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Fluctuating asymmetry of dynamic smiles in normal individuals

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- 21
- 22 Key words
- stereophotogrammetry; dynamic; 3D motion capture; normal; 4D; adult; fluctuating
- 24 asymmetry; Procrustes
- 25 Short title : Fluctuating asymmetry of dynamic smiles

26 **ABSTRACT**

The aim of this study was to use 3D motion facial capture technology to quantify the 27 fluctuating dynamic facial asymmetry, during smiling, in a group of "normal" adults. 54 28 male and 54 female volunteers were recruited. Each subject was imaged using a 29 passive markerless 3D motion capture system (DI4D). Eighteen landmarks were 30 tracked through the 3D capture sequence. Based on either a clinically derived midline 31 32 or on Procrustes alignment a facial asymmetry score was calculated; based on the Euclidian distance between landmark pairs. Facial asymmetry scores were 33 34 determined at three-time point; rest, median and maximum frame. Based on both the clinically derived midline and on Procrustes alignment, the differences between males 35 and females, and at the three different time points were not clinically significant. 36 However throughout a smile, facial and lip asymmetry scores increase over the 37 duration of the smile. Fluctuating facial asymmetry exists within individuals, as well as 38 between individuals. The use of Procrustes superimposition or a clinically derived 39 midline produces similar asymmetry scores and is valid for symmetrical faces. 40 However with facial asymmetry, Procrustes superimposition may not be a valid 41 measure, and the use of a clinically derived midline may be more appropriate but this 42 requires further investigation. 43

44

45 **INTRODUCTION**

Facial attractiveness and beauty are important underling psychological cues in judging 46 an individual's health. Evolutionary psychology proposes that there are four main cues 47 that determine facial attractiveness with respect to mate preference; these are 48 averageness, symmetry, youthfulness and sexual dimorphism¹. Facial symmetry, from 49 a clinical perspective, is probably best thought of as "reflection symmetry"; where 50 features of the face do not change on reflection. Perfectly symmetrical faces do not 51 occur naturally and there is a baseline level of symmetry or "fluctuating asymmetry" 52 53 between individuals, which is characterized by small random deviations from perfect bilateral symmetry². Individuals with a marked facial asymmetry are known to have a 54 lower quality of life³. Hence one of the aims of facial reconstructive surgery and 55 orthognathic surgery is to minimise facial asymmetry and to correct any clinically 56 significant facial asymmetry respectively. As well as assessing pan-facial symmetry, 57 the symmetry of specific facial regions have been reported, for instance the nasio-58 59 labial region in cleft lip and palate patients⁴, the mandible in orthognathic patients⁵, the nose in rhinoplasty patients and the orbits in cranial abnormalities. It is crucial that the 60 clinical team is aware of the site and severity of the asymmetry in comparison to a 61 "normal" group before embarking on surgical correction of the facial deformity. 62

63

Previously, the assessment of static facial symmetry (at rest) in a normal group of individuals has been based on two-dimensional (2D) images, using angular and linear measurements⁶ and statistical shape analysis⁷. The introduction of three-dimensional (3D) imaging has allowed further comprehensive evaluation of static facial symmetry. A recent study assessed the 3D facial symmetry of 20 male and 20 female normal individuals at two discrete time points, i.e. rest and at maximum smile⁸. The study

70 found a statistically significantly higher asymmetry score at maximum smile than at rest based on 27 landmarks. Rather than assessing the expression at rest and 71 maximum smile, dynamic facial asymmetry assessment over the entire smile should 72 be the gold standard. Recently, this has partly been addressed in a comparative study 73 of a small group of non-cleft controls (n=11) with repaired unilateral cleft lip and palate 74 patients (n=12) using 3D motion capture technology⁹. However, only the motion of the 75 upper lip was assessed; at the oral commissure, within the cupids bow, the cupids 76 bow peak, upper lip lateral to the cupids bow and the mid philtral ridge. Although these 77 78 studies provide some limited information, they either fail to capture the true dynamic nature of smiling or present limited data. 79

80

The development of 3D motion capture technology has allowed capture of non-verbal expressions from rest to maximum expression. To assess reflective symmetry, the left and right sides of the face need to reflected or mirrored around a mid-facial plane. The mid-facial plane can be clinically determined based on anatomical landmarks, or mathematically derived¹⁰. The later analysis is based on Procrustes "best-fit" superimposition where distances between the original 3D landmark configuration and their mirror image can be calculated and expressed as an "asymmetry score" ^{11, 12}.

88

The aim of this study is to use 3D motion facial capture technology to quantify the fluctuating dynamic facial asymmetry between a group of clinically "normal" Caucasian adult males and females. The null hypothesis states that there is no difference in the magnitude of overall facial asymmetry, based on the asymmetry score, between genders. In addition, the effects of using a clinically or mathematically derived midline will be investigated.

95

96 MATERIALS AND METHODS

97 Sample size calculation

A pilot study was undertaken to determine the asymmetry scores of a group of 7 volunteers with a clinically significant asymmetric smile (assessed by BSK and CL), and 7 individuals with a clinically symmetrical smile. The difference in asymmetry scores of 0.5 determined the threshold of clinical significance. This together with the standard deviation of the differences (0.7), power of 0.8 and statistical difference of (0.0035), following a Bonferroni correction for multiple testing, resulted in a sample size of a minimum of 43 individuals per group.

105

106 Subjects

Following ethical approval from the Dental Research Ethics Committee (DREC) at the 107 University of Leeds, U.K. (DREC reference 240915/BK/179), 54 male and 54 female 108 volunteers were recruited to take part in the study. Volunteers were recruited if they 109 meet the following inclusion criteria: they were between the ages of 18 and 40 years, 110 no previous facial surgery, no lip piercing, no history of facial trauma or neurological 111 facial problems. In addition subjects recruited were clinically symmetrical and had 112 class I incisors as judged by one experienced Consultant NHS Orthodontist and an 113 114 orthodontic trainee.

115

116 Imaging using DI4D[™] Pro passive stereophotogrammetric capture system

Each subject was imaged using a passive markerless 3D motion capture system (DI4D, Dimensional Imaging, Hillington, Glasgow). Prior to capture, the system was calibrated according to the manufacturer's instructions. The procedure for capture has

been described elsewhere in detail¹³. In summary, each subject practiced the rest 120 position and maximum smile expression until the researcher was happy they had fully 121 understood the facial expression they would need to perform. Following this, the 122 patients were imaged at 60 3D images per second, performing the desired facial 123 expression from rest to maximum smile. Each capture sequence was approximately 3 124 seconds in duration. The captured sequence and appropriate calibration file were 125 imported into the specialised software DIHydra, which generated approximately 180 126 individual 3D images, which were saved for post-capture processing. 127

128

129 Post-capture processing

For each subject, the first frame of the sequence was imported into DI3DView 130 software. Using the alignment function, the initial image was re-orientated so the x-131 plane (axial plane) passed through the inter-canthal line and was parallel to the 132 Frankfort plane, the y-plane (sagittal plane) passed through the mid inter-canthal point 133 at nasion, and the z-plane (coronal plane) passed through the bilateral tragal points. 134 The image was adjusted manually until both operators (BSK and CL) agreed the 135 orientation was correct, Figure 1. The re-oriented 3D image was then saved. The 136 transformation matrix used to re-orientate the initial image was used to re-orientate all 137 of the remaining images in the sequence into the new co-ordinate system. The initial 138 139 image was landmarked with 22 landmarks (Table 1) and the same landmarks were tracked through the entire image sequence using the automatic tracking function within 140 the software. The accuracy of the automatic landmark tracking algorithm has 141 previously been validated and was found to be clinically acceptable¹⁴. To account for 142 head movement, the forehead landmarks (1 to 4) were used for image stabilisation, 143 while the remaining 18 landmarks were used in the analysis. Finally, the tracked 144

landmark data (x, y and z-coordinates) were exported in .PC2 file format and
converted into a format readable by Microsoft Excel using in-house software.

147

148 ANALYSIS

149 Asymmetry score based on clinically derived midline

The 3D co-ordinate configuration (original configuration) for each frame was imported 150 into MATLAB from the Microsoft Excel file. Firstly, the centroid (geometric centre) of 151 the 18 landmark configuration was computed. Secondly, the 3D configuration was 152 153 scaled to a common centroid size. Finally, a "reflected" landmark configuration was produced by reflecting the re-scaled original landmark configuration around the sagittal 154 plane, which represented the "clinically derived midline". An "individual midline 155 configuration" was created by calculating the mean of the original configuration and its 156 reflected version. The Euclidian distances between each of the pairs of landmarks, i.e. 157 the original landmark and the individualised midline, were calculated. The facial 158 asymmetry score was calculated as follows; the Euclidian distance between landmark 159 pairs were squared and summed, then divided by the total number of landmarks 160 (n=18) in the analysis. This procedure was repeated for each of the 3D images in the 161 subject's 3D capture sequence from rest to maximum smile. 162

163

The higher the facial asymmetry score, the greater the disparity between the landmark pairs and so the greater the degree of facial asymmetry. A score of zero would represent a perfectly symmetrical face. A facial asymmetry score was produced for each individual frame from rest to maximum smile. The facial asymmetry score was recorded at three time points; rest (T_0), median time point (T_1) and maximum smile

(T₂). The median time point was defined as the middle frame of the sequence fromrest to maximum smile.

171

172 Asymmetry score based on Procrustes alignment

As previously described, the 3D facial landmark configuration (original configuration) 173 was imported into MATLAB. New code was written to align the 3D configurations using 174 175 generalised Procrustes analysis instead of using the clinically derived midline. As before, this involved computing the centroid for each 3D configuration and scaling the 176 177 configuration to a common centroid size. However, this time the original landmark configuration was reflected around an arbitrary plane, translating and rotating the 178 reflected 3D configuration over the original configuration to achieve "best-fit". Best-fit 179 was achieved when the sum of the squared distances between the original landmark 180 configuration and its reflected 3D configuration were minimal. For each frame an 181 'individual midline configuration' was created by calculating the mean of the original 182 configuration and its reflected version and the facial asymmetry score was calculated.⁸ 183 In addition to the facial asymmetry score based on the 18 landmark pairs, a 184 decomposed lip asymmetry score based on the 10 lip landmarks alone was 185 calculated¹⁵. This method allows facial features, i.e. the lips, which have different 186 numbers of landmarks, to be compared on the same scale. 187

188

189 Error study

The error of the method was determined by taking the facial capture sequence of 12 volunteers at random and repeating the alignment and landmarking procedure as previously described. The landmarking error was not assessed in isolation, as there would be additional error associated with image re-orientation. There was a period of

over 4 weeks between first and second reorientation and landmark digitisations to
avoid memory bias. The difference in magnitude of the asymmetry scores as well as
the random and systematic error, was assessed between the two digitisations.

197

198 **RESULTS**

199 Error study

The difference in magnitude of the asymmetry score for the face and lips was less than 0.1 between the two digitisations, Table 2. Systematic error was assessed by paired *t*-tests and random error assessed by coefficients of reliability. No systematic errors were observed and all coefficients of reliability were above 90%.

204

205 Asymmetry score based on clinically derived midline

206 Gender differences

Following a two-sample *t*-test, there were no statistical differences between the female 207 and male facial asymmetry scores at rest (p=0.363), median time point (p=0.559) and 208 at maximum smile (p=0.888). For the lips, males presented with a statistically 209 significantly higher lip asymmetry score than females (p=0.043) at the median time 210 point; however the difference in asymmetry score was only 0.18. There were no 211 significant differences in asymmetry scores at rest (p=0.217) and at maximum smile 212 213 (p=0.284). As these differences were not clinically significant, the results for males and females were combined for further analysis. 214

215

216 Temporal differences

A one-way repeated measures analysis of variance (ANOVA) with a Bonferroni adjustment was used to determine whether there are any statistically significant

differences between the facial asymmetry scores at rest, median time point and 219 maximum smile. There was a significantly lower facial asymmetry score at rest (0.76) 220 compared to the median time point (0.93) and maximum expression (0.98). In addition 221 there was as a significant difference between the median time point (0.93) and 222 maximum expression (0.98). This was also the case for the lips; at rest (0.93), at the 223 median time point (1.34) and maximum expression (1.45), Table 3. None of the mean 224 225 differences or 95% confidence intervals for the facial or lip asymmetry scores between the three time points were greater than 0.5. 226

227

228 Asymmetry score based on Procrustes alignment

229 Gender differences

Following a two-sample *t*-test there were statistical difference between the female and 230 male facial asymmetry scores at rest (p=0.041), median time point (p=0.001) and at 231 maximum smile (p=0.008). This would not be clinically significant as none of the mean 232 differences or 95% confident limit intervals for the facial or lip asymmetry scores 233 reached the threshold value of 0.5 derived following the pilot study. In all cases males 234 had higher scores than females. For the lips, there was a statistical difference in 235 asymmetry scores between males and females at the median time point (p=0.002) 236 and at maximum smile (p=0.007). There was no difference at rest (p=0.064). Again 237 the differences were sub-clinical and the results for males and females were combined 238 for further analysis. 239

240

241 Temporal differences

A one-way repeated measures analysis of variance (ANOVA) with a Bonferroni adjustment showed a significantly lower facial asymmetry score at rest (0.81) than at

the median time point (0.99), and at maximum smile (1.02). There was no significant difference between the median time point and maximum smile. For the lips, there were statistical differences in asymmetry score at rest (1.05), median time point (1.42) and at maximum smile (1.50), Table 4. None of the mean differences or 95% confidence intervals for the facial or lip asymmetry scores between the three time points were greater than 0.5.

250

251 **DISCUSSION**

252 It is widely accepted that facial asymmetry is an undesirable characteristic that has a negative impact on the quality of life of an individual³. Currently, quantifying the degree 253 of facial asymmetry is based on static two-dimensional or three-dimensional images. 254 This method of assessment, based on two time points, is unable to capture the 255 dynamic nature of the smile. The present study uses a validated and clinically 256 acceptable imaging modality, passive 3D motion markerless stereophotogrammetry, 257 to capture dynamic facial motion. The system was set to capture the smile at 60 3D 258 frames per second at the correct fidelity. The inclusion criteria, based on assessment 259 of the 3D images and examination of the volunteers, contributed to a "normal" 260 homogenous sample of female and male adult patients. The authors acknowledge the 261 cost and expertise involved in the routine capture of facial dynamics using this 262 technology but such methods could be beneficial to objectively quantify the complex 263 dynamic nature of facial motion following surgical and non-surgical intervention. For 264 example, monitoring the resolution of Bell's palsy, post-stroke rehabilitation or 265 following facial nerve grafting. Previous studies, based on clinical anthropometric 266 measurements and on static 3D images, have reported a baseline level of asymmetry, 267 at rest, in clinically symmetrical faces between individuals^{8,16,17,18,19,20,21,22}. A statistical 268

difference in asymmetry score, at rest, between genders was not found in the present
study, which was in agreement with previously published data^{8,17,20,23}.

The present study also found no clinical difference in facial and lip asymmetry scores 271 between males and females half way through the smile (median time point) and 272 maximum smile. Direct comparison of the results with previous studies is not possible 273 as the outcome measures vary between studies. Published outcome measures 274 include asymmetry based on shell-to-shell deviations (root mean square distances) 275 between the original and mirrored facial meshes of individuals^{17,18,19,20}. This method 276 277 may yield incorrect results as the deviations are based on distances between two nearest points on a surface rather than corresponding points²⁴. In addition the use of 278 Euclidean Distance Matrix Analysis (EDMA) to quantify changes in shape has also 279 been reported²³. Other studies have used landmark analysis and morphometric 280 outcomes to present an "asymmetry index"²². The only study which uses a similar 281 method of analysis and "asymmetry score" found very similar asymmetry scores at 282 rest (0.80) and at maximum smile $(0.91)^8$. This was a 3D study and assessed the 283 facial asymmetry score, based on 27 landmarks. 284

285

A novel finding of the present study was that facial asymmetry increases over the 286 duration of the smile in a non-linear fashion. This would suggest that with minimal oral 287 288 facial musculature activity, faces at rest, are at their most symmetrical. From rest to median smile, individuals have greater scope to smile asymmetrically as there are 289 minimal anatomical constraints. At the extremes of the smile the muscle bundle length, 290 orientation and overlying facia may begin to restrict this ability. This could result in a 291 non-linear increase in asymmetry over time. Hallac et al., (2015) reported the mean 292 asymmetry score from rest to maximum smile based on a small number of controls⁹. 293

Using the mean asymmetry score over the entire duration of the smile may over- or under- estimate the asymmetry score depending on the individual scores or outliers for each frame between rest and maximum smile. The present study uses a specific, well defined, third time point (median frame) between rest and maximum smile for each individual to overcome this problem. Even though there was a statistically significant increase in smile asymmetry over the duration of the smile, it would not be clinically significant. This would be as expected based on the inclusion criteria.

301

302 The asymmetry scores at the three time points based on the clinical midline, and on Procrustes superimposition, were similar. This would be expected as both methods 303 scale the 3D landmark configuration to a common centroid size. Using Procrustes 304 superimposition, the original and reflected configurations are translated to a common 305 centroid position, then rotated to minimise the distances between the landmarks for 306 "best fit". Using the clinically derived midline, the landmarks are reflected following 307 rescaling. For symmetrical faces there would be minimal translation and rotation 308 during Procrustes superimposition, as the centroids for the original and reflected 309 landmark configurations would be identical in size and similar in location; hence the 310 small differences between the asymmetry scores compared to the clinically derived 311 midline technique. Interestingly, the Procrustes based asymmetry scores were slightly 312 313 larger than those based on the clinically derived midline. During Procrustes superimposition, all the landmarks will move as the 3D configuration re-orientates and 314 so the distance between landmark pairs will all increase (unless there is absolutely no 315 asymmetry). On the other hand, landmarks in the midline, using the clinically derived 316 midline, will not move and so will reduce the mean score by contributing in number but 317 not in magnitude. 318

This is not the case for asymmetrical faces. In this example of an individual presenting 320 with Bell's Palsy affecting the left side of the face, the asymmetry scores are greater 321 when using the clinically derived midline than using Procrustes superimposition, 322 Figure 2. For the global facial asymmetry score, the differences are less marked 323 because the landmark configuration following Procrustes superimposition will re-324 325 orientate the entire 3D facial landmark configuration for "best fit". Clinically this would be equivalent to the patient smiling asymmetrically, but changing the orientation of 326 327 their head to minimise their smile asymmetry. Even though the smile is asymmetric, the displacement of the landmarks around the upper face and eyes during the 328 Procrustes superimposition are contributing to the overall global asymmetry score, 329 Figure 3. Procrustes superimposition is integral in Procrustes analysis, which 330 compares the shape of two objects, for example human skull shapes.²⁵ This method 331 of superimposition works well on static objects. However applying the same technique 332 to a dynamic series of objects i.e. a non-symmetric smiling face forces the "best fit" 333 component of the algorithm to over-ride the need to maintain the orientation of the 334 facial image. In other words shape differences are determined but at the cost of 335 reducing the clinically validity of the outcome. This situation does not occur clinically, 336 and a more clinically valid representation is obtained using the clinically derived 337 338 midline, where the upper face remains static and the true asymmetry of the smile is seen over the expression of the smile, Figure 4. The use of a clinically derived midline 339 may be controversial but a previous study has shown that "direct manual placement" 340 of geometric vertical midlines on facial images was rated as the best method of 341 determining the midline over automated methods.¹⁰ 342

343

In conclusion, fluctuating facial asymmetry exists within individuals, as well as between 344 individuals. The difference between facial and lip asymmetry scores between males 345 and females is probably subclinical. Throughout a smile, facial and lip asymmetry 346 scores increase over the duration of the expression, from rest to maximum smile. The 347 use of Procrustes superimposition or a clinically derived midline produces similar 348 asymmetry scores and is valid for symmetrical faces. However with facial asymmetry, 349 Procrustes superimposition may not be a valid measure, and the use of a clinically 350 derived midline may be more appropriate. A novel baseline data set of dynamic facial 351 352 and lip asymmetry scores has been presented, which can be used as a yard-stick to compare the outcome of facial surgery or emotion where facial function may be 353 affected. 354

- 355
- 356 **Declarations**
- 357 **Funding:** None
- 358 **Competing Interests:** None
- 359 Ethical Approval: Ethical approval from the Dental Research Ethics Committee
- 360 (DREC) at the University of Leeds, U.K. (DREC reference 240915/BK/179).
- 361 **Patient Consent:** Patient consent has been obtained to publish clinical photographs

362 **REFERENCES**

- Bashour M. An objective system for measuring facial attractiveness. *Plast Reconstr Surg* 2006;**118**:757-74.
- Tomkins JL, Kotiaho JS Fluctuating Asymmetry. In: Encyclopedia of Life
 Sciences. MacMillan Publishers Ltd., Nature Publishing Group, London;
 2002:1–5.
- Millsopp L, Brandom L, Humphris G, Lowe D, Stat C, Rogers S. Facial
 appearance after operations for oral and oropharyngeal cancer: a comparison
 of casenotes and patient-completed questionnaire. *Br J Oral Maxillofac Surg* 2006;**44**:358-63.
- Asher-McDade C, Roberts C, Shaw WC, Gallager C. Development of a method
 for rating nasolabial appearance in patients with clefts of the lip and palate. *Cleft Palate Craniofac J* 1991;**28**:385-90.
- 5. Edler RJ, Wertheim D, Greenhill D, Jaisinghani A. Quantitative use of
 photography in orthognathic outcome assessment. *Br J Oral Maxillofac Surg* 2011;49:121-6.
- 378 6. Lee MS, Chung DH, Lee JW, Cha KS. Assessing soft-tissue characteristics of
 379 facial asymmetry with photographs. *Am J Orthod Dentofacial Orthop*380 2010;**138**:23-31.
- Frcan I, Ozdemir ST, Etoz A, Sigirli D, Tubbs RS, Loukas M, Guney I. Facial
 asymmetry in young healthy subjects evaluated by statistical shape analysis. *J Anat* 2008;213:663-9.
- Barby LJ, Millett DT, Kelly N, McIntyre GT, Cronin MS. The effect of smiling
 on facial asymmetry in adults: a 3D evaluation. *Aust Orthod J* 2015;**31**:132-7.

- Hallac RR, Feng J, Kane AA, Seaward JR. Dynamic facial asymmetry in
 patients with repaired cleft lip using 4D imaging (video stereophotogrammetry).
 J Craniomaxillofac Surg 2017;45:8-12.
- 10. Wu J, Heike C, Birgfeld C, Evans K, Maga M, Morrison C, Saltzman B, Shapiro

390

L, Tse R. Measuring Symmetry in Children With Unrepaired Cleft Lip: Defining

- a Standard for the Three-Dimensional Midfacial Reference Plane. *Cleft Palate Craniofac J* 2016;**53**:695-704.
- 11. Mardia KV, Bookstein F, Moreton I. Statistical assessment of bilateral symmetry
 of shapes. *Biometrika* 2000; 87: 285–300.
- 12. Hood CA, Bock M, Hosey MT, Bowman A, Ayoub AF. Facial asymmetry-3D
 assessment of infants with cleft lip & palate. *Int J Paediatr Dent* 2003;**13:**40410.
- 13. Lowney CJ, Hsung TC, Morris DO, Khambay BS. Quantitative dynamic analysis
 of the nasolabial complex using 3D motion capture: A normative data set. J
 Plast Reconstr Aesthet Surg 2018;**71**:1332-45.
- 401 14. Al-Anezi T, Khambay B, Peng MJ, O'Leary E, Ju X, Ayoub A. A new method for
 402 automatic tracking of facial landmarks in 3D motion captured images (4D). *Int*403 *J Oral Maxillofac Surg* 2013;**42**:9-18.
- 404 15. Bock M, Bowman, A. On the measurement and analysis of asymmetry with
 405 applications to facial modeling. *J R Stat Soc Ser C Appl Stat* 2006;**55**:77-91
- 406 16. Farkas LG, Cheung G. Facial asymmetry in healthy North American
 407 Caucasians: an anthropometrical study *Angle Orthod* 1981;**51**:70-77.
- 408 17. Djordjevic J, Toma AM, Zhurov AI, Richmond S. Three-dimensional
 409 quantification of facial symmetry in adolescents using laser surface scanning.
 410 *The European Journal of Orthodontics*. 2014;**36**:125-132.

- 411 18. Kornreich D, Mitchell AA, Webb BD, Cristian I, Jabs EW. Quantitative
 412 Assessment of Facial Asymmetry Using Three-Dimensional Surface Imaging in
 413 Adults: Validating the Precision and Repeatability of a Global Approach. *Cleft*414 *Palate Craniofac J* 2016;**53**:126-31.
- 415 19. Patel A, Islam SM, Murray K, Goonewardene MS. Facial asymmetry
 416 assessment in adults using three-dimensional surface imaging. *Prog Orthod*,
 417 2015:36.
- 20. Alqattan M, Djordjevic J, Zhurov AI, Richmond S. Comparison between
 landmark and surface-based three-dimensional analyses of facial asymmetry
 in adults. *Eur J Orthod* 2015;**37**:1-12.
- 21. Taylor HO, Morrison CS, Linden O, Phillips B, Chang J, Byrne ME, Sullivan SR,
 Forrest CR. Quantitative facial asymmetry: using three-dimensional
 photogrammetry to measure baseline facial surface symmetry. *J Craniofac Surg* 2014;**25**:124-8.
- 425 22. Huang CS, Liu XQ, Chen YR. Facial asymmetry index in normal young adults.
 426 Orthod Craniofac Res 2013;16:97-104.
- 427 23. Ferrario VF, Sforza C, Miani A Jr, Serrao G. A three-dimensional evaluation of
 428 human facial asymmetry. *J Anat* 1995;**186**:103-10.
- 429 24. Khambay B, Ullah R. Current methods of assessing the accuracy of three 430 dimensional soft tissue facial predictions: technical and clinical considerations.
- 431 *Int J Oral Maxillofac Surg* 2015;**44**:132-8.
- 432 25. Gateño J, Jones TL, Shen SGF, Chen KC, Jajoo A, Kuang T, English JD, Nicol
- 433 M, Teichgraeber JF, Xia JJ. Fluctuating asymmetry of the normal facial 434 skeleton. *Int J Oral Maxillofac Surg* 2018;**47**:534-40.

Table 1 Landmark definitions

Number	Name	Landmark definition
1 - 4	Stabilisation points	Points placed in each corner of the forehead, used as stable points to eliminate head movement.
5	Right Cheilion	Point located at the right labial commissure.
11	Left Cheilion	Point located at the left labial commissure.
6		Point located on the vermilion border midway between right christa philtre.
10		Point located on the vermilion border midway between left christa philtre.
7	Right christa philtre	Point on the right crest of the philtrum, located just above the vermilion border.
9	Left christa philtre	Point on the left crest of the philtrum, located just above the vermilion border.
13	Labrale inferius	Point indicating the lower border of the lower lip.
12		Point midway between right cheilion and labrale inferius.
14		Point midway between left cheilion and labrale inferius.
15	Right subalare	Point on the margin of the base of the right ala where it disappears into the skin of the upper lip.
16	Left subalare	Point on the margin of the base of the left ala where it disappears into the skin of the upper lip.
17	Right exocanthion	Point on the outer commissure of the right eye fissure.
20	Left exocanthion	Point on the outer commissure of the left eye fissure.
18	Right endocanthion	Point on the inner commissure of the right eye fissure.
19	Left endocanthion	Point on the inner commissure of the left eye fissure.
21	Nasion	Point in the midline of the both the nasal root and the nasofrontal suture, always above the line that connects the two inner canthi.
22	Pronasale	Point on the tip of the nose.

Table 2Error study - the difference in magnitude of the asymmetry score for the face and lips

	Rest (T ₀)				Median time point (T1)				Maximum smile (T ₂)			Г2)
	Face		Lips		Face		Lips		Face		Lips	
	Mean SD		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Asymmetry score based on clinically derived midline	0.1	0.2	-0.1	0.4	0.1	0.2	-0.1	0.3	0.1	0.2	0.0	0.4
Asymmetry score based on Procrustes alignment	0.0	0.1	0.3	0.2	0.0	0.1	-0.1	0.1	0.0	0.1	-0.1	0.2

Table 3Descriptive statistics showing the differences in asymmetry score, based on clinically derived midline, between
females, males and combined values at rest, median and maximum frames for the face and lips during smiling.

		Res	st (T ₀)		M	edian ti	me point	(T ₁)	Maximum smile (T ₂)			
_	Mean	SD	95% CI		Mean	SD	95% CI		Mean	SD	95% CI	
			Lower	Upper			Lower	Upper			Lower	Upper
Face												
Females	0.77	0.20	0.72	0.83	0.91	0.22	0.87	0.85	0.98	0.26	0.91	1.05
Males	0.76	0.19	0.71	0.81	0.94	0.27	0.87	1.01	0.99	0.33	0.90	1.07
Combined	0.76	0.20	0.73	0.80	0.93	0.24	0.88	0.97	0.98	0.29	0.93	1.04
Lips												
Females	0.90	0.28	0.83	0.98	1.25	0.37	1.15	1.35	1.40	0.48	1.27	1.53
Males	0.97	0.26	0.90	1.04	1.43	0.52	1.57	1.29	1.50	0.48	1.37	1.63
Combined	0.93	0.27	0.88	0.99	1.34	0.46	1.25	1.43	1.45	0.48	1.36	1.54

Table 4Descriptive statistics showing the differences in asymmetry score, based on Procrustes alignment, between females,
males and combined values at rest, median and maximum frames for the face and lips during smiling.

	Rest (T ₀)				Me	edian ti	me point	(T ₁)	Maximum smile (T2)			
-	Mean	SD	95% CI		Mean	SD	95% CI		Mean	SD	95% CI	
			Lower	Upper			Lower	Upper			Lower	Upper
Face												
Females	0.78	0.19	0.73	0.83	0.91	0.23	0.85	0.97	0.94	0.22	0.88	1.00
Males	0.85	0.19	0.80	0.90	1.06	0.24	1.00	1.13	1.10	0.37	1.00	1.20
Combined	0.81	0.19	0.78	0.85	0.99	0.25	0.94	1.03	1.02	0.31	0.96	1.08
Lips												
Females	1.00	0.28	0.92	1.07	1.31	0.37	1.21	1.41	1.39	0.37	1.29	1.48
Males	1.09	0.26	1.03	1.16	1.54	0.39	1.43	1.64	1.59	0.40	1.48	1.69
Combined	1.05	0.27	0.99	1.10	1.42	0.39	1.35	1.50	1.49	0.40	1.41	1.56

Figure legends

- Figure 1 Re-orientated image x-plane (axial plane green) passed through the inter-canthal line and parallel to the Frankfort plane, the yplane (sagittal plane - red) passing through the mid inter-canthal point at nasion, and the z-plane (coronal plane - blue) passing through the bilateral tragal points.
- Figure 2 Asymmetry scores based the clinically derived midline than using Procrustes superimposition.
- Figure 3 In an asymmetric, the displacement of the landmarks around the upper face and eyes during the Procrustes superimposition are contributing to the overall global asymmetry score.
- Figure 4 Using the clinically derived midline, the upper face remains static and the true asymmetry of the smile is seen over the expression of the smile. Using Procrustes superimposition the face changes in orientation during smiling, which is not valid clinically.