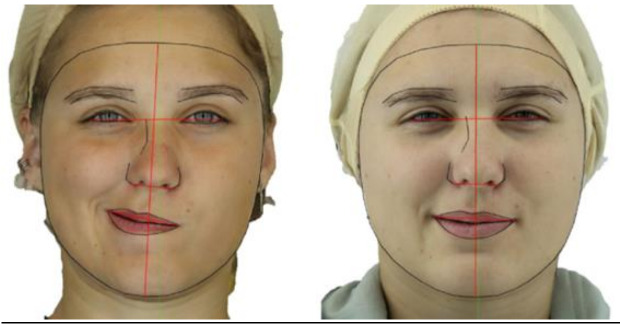

Figure 6. Errors related to the repeatability of performing the mimicry probe (4.1°).

The mean symmetry angle for the group of 6 patients was less than -0.1° (which tends to zero with a larger sample). At the same time, the mean deviation was 0.5° (which tends to zero in a larger sample).

Measurement of reference line angles. Facial convexity angle (G-SN-Pg) varies from session to session between 165.8° and 175.5° and averages 170.2° (with a norm of 165-175).

Mentholabial angle (Li-Sm-Pg) varies from session to session between 132.7° and 145.9° and averages 136.9° (with a norm of 107-118 or ‘a range up to 140° was considered acceptable’). The variation of the mentolabial angle varies more with mandibular position. The T angle varies from session to session between 11.1° and 14.1° and averages 12.9°.

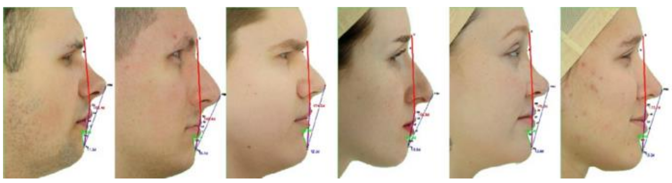

Figure 7. Automatic measurement of reference line angles.

	G-SN-Pg, °	Li-Sm-Pg, °	SN-Pg-PRN, °
patient1	174.0	132.7	12.4
patient2	166.6	134.0	13.8
patient3	165.8	141.9	11.1
patient4	166.6	145.9	14.1
patient5	175.5	133.6	13.6
patient6	172.8	133.3	12.7
average	170.2	136.9	12.9

Table 2. Measurements of soft tissue parameters by profile

The method of automatic measurement of reference line angles showed quite reliable results, and corresponds to the results determined manually (Sviridov at al., 2019). However, it has errors in the case of determining parameters from orthophotos of patients with flat chins or hair (bristles). In the future, it is planned to connect a neural network to search for peaks.

4. CONCLUSIONS

The study showed that staticity, repetition of facial grimaces and facial asymmetry are interrelated parameters that were quantified using 3D photogrammetric models and orthophotos.

These data can be used to:
-Development of personalised approaches in cosmetology.
-Diagnosis of pathological changes.
-Prediction of age-related changes.

In this work we have developed a methodology for fixing changes in the shape of the facial surface based on the determination of a number of indicators of natural facial variability using modern photogrammetric technologies. The basis for approbation of this methodology were digital models of faces of young men and girls without pathologies, who performed mimicry exercises for six months.

In the case when the researched person is in a calm state - gender differences are not revealed, the norm of statics is 0.6 mm. However, gender differences begin to manifest themselves when performing mimic exercises (the greatest - smiling to the side, frowning the forehead). Females perform the exercises with a greater degree of similarity, males are more variable, with the total range of statics being no more than 1,5 mm. The maximum values in the change of facial shape in the samples of both males and females could vary +/- 5 mm, which is an indicator of dynamism.

In addition to the assessment of staticity, which was determined by comparing three-dimensional models and variability of mimicry performance, the results of which can be seen in graphs and images, the paper proposed a variant of automated angle measurement using orthophotos in full-face and profile. In this case, if in the case of measuring angles in profile there is a sufficient number of studies (Bottino and Cumani, 2008; Milosevic at al., 2011; Sviridov at al., 2019), some standards in determining the measured values are defined and some averaged values for different groups of subjects are presented, then in the case of determining the angle of asymmetry in full-face the methods proposed to date are very different (Wei at al., 2022).
In this paper we propose a method of determining the total angle of asymmetry as the average of the angles of the eyebrows, eyes, nose and mouth. However, the accuracy of facial orientation has a strong influence on the obtained measurements. In the future, it is planned to compensate this error by measuring relative angles (inclination of the mouth relative to the eyes, etc.) or to calculate the vertical axis through points in the sagittal plane.

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