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Quantitative dynamic analysis of the nasolabial complex using 3D motion capture – a normative data set.

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Introduction: Smile reanimation should be considered from a dynamic perspective. Any intervention should restore normality. To date no such normative dynamic data has been published.

Aim: To quantitatively analyse maximal smiles between a healthy group of Caucasian male and female adults using 3D motion capture (4D stereophotogrammetry).

Method: Using a 3D facial motion capture system 54 males and 54 female volunteers were imaged whilst performing a maximal smile. Eight nasolabial landmarks were digitised and tracked. Differences in displacement and speed of bilateral landmarks between males and females were analysed in each direction (x, y, z and Euclidian), from rest (T_0), to median smile (T_1) and maximal smile (T_2), using paired *t*-tests and Wilcoxon-Signed Rank tests.

Results: In males and females the displacement and speed of the left and right alar base landmarks were similar in the x and y directions but less in the z direction. For the philtrum, the displacement and speed of the bilateral landmarks were similar in the y and z directions, but less in the x direction. The left alar base and left philtrum moved significantly more in males. Left and right cheilion moved a similar amount in the x and y directions but more in the z direction. Labiale superius moved significantly more in the z direction, and labiale inferius moved significantly more in the y direction in males.

In conclusion, this study has presented a novel normative data set of dynamic nasolabial complex movement for males and females during maximum smile. The data, as well as providing magnitudes of displacements of the nasolabial complex, also provides the speeds of movement.

INTRODUCTION

The human face is a complex and dynamic three-dimensional structure which is involved in verbal and non-verbal communication, identification, perception, creativity and sexuality.[1] Numerous facial muscles are responsible for the myriad of expressions that can be made including: joy, shock, fear and sadness. Diminished facial expression or facial paralysis has been shown to have a negative effect on an individual's psychological wellbeing and quality of life.[2]

Various surgical procedures are undertaken to restore function and re-establish facial dynamics. These include nerve repair and grafting,[3,4] cross-face nerve graft,[5] hypoglossal-nerve transfer,[6] masseter or temporalis muscle transposition[7] and free muscle flaps.[8] The outcome of the intervention is often assessed using subjective measures based on comparison with the patient's unaffected side. Two of these include the House-Brackman facial grading system (HB FGS) [9] and the Sunnybrook Scale (SB FGS).[10] While many of the subjective grading systems are easy to use and inexpensive, the HB FGS is prone to inter-observer variability and may not be sensitive enough to detect clinically important changes over time or with treatment.[11] When assessed by 28 Doctors the HB FGS was found to have fair to good intra-rater reliability but poor to fair inter-rater agreement scores. Whilst the SB FGS showed good to excellent intra-rater reliability and moderate to excellent inter-rater agreement scores. Voluntary movement was the most agreed on score for the SB FGS and the resting symmetry component the least agreed on between raters and within raters.[10] The same author, following a large scale study, concluded "the need for a more accurate facial grading system both in everyday clinical settings and for research purposes".[13]

Reproducibility of a specific facial animation is a fundamental prerequisite to be able to assess whether an intervention has had a clinically significant effect. Recent studies have shown maximal smile to be the most reproducible facial expression in static[14] and dynamic function.[15] Even though reproducible, work by Rubin has shown that not all smiles are the same between individuals. [16] It has been suggested there should be co-ordinated contraction of the perioral muscles for a smile to be considered “normal”.

Previous studies have quantitatively analysed normal smiles using 3D stereophotogrammetry to help in facial reanimation surgery.[17] All studies to date have assessed the magnitude of change in landmark positions at two discrete time points - rest position and maximum expression. 3D motion capture (4D stereophotogrammetry), unlike static 3D imaging is able to capture the rate of change of the smile, or the characteristics of the smile between rest and maximal expression.

Technological advances in the games and entertainment industry have recently been used to assess facial motion in a clinical environment. The technology has been used to assess changes in facial animation following orthognathic surgery, cleft lip and palate repair[18] and oncology access procedures.[19] The studies to date have assessed the result of the intervention, i.e. has the surgery improved (in cleft patients) or at least maintained (in oncology access patients) the pre-treatment situation with respect to facial dynamics. None have assessed whether the patients facial animation has returned to “normal”. A previous study reporting 3D dynamic normative data was based on a small sample size and reported inter-landmark

Euclidian distances rather then the x, y and z distances.[20] In addition another study used pre-placed large 4mm retro-reflective markers to assess landmark displacement and a facebow protruding through the lips for head movement registration.[21] The large markers would make precise landmark identification difficult and the facebow may interfere with labial soft tissue movement. Both studies also only reported displacement of landmarks from rest to maximum expression; one could argue this could be carried out using two 3D images. The dynamic movement between these two time points, even though recorded was not analysed.

Therefore, the aim of this study is to quantitatively analyse dynamic smiles, from a spatial–temporal perspective, between a healthy group of Caucasian male and female adults, using 3D motion capture (4D stereophotogrammetry). Giving the potential to allow diagnosis, aid facial reanimation procedures and assess outcome. The null hypothesis is that there is no statistical difference in nasolabial movement between males and females both at maximum expression, and half way through the expression.

MATERIALS AND METHODS

Ethical approval was granted by the Dental Research Ethics Committee (DREC) at the University of Leeds, U.K. (DREC reference 240915/BK/179).

Sample size calculation

A clinically significant difference in landmark position between males and females was set at 2mm.[22] The expected variability (standard deviation) of the differences was ± 2.9mm.[15] Using a significance level of 0.05 and a power of 90%, a sample size of 46 subjects was required. To account for drop outs and bad data a minimum of 50 subjects (10% extra) were recruited.

Sample

One hundred and eight health volunteers were recruited. All subjects were Caucasian adults aged 18-40 years, had clinically normal facial function, no clinically apparent facial asymmetry and had a normal dental relationship (Class I incisor relationship), as judged by two experienced orthodontists (CL and BSK). In addition there was no previous history of facial trauma, paralysis, surgery or history of neurological disease. No volunteers were currently undergoing active orthodontic treatment.

DI4D™ Pro passive stereophotogrammetric capture system

The 3D motion capture sequence was obtained using the DI4D™ Pro passive stereophotogrammetric capture system (Dimensional Imaging Ltd, Glasgow, Scotland, U.K.). The system captured high resolution 3D images of facial movement using digital video cameras. The system was composed of two pods of three cameras (two monochrome and one colour). The cameras, with resolutions of 2048 × 2048 pixels were synchronised and set to capture the sequences at a rate of 60 3D images per second. The system is markerless and produces multiple 3D images over the sequence range which allows easy extraction of the x, y and z co-ordinates over a know time period i.e. allows spatial–temporal analysis.

The system was calibrated prior to each session using the calibration target provided with the system. The calibration images were processed, to produce a calibration file, using DIHydra software (Dimensional Imaging Ltd, Glasgow, Scotland, U.K.).

Imaging

Prior to imaging volunteers were asked to remove any spectacles, sit in a chair and were positioned according to the manufacturer's instructions. The desired facial expression (maximal smile) was explained and demonstrated by the researcher. The facial expression began with the lips together lightly, and without muscular tension in the muscles of facial expression (rest position). The participants were asked to smile maximally, whilst biting their back teeth together lightly (maximum smile), and then return to the rest position.[14] Once each participant was comfortable and understood the facial expression a 3 second motion capture sequence was recorded and saved as a .SQE file.

Using the calibration file, the video sequence file and DIHydra software a 4D reconstruction was produced. The process resulted in the production of a 3D motion capture sequence; the individual 3D frames of which were accessible in each volunteer's folder.

Landmarking and tracking

One operator (CL) identified and placed 22 facial landmarks on the first frame of each image, Figure 1. The landmarks were chosen to represent clinically relevant areas and were used in previous studies.[17,20,23,24] An automatic landmark tracking function in the Di4D software was used to track the landmarks through the remaining frames in the 4D sequence. The automatic tracking function is valid and has a mean accuracy of within 0.55mm.[25] Using this function, it is possible to track the coordinates for each landmark on any frame during the movement. Four landmarks on the forehead region were selected and used for image stabilisation. By playing through the video sequence, the frame number representing the frame immediately prior to the start of the smile (rest frame) together with the frame number when maximum smile had been reached (maximum smile frame), was noted by two independent operators (CL and BSK) for each individual. The median frame number was then determined; for sequences with an even number of frames, the frame number was rounded up, Figure 2.

Landmark extraction

The landmark data (x, y, and z coordinates) were then exported from the Di4DView software in .pc2 file format. An in-house developed software routine was used to convert this file into a format that could be saved in a Microsoft Excel spreadsheet. This spreadsheet contained the subject number, the number of landmarks, the number of frames from rest to maximal smile and the x, y and z coordinates for each landmark for each frame of the sequence.

Outcome measures

The saved Excel spreadsheet was read into MATLAB software (MATLAB and Statistics Toolbox Release 2017b, The MathWorks, Inc., Natick, Massachusetts, United States). MATLAB code was written (T-CH, BSK) to analyse the data. For each bilateral landmark pair (e.g. LM5 and LM11) the following measurements were determined,

- Euclidian distance and distances in the x, y and z directions each landmark has moved from rest to median smile.
- Euclidian distance and distances in the x, y and z directions each landmark has moved from rest to maximum smile.
- Speed each landmark has moved from rest to maximum smile over the Euclidian distance and in the x, y and z directions.

Error study

A number of different sources of error were identified in this study, including selection of “rest” and “maximal smile” frames, landmarking error and tracking of landmarks. In order to factor all possible sources of error into the error study, the entire process of image preparation and data analysis was repeated for 12 randomly selected subjects. The systematic and random errors were then determined for all landmark displacements and for speed of landmark displacements from rest to maximal smile between the two time intervals (T_1 and T_2).

ANALYSIS

The data was inspected for outliers by visual inspection of boxplots. In the case of extreme outliers, the data analysis was run with and without the outliers to determine if the outlier had an appreciable effect on the analysis. The normality of data was assessed using the Shapiro-Wilk test. For normally distributed data, independent samples *t*-tests were used to compare the differences in displacement of each landmark in the x, y and z directions, and Euclidian distances, between males and females. For data with a non-parametric distribution, the Mann-Whitney U test was used to compare the median difference in displacement. If there was no difference in the statistical outcome the parametric test result was reported. In addition a Pearson's correlation was run to assess the relationship between resting mouth width and the displacement of left and right cheilion. The same test was also conducted to assess the relationship between resting mouth height and the displacement of labiale superius and labiale inferius.

RESULTS

Error study

The difference in landmark displacements between T_1 and T_2 in the x, y and z directions and Euclidian distance was 0.03mm ± 0.72mm. For speed of landmark displacements, the difference between T_1 and T_2 was 1.26mm/sec ± 2.57mm/sec. Systematic error was assessed by paired *t*-tests and random error assessed by coefficients of reliability.[25] No systematic errors were observed. All coefficients of reliability were above 90%.

Alar base

The results for alar base displacement and speed are shown in Tables 1 to 3. Left and right landmarks moved a similar amount in the x and y directions but less in the z direction. Both maximum and median displacement of the alar bases were greater in males than in females. This was significantly greater for the right alar base in the z direction. For the left alar base there were significant differences between males and females in all displacements. Even though the mean differences were small (1.3mm or below), the 95% CI for the difference in displacement (Euclidian distance) of the left alar base between males and females had an upper limit of 2.0mm. For males the Euclidian distance landmark displacement was greater on the left than on the right for males but similar in females. There were statistical differences in the speed of right alar base movement between males and females in the z direction. For the left alar base there were statistical differences in all but the z direction.

Philtrum

The displacement and speed of the bilateral philtrum landmarks were similar in the y and z directions but less in the x direction. The landmarks showed a greater displacement in males than in females and greater on the left than on the right. These were statistically different in the x and z direction, and in the Euclidian distance on the left, and only statistically different in the z direction on the right. These differences were also reflected in the speed of maximum displacement, Tables 4 to 6.

Cheilion

Tables 7 to 9 show the maximum, median, and speed to maximum displacement for left and right cheilion for males and females. Left and right landmarks moved a similar amount in the x and y directions, but more in the z direction. For both males and females the Euclidian distance landmark displacement was greater on the left than on the right. For left cheilion males showed more displacement and higher speeds of displacement in the x and y directions of than females; this was statically significant for both measurements. This is obviously accompanied by a greater displacement of the corners of the mouth in males than females in terms of the Euclidian distance. However, the magnitude of displacement and speed of displacement in the z direction was not statistically different between males and females. There was no relationship between the width of the mouth and the magnitude and cheilion displacement.

Labiale superius and labiale inferius

The maximum and median displacements of both labiale superius and labiale inferius were also greater for males then for females with labiale superius displacing further than labiale inferius. Labiale superius moved significantly more in the z direction, and labiale inferius significantly more in the y direction in males. There was no relationship between lip height and displacement of either labiale superius or labiale inferius. Regarding speed to maximum displacement, the only statistically significant difference between males and females was for labiale superius in the z direction, Tables 10 to 12.

DISCUSSION

This study was conducted to address the short comings of previous articles based on static 3D imaging, by capturing and analysing the dynamic nature of the smile. The human smile is complex and involves several muscle groups working together to produce a clinically symmetrical smile. This study uses a validated and clinically accurate 3D motion capture system to quantitatively analyse maximum smiles in a group of healthy adults.[15,18] Previous studies using static 3D images only capture the rest and maximum expressions.[14,27] The current system captures images at a rate of 60 3D images per second, similar to previous studies. The analysis of over 150 frames would be exhaustive, so to simplify the analysis the median frame of the sequence was used in addition to the frame at maximum smile. The authors acknowledge the gross simplification of the analysis and the disregarded data. The median frame was chosen as it was a discrete time point which could be easily found between subjects. Alternatively, the sequence could have been divided into blocks, i.e. 1/10, and the mean displacement of landmarks over this duration calculated. However, any outliers could potentially skew the results. Small-scale studies using 3D motion capture systems to analyse and compare lip movement between different groups have also been published.[18,19,28-32] However, these studies have small numbers in their reference groups and are of limited value as a reference group for future studies. Others have sufficient sample sizes but concentrate on assessing lip movement with respect to verbal communication.[29,-30]

Weeden et al. used a marker based 3D video tracking system (Motion Analysis) to quantify 3D facial movement in healthy subjects (25 males and 25 female).[21] The study was based on 30 spherical retro-reflective markers (4mm diameter) on the facial soft tissue and an intra-oral face bow for image alignment / stabilisation. Based on Mahalanobis scores, the study concluded that males and females showed differences in maximum facial movements, and in general, males had greater movement than females. The Mahalanobis score is a complex morphometric measure used by statisticians and probably not well understood by clinicians. In addition, the animation was based on a “smile”, and if this was not a “maximum smile”, may not be reproducible.[15] Other studies have used direct facial landmarks and video capture systems based on complex mirror systems to determine the mean standard values of healthy facial movements.[20,24] Based on inter-landmark distances men showed larger movements of the corner of the mouth than women. Unfortunately the results of the present study are not comparable to the study by Giovanali et al. as measurements were taken from the tragus, and the differences were Euclidian distances only. Kang et al. used conventional two-dimensional video imaging to extract the x and y displacements from a still of the frontal image, and the z displacement from the profile still.[29] The sample consisted of 25 male and 25 female Korean volunteers performing a “normal smile”. The two groups were then amalgamated to produce differences in x, y and z displacements. Although this study reported 3D data, it was really based on 2D images, and therefore prone to perspective and individual positioning error. Earlier research has shown that 2D analysis of 3D landmark displacement can underestimate the magnitude of 3D displacement by up to 43%.[33]

Previous studies have predominantly assessed the magnitude of displacement, often as single unit of measure, i.e. Euclidian distance, rather than decomposing the landmark motion into separate x, y and z directions.[21] The present study reports both and found that all landmark displacements and speeds were larger for males than females. However, the displacement of the alar base, philtrum and cheilion were different depending on direction. For the alar base, the landmarks moved a similar amount in the x and y directions but less in the z direction. For cheilion, the landmarks moved a similar amount in the x and y directions, but more in the z direction. For the philtrum, there was similar movement in the y and z directions but less in the x direction. This was found for the median and maximal smile frames and may be related to the underlying anatomy and innervation. The alar base is bound posteriorly by the hard tissue (maxillary bone), so has limited movement in the z direction. Lateral expansion (x direction) of the philtrum is restricted by the overlying cutaneous tissue. Finally, the direction and insertion of the zygomaticus major muscle will pull the corners of the mouth posteriorly (z direction), as orbicularis oris muscle relaxes. Interestingly, differences in the movement of the upper and lower lip were also seen between males and females, with the upper lip moving further posteriorly, and the lower lip further inferiorly, in males.

Reporting these complex naso-labial movements as a Euclidian distance underestimates the differential movements occurring in the x, y and z directions. These novel findings and the normative data set could be used to assess the outcome of treatment for cleft patients, or patients with a facial paralysis, to quantify the site and severity of any residual deformity in a patient-centred approach to treatment. A study reporting the use of the same 3D motion capture technology found more asymmetry in repaired unilateral cleft lip and palate individuals compared to a group of non-cleft individuals.[18] However this study was based on small numbers (12 cleft and 11 non cleft individuals), with a wide age range (8-18 years old), and gender was not taken into account. The outcome measures were based on asymmetry and are not comparable to the present study. The study reported movement of the mid-philtrum ridge as minimal (0.5mm ± 0.2mm) whereas the present study reported movements of 7-8mm at the junction of the upper lip and the philtrum. The smaller movement of the mid philtrum ridge could be explained the diminished movement from the vermilion border of the upper lip to the base of the nose as the orbicularis oris muscle inserts into the maxilla. The authors felt fuller movement of the philtrum would add more comparative information for future outcome assessment studied i.e. cleft lip patients.

The present study found clinically significant differences (95% CI greater than 2mm) between males and females in right cheilion y direction and Euclidian distance; left cheilion x, y direction and Euclidian distance; and for the left alar base Euclidian distances. This would question the validity of grouping the genders together to form one group which would be heterogeneous. In addition there was a left sided predominance in the magnitude of movement in the majority of landmark. The reason for this difference remains unknown but it has been suggested it may be a manifestation of the underlying skeletal left side predominance[34] or due the overlying soft tissue[24] or a combination of both. In the present study differences between left and right cheilion movement were 1.6mm ± 1.1mm for males and 1.3mm ± 0.9mm, these were similar to previous studies (1.3mm ± 1.1mm). [24]

This study similar to previous studies found landmark displacements greater in males than in females. For cheilion the actual maximum displacements of the landmarks were statistically significantly different in the x and y directions as well as the Euclidian distance and similar to those reported by Swayer et al. The landmark displacements were smaller to those reported by Kang et al. This could be due to a different method of 3D co-ordinate generation, as discussed above, or due to a different ethic group. Tzou et al. have reported Asians having significantly smaller facial movements compared to Europeans.[24] There was no relationship between the width of the mouth and the magnitude and cheilion displacement. The difference found between males and females could be due to the larger male facial musculature and skull growth compared with the lighter features of the female face, which was reported to be about four-fifths the size of men's.[35]

Movement of the alar bases during smile has been infrequently reported during smiling. In a study comparing the amplitude of facial movement using 2D and 3D imaging a maximum displacement of 5.7mm ± 4.0mm was reported, which was similar to the present study 4.8mm to 6.2mmF.[33] Quantifying the alar base movement over the duration of the smile will provide comparative data for cleft lip patients, rhinoplasty patients and orthognathic patients.

A unique finding of the present study is the speed of naso-labial landmark displacement from rest to maximum smile. As expected, there is an increased rate of change of landmark displacement from the alar base to cheilion. There was no relationship between upper lip height and displacement of the upper lip. Between 65% and 78% of the maximum displacement of the all the landmarks was complete by the median frame, except for labiale inferius. Between 75% and 92% of the movement was complete for these landmarks, which would indicate that movement of the lower lip inferiorly is at its maximum by the median frame whilst, the remaining landmarks continue their displacements. In other words, the contractions of depressor anguli oris, depressor labii inferioris and mentalis muscles, which all pull the lower lip downwards, are occurring before the muscles that elevate the upper lip. There was no relationship between lip height and magnitude of lower lip movement. This may have clinical implications in detecting conditions in which facial bradykinesia maybe present, i.e. Parkinson’s disease or stoke patients were the innervation is disrupted. This inferior and posterior movement of the lower lip at a different rate will potentially make reconstruction of the lower lip difficult and a challenge for facial reanimation surgery.[17]

In conclusion, this study has presented a novel normative data set of dynamic nasolabial complex movement for males and females during maximum smile. The data, as well as providing magnitudes of displacements of the nasolabial complex, also provides the speeds of movement which has not been previously reported. This provides a unique opportunity to objectively benchmark outcome measures for dynamic nasolabial complex movement. This is probably more valid for the face, given the dynamic nature of facial expression.

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Figure legends

Figure 1 Facial landmarks used for analysis (landmarks 1 to 4 used for image stabilisation).

Figure 2 Landmarked frames at (A) rest, (B) median frame and (C) maximum smile.

Table 1 Alar base – maximum displacement, median displacement, and speed to maximum displacement in the x, y and z directions, and the Euclidian distance

	x direction				y direction				z direction				Euclidian distance			
	Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)	
			Lower	Upper			Lower	Upper			Lower	Upper			Lower	Upper
Maximum displacement																
Male right	3.1	1.1	2.8	3.4	3.8	1.7	3.4	4.3	2.1	1.2	1.7	2.4	5.6	1.7	5.1	6.1
Male left	3.6	1.3	3.3	4.0	4.2	1.8	3.7	4.7	2.2	1.2	1.8	2.5	6.2	1.9	5.7	6.7
Female right	2.9	1.0	2.7	3.2	3.6	1.2	3.3	4.0	1.6	1.0	1.3	1.9	5.1	1.4	4.7	5.5
Female left	2.7	0.9	2.4	2.9	3.5	1.1	3.2	3.8	1.6	1.0	4.8	1.9	4.8	1.3	4.5	5.2
Median displacement																
Male right	2.1	1.0	1.9	2.4	2.7	1.3	2.3	3.0	1.5	0.9	1.3	1.8	3.9	1.6	3.5	4.4
Male left	2.6	1.2	2.3	2.9	3.0	1.4	2.6	3.4	1.6	1.0	1.3	1.9	4.5	1.8	4.0	5.0
Female right	1.9	0.7	1.7	2.1	2.3	1.0	2.0	2.6	1.1	0.7	0.9	1.3	3.3	1.2	3.0	3.6
Female left	1.8	0.8	1.6	2.0	2.3	1.0	2.0	2.5	1.1	0.7	0.9	1.3	3.3	1.2	2.9	3.6
Speed to maximum displacement																
Male right	8.0	3.7	6.9	9.0	9.8	5.7	8.3	11.4	5.1	3.0	4.2	5.9	14.2	6.2	12.5	15.9
Male left	9.2	4.0	8.1	10.3	10.6	5.8	9.1	12.2	5.3	3.1	4.5	6.2	15.6	6.5	13.8	17.4
Female right	7.5	3.0	6.7	8.3	9.1	3.2	8.2	10.0	4.0	2.6	3.2	4.7	12.8	4.1	11.7	13.9
Female left	6.8	2.8	6.0	7.5	8.8	3.3	7.9	9.7	4.1	2.7	3.4	4.8	12.2	4.1	11.1	13.4

Table 2 Alar base – differences in maximum displacement in the x, y and z directions and the Euclidian distance between males and females.

	Mean Difference (mm)	Std. Error Difference (mm)	95% CI of the Difference (mm)		p-value
Right			Lower	Upper	
x direction	0.2	0.2	-0.2	0.6	0.351
y direction	0.2	0.3	-0.3	0.8	0.420
z direction*	0.5	0.2	0.1	0.9	0.021
Euclidian distance	0.5	0.3	0.0	1.1	0.069
Left					
x direction*	1.0	0.2	0.6	1.4	0.001
y direction*	0.7	0.3	0.1	1.3	0.017
z direction*	0.6	0.2	0.1	1.0	0.011
Euclidian distance*	1.3	0.3	0.7	2.0	0.001

Table 3 Alar base – differences in speed to maximum displacement in the x, y and z directions and the Euclidian distance between males and females.

	Mean Difference (mm/s)	Std. Error Difference (mm/s)	95% CI of the Difference (mm/s)		p-value
Right			Lower	Upper	
x direction	0.5	0.6	-0.8	1.8	0.440
y direction	0.7	0.9	-1.1	2.5	0.433
z direction*	1.1	0.5	0.0	2.2	0.044
Euclidian distance	1.4	1.0	-0.6	3.5	0.156
Left					
x direction*	2.4	0.7	1.1	3.7	0.001
y direction*	1.8	0.9	0.0	3.6	0.049
z direction	1.2	0.6	0.1	2.4	0.029
Euclidian distance*	3.3	1.0	1.3	5.4	0.002

*Indicates statistically significant result

Table 4 Philtrum – maximum displacement, median displacement, and speed to maximum displacement in the x, y and z directions and the Euclidian distance

	x direction				y direction				z direction				Euclidian distance			
	Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)	
			Lower	Upper			Lower	Upper			Lower	Upper			Lower	Upper
Maximum displacement																
Male right	1.9	1.1	1.6	2.2	5.3	2.1	4.8	5.9	4.8	1.8	4.3	5.3	7.7	1.9	7.2	8.3
Male left	2.7	1.3	2.4	3.1	5.5	2.0	4.9	6.0	5.1	1.9	4.6	5.6	8.3	2.0	7.8	8.9
Female right	2.0	1.1	1.7	2.3	5.3	1.8	4.8	5.8	3.9	1.7	3.5	4.4	7.2	1.8	6.7	7.7
Female left	1.9	0.9	1.7	2.2	5.3	1.8	4.8	5.8	4.2	1.7	3.7	4.6	7.3	1.8	6.8	7.8
Median displacement																
Male right	1.4	1.0	1.1	1.6	3.9	1.8	3.4	4.4	3.6	1.5	3.2	4.0	5.8	2.1	5.2	6.3
Male left	2.1	1.1	1.8	2.4	4.1	1.8	3.6	4.5	3.9	1.5	3.5	4.3	6.3	2.1	5.7	6.8
Female right	1.4	0.8	1.2	1.6	3.7	1.7	3.2	4.1	2.9	1.3	2.6	3.3	5.2	1.6	4.7	5.6
Female left	1.5	0.7	1.3	1.7	3.6	1.6	3.2	4.1	3.1	1.3	2.8	3.5	5.3	1.7	4.8	5.8
Speed to maximum displacement																
Male right	4.8	3.2	4.0	5.7	13.5	6.7	11.7	15.4	12.0	4.9	10.6	13.3	19.5	7.0	17.6	21.4
Male left	6.9	4.0	5.9	8.0	13.9	6.5	12.1	15.7	12.8	5.3	11.3	14.2	20.9	7.3	18.9	22.9
Female right	5.2	2.9	4.4	6.0	13.5	5.1	21.1	14.9	9.9	4.5	8.7	11.2	18.2	5.4	16.7	19.7
Female left	4.9	2.4	4.3	5.6	13.5	5.3	12.0	14.9	10.5	4.7	9.2	11.8	18.4	5.7	16.8	19.9

Table 5 Philtrum – differences in maximum displacement in the x, y and z directions and the Euclidian distance between males and females.

	Mean Difference (mm)	Std. Error Difference (mm)	95% CI of the Difference (mm)		p-value
Right			Lower	Upper	
x direction	-0.2	0.2	-0.6	0.3	0.439
y direction	0.0	0.4	-0.7	0.7	0.974
z direction*	0.9	0.3	0.2	1.5	0.009
Euclidian distance	0.5	0.4	-0.2	1.2	0.142
Left					
x direction*	0.8	0.2	0.3	1.2	0.001
y direction	0.2	0.4	-0.6	0.9	0.652
z direction*	1.0	0.3	0.3	1.6	0.006
Euclidian distance*	1.0	0.4	0.3	1.8	0.006

Table 6 Philtrum – differences in speed to maximum displacement in the x, y and z directions and the Euclidian distance between males and females.

	Mean Difference (mm/s)	Std. Error Difference (mm/s)	95% CI of the Difference (mm/s)		p-value
Right			Lower	Upper	
x direction	-0.3	0.6	-1.5	0.8	0.579
y direction	0.0	1.1	-2.2	2.3	0.966
z direction*	2.1	0.9	0.3	3.9	0.025
Euclidian distance	1.3	1.2	-1.1	3.7	0.290
Left					
x direction*	2.0	0.6	0.8	3.3	0.002
y direction	0.4	1.1	-1.8	2.7	0.718
z direction*	2.3	1.0	0.4	4.2	0.018
Euclidian distance*	2.5	1.3	0.0	5.0	0.049

*Indicates statistically significant result

Table 7 Cheilion – maximum displacement, median displacement, and speed to maximum displacement in the x, y and z directions and the Euclidian distance

	x direction				y direction				z direction				Euclidian distance			
	Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)	
			Lower	Upper			Lower	Upper			Lower	Upper			Lower	Upper
Maximum displacement																
Male right	8.6	1.9	8.1	9.1	9.4	2.7	8.6	10.1	10.7	2.8	10.0	11.5	16.9	3.0	16.1	17.8
Male left	9.6	2.3	8.9	10.2	9.4	2.7	8.7	10.1	10.8	3.0	10.0	11.6	17.5	3.4	16.6	18.5
Female right	7.8	1.9	7.3	8.3	8.2	2.1	7.6	8.8	10.7	2.8	9.9	11.4	15.8	2.8	15.0	16.5
Female left	8.1	1.8	7.6	8.6	8.0	2.1	7.4	8.6	10.9	2.6	10.2	11.6	16.0	2.7	15.2	16.7
Median displacement																
Male right	5.5	2.3	4.9	6.1	6.8	2.5	6.1	7.5	8.5	2.4	7.8	9.1	12.4	3.4	11.5	13.4
Male left	6.4	2.4	5.8	7.1	7.0	2.3	6.4	7.7	8.7	2.7	8.0	9.4	13.2	3.5	12.2	14.1
Female right	5.1	1.6	4.6	5.5	6.0	2.1	5.4	6.5	8.4	2.4	7.8	9.1	11.7	2.7	11.0	12.5
Female left	5.4	1.7	4.9	5.8	5.9	2.1	5.3	6.5	8.6	2.5	7.8	9.3	12.0	2.8	11.2	12.8
Speed to maximum displacement																
Male right	21.6	7.2	19.6	23.6	23.7	9.6	21.0	26.3	26.8	9.3	24.3	29.3	42.5	13.0	38.9	46.0
Male left	23.9	8.3	21.6	26.1	23.8	9.6	21.2	26.4	27.0	9.3	24.5	29.5	43.9	13.6	40.2	47.6
Female right	19.9	6.2	18.2	21.6	20.6	6.3	18.9	22.4	27.1	9.1	26.9	29.6	40.1	10.7	37.1	43.0
Female left	20.5	5.6	19.0	22.1	20.1	6.5	18.3	21.9	27.6	8.7	25.2	29.9	40.4	10.1	37.7	43.1

Table 8 Cheilion – differences in maximum displacement in the x, y and z directions, and the Euclidian distance between males and females.

	Mean Difference (mm)	Std. Error Difference (mm)	95% CI of the Difference (mm)		p-value
Right			Lower	Upper	
x direction*	0.8	0.4	0.1	1.5	0.033
y direction*	1.2	0.5	0.3	2.1	0.012
z direction	0.1	0.5	-1.0	1.1	0.884
Euclidian distance*	1.2	0.6	0.1	2.3	0.040
Left					
x direction*	1.4	0.4	0.6	2.2	0.001
y direction*	1.4	0.5	0.5	2.4	0.003
z direction	0.0	0.5	-1.1	1.0	0.953
Euclidian distance*	1.6	0.6	0.4	2.7	0.010

Table 9 Cheilion – differences in speed to maximum displacement in the x, y and z directions and the Euclidian distance between males and females.

	Mean Difference (mm/s)	Std. Error Difference (mm/s)	95% CI of the Difference (mm/s)		p-value
Right			Lower	Upper	
x direction	1.7	1.3	-0.9	4.3	0.195
y direction	3.0	1.6	-0.1	6.1	0.057
z direction	-0.3	1.8	-3.8	3.2	0.859
Euclidian distance	2.4	2.3	-2.1	7.0	0.289
Left					
x direction*	3.3	1.4	0.6	6.0	0.016
y direction*	3.7	1.6	0.5	6.8	0.022
z direction	-0.5	1.7	-4.0	2.9	0.751
Euclidian distance	3.5	2.3	-1.1	8.1	0.133

*Indicates statistically significant result

Table 10 Labiale superius (Ls) and labiale inferius (Li) – maximum displacement, median displacement and speed to maximum displacement in the x, y and z directions and the Euclidian distance

	x direction				y direction				z direction				Euclidian distance			
	Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)		Mean (mm)	SD (mm)	95% CI (mm)	
			Lower	Upper			Lower	Upper			Lower	Upper			Lower	Upper
Maximum displacement																
Male Ls	0.6	0.6	0.5	0.8	5.8	2.0	5.2	6.3	4.5	1.8	4.0	5.0	7.7	1.7	7.2	8.2
Male Li	0.9	0.7	0.7	1.1	4.4	1.9	3.9	5.0	5.3	2.1	4.7	5.8	7.2	2.2	6.6	7.8
Female Ls	0.6	0.6	0.5	0.8	5.6	1.8	5.1	6.1	3.5	1.6	3.1	4.0	6.9	1.6	6.5	7.4
Female Li	0.7	0.6	0.6	0.9	3.5	2.1	2.9	4.1	4.9	2.1	4.3	5.5	6.4	2.4	5.7	7.0
Median displacement																
Male Ls	0.5	0.4	0.4	0.6	4.4	1.8	3.9	4.9	3.3	1.5	2.9	3.7	5.8	1.9	5.3	6.3
Male Li	0.7	0.6	0.5	0.9	4.0	2.0	3.5	4.6	4.1	1.7	3.6	4.6	6.2	2.2	5.6	6.8
Female Ls	0.4	0.4	0.3	0.5	3.9	1.7	3.4	4.4	2.7	1.2	2.3	3.0	5.0	1.6	4.6	5.4
Female Li	0.5	0.4	0.4	0.6	3.3	2.1	2.8	3.9	4.1	1.8	3.6	4.6	5.7	2.3	5.0	6.3
Speed to maximum displacement																
Male Ls	1.6	1.6	1.2	2.1	14.6	6.6	12.8	16.4	11.0	4.8	9.7	12.3	19.3	6.3	17.5	21.0
Male Li	2.3	2.0	1.7	2.8	11.2	5.7	9.6	12.7	12.9	5.3	11.5	14.4	18.0	6.4	16.3	19.8
Female Ls	1.5	1.5	1.1	2.0	14.3	5.2	12.8	15.7	8.9	4.2	7.7	10.0	17.5	5.1	16.1	18.9
Female Li	1.8	1.5	1.4	2.2	9.1	6.2	7.4	10.8	12.5	6.8	10.7	14.4	16.4	7.9	14.3	18.6

Table 11 Labiale superius and labiale inferius – differences in maximum displacement in the x, y and z directions and the Euclidian distance between males and females.

	Mean Difference (mm)	Std. Error Difference (mm)	95% CI of the Difference (mm)		p-value
Labiale superius			Lower	Upper	
x direction	0.0	0.1	-0.2	0.3	0.791
y direction	0.2	0.4	-0.6	0.9	0.665
z direction*	0.9	0.3	0.3	1.6	0.005
Euclidian distance*	0.8	0.3	0.1	1.4	0.021
Labiale inferius					
x direction	0.2	0.1	-0.1	0.4	0.223
y direction*	0.9	0.4	0.1	1.7	0.021
z direction	0.4	0.4	-0.4	1.2	0.332
Euclidian distance	0.9	0.4	0.0	1.7	0.053

Table 12 Labiale superius and labiale inferius – differences in speed to maximum displacement in the x, y and z directions and the Euclidian distance between males and females.

	Mean Difference (mm/s)	Std. Error Difference (mm/s)	95% CI of the Difference (mm/s)		p-value
Labiale superius			Lower	Upper	
x direction	0.1	0.3	-0.5	0.7	0.752
y direction	0.4	1.1	-1.9	2.7	0.739
z direction*	2.2	0.9	0.4	3.9	0.014
Euclidian distance	1.8	1.1	-0.4	4.0	0.112
Labiale inferius					
x direction	0.4	0.3	-0.2	1.1	0.199
y direction	2.1	1.1	-0.2	4.3	0.073
z direction	0.4	1.2	-1.9	2.7	0.737
Euclidian distance	1.6	1.4	-1.2	4.3	0.254

*Indicates statistically significant result

Figure 1
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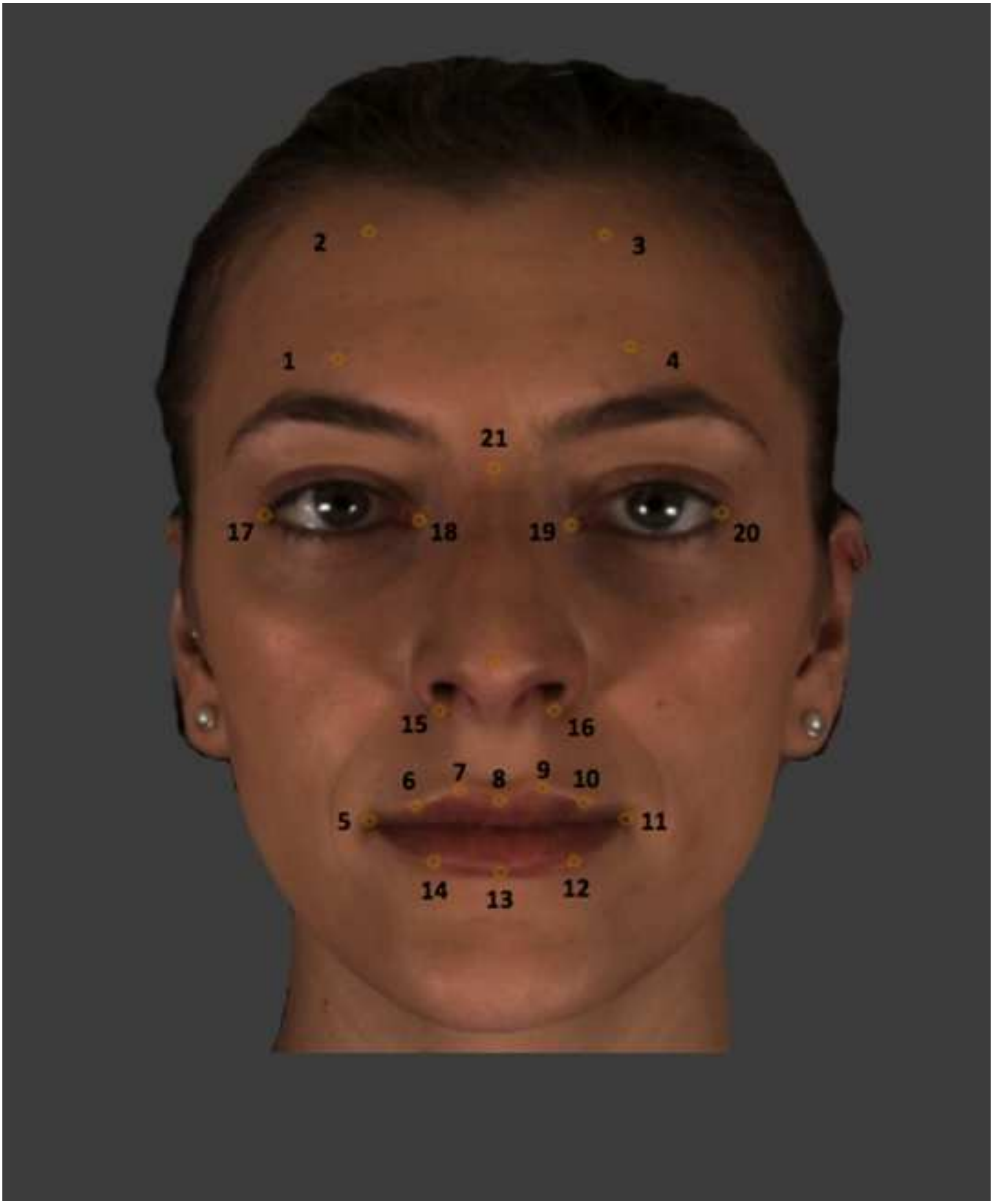

Figure 2
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