Supplementary Material

MeshMonk: open-source large-scale intensive 3D phenotyping

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# Supplementary Data

**Supplementary Table 1.** Descriptive data for the validation sample used. These data are included only to describe the variation present in the sample and were not used as covariates in statistical analyses.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ID | Sex | Age | Height (cm) | Weight (kg) | Self-identified population | Camera |
| 61549 | F | 33 | 155.00 | 48.00 | Admixed African and European | 2006, 2-pod |
| 61587 | F | 20 | 158.00 | 43.00 | Italian | 2006, 2-pod |
| 61622 | M | 21 | 175.00 | 71.99 | Italian | 2006, 2-pod |
| 62102 | M | 22 | 178.00 | 60.01 | Polish | 2006, 2-pod |
| 62588 | M | 21 | 172.00 | 57.02 | Portuguese | 2006, 2-pod |
| 62633 | M | 41 | 176.00 | 76.02 | Portuguese | 2006, 2-pod |
| 62659 | F | 28 | 169.00 | 57.02 | Portuguese | 2006, 2-pod |
| 62677 | M | 24 | 175.00 | 65.00 | Portuguese | 2006, 2-pod |
| 62695 | F | 30 | 165.00 | 66.00 | Portuguese | 2006, 2-pod |
| 63096 | F | 20 | 165.10 | 57.15 | Irish | 2006, 2-pod |
| 63123 | F | 27 | 165.00 | 57.15 | Irish | 2006, 2-pod |
| 63151 | F | 43 | 165.10 | 69.85 | Irish | 2006, 2-pod |
| 63156 | M | 19 | 184.00 | 60.33 | Irish | 2006, 2-pod |
| 63173 | M | 19 | 180.00 | 66.00 | Irish | 2006, 2-pod |
| 131213 | M | 23 | 172.55 | 72.85 | Broadly European | 2013, 2-pod |
| 140241 | F | 33 | 160.70 | 57.40 | Unknown | 2014, 3-pod |
| 140268 | M | 19 | 179.00 | 103.80 | Mixed European and European American | 2014, 3-pod |
| 140679 | M | 62 | 166.00 | 63.30 | Mixed European and European American | 2014, 3-pod |
| 140721 | F | 26 | 165.00 | 101.30 | Mixed European and European American | 2014, 3-pod |
| 140739 | F | 73 | 169.00 | 83.00 | Mixed European and European American | 2014, 3-pod |
| 140956 | M | 21 | 168.60 | 70.80 | Broadly European | 2014, 3-pod |
| 141280 | F | 79 | 149.86 | 70.31 | Broadly European | 2014, 3-pod |
| 141527 | F | 66 | 170.18 | 97.07 | Mixed European and European American | 2014, 3-pod |
| 141563 | F | 24 | 154.94 | 52.16 | Mixed European and European American | 2014, 3-pod |
| 141706 | F | 63 | 170.18 | 81.65 | Broadly European | 2014, 3-pod |
| 141713 | F | 53 | 162.56 | 86.18 | Broadly European | 2014, 3-pod |
| 141869 | F | 25 | 152.40 | 46.72 | Mixed European and European American | 2014, 3-pod |
| 141875 | F | 55 | 165.10 | 62.60 | Mixed European and European American | 2014, 3-pod |
| 141913 | F | 20 | 162.56 | 68.04 | Mixed European and European American | 2014, 3-pod |
| 141979 | F | 65 | 157.48 | 54.43 | Mixed European and European American | 2014, 3-pod |
| 143007 | F | 27 | 156.40 | 62.40 | Mixed European and European American | 2014, 3-pod |
| 143076 | F | 19 | 181.00 | 68.40 | Mixed European and European American | 2014, 3-pod |
| 143093 | F | 18 | 179.00 | 65.00 | Broadly European | 2014, 3-pod |
| 143126 | F | 20 | 162.30 | 98.90 | Broadly European | 2014, 3-pod |
| 143162 | F | 19 | 170.00 | 75.70 | Broadly European | 2014, 3-pod |
| 143221 | F | 53 | 164.00 | 50.80 | Mixed European, Jewish | 2014, 3-pod |
| 143235 | F | 22 | 169.90 | 55.00 | Mixed European and European American | 2014, 3-pod |
| 143340 | M | 28 | 174.00 | 65.30 | Broadly European | 2014, 3-pod |
| 143578 | F | 23 | 161.00 | 78.20 | Broadly European | 2014, 3-pod |
| 143651 | F | 19 | 162.00 | 59.40 | Mixed European, Jewish | 2014, 3-pod |
| 143670 | F | 21 | 164.60 | 67.20 | Mixed European and European American | 2014, 3-pod |

# Supplementary Figures and Tables

## Supplementary Figures

## Supplementary Tables

**Supplementary Table X**. Intra- and inter-observer error along the *x*, *y*, and *z* axis, averaged across images for each landmark. The means for each observer as well as the inter-observer error are reported in Table X of the accompanying manuscript.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Landmark | Standard deviation (mm) | | | | | | | | RMSE (mm) | | | |
| *Observer AJ* | | | | *Observer JW* | | | | *Inter-observer* | | | |
| *X* | *Y* | *Z* | *Mean* | *X* | *Y* | *Z* | *Mean* | *X* | *Y* | *Z* | *Mean* |
| Alar curvature left | 0.21 | 0.68 | 0.92 | **0.60** | 0.15 | 0.55 | 0.61 | **0.43** | 0.17 | 0.53 | 0.60 | **0.43** |
| Alar curvature right | 0.21 | 0.75 | 0.93 | **0.63** | 0.13 | 0.46 | 0.54 | **0.38** | 0.17 | 0.48 | 0.75 | **0.46** |
| Chelion left | 0.86 | 0.54 | 0.43 | **0.61** | 0.67 | 0.35 | 0.32 | **0.45** | 0.84 | 0.42 | 0.51 | **0.59** |
| Chelion right | 0.81 | 0.49 | 0.50 | **0.60** | 0.74 | 0.35 | 0.39 | **0.49** | 0.60 | 0.38 | 0.28 | **0.42** |
| Crista philtri left | 0.55 | 0.67 | 0.29 | **0.50** | 0.43 | 0.30 | 0.18 | **0.30** | 0.73 | 0.65 | 0.27 | **0.55** |
| Crista philtri right | 0.55 | 0.71 | 0.34 | **0.54** | 0.47 | 0.25 | 0.17 | **0.29** | 0.92 | 0.81 | 0.28 | **0.67** |
| Endocanthion left | 0.92 | 0.63 | 0.69 | **0.74** | 0.55 | 0.39 | 0.37 | **0.44** | 0.83 | 0.46 | 0.55 | **0.62** |
| Endocanthion right | 1.19 | 0.50 | 0.62 | **0.77** | 0.56 | 0.36 | 0.41 | **0.45** | 0.68 | 0.38 | 0.47 | **0.51** |
| Exocanthion left | 0.69 | 0.51 | 0.56 | **0.59** | 0.50 | 0.40 | 0.41 | **0.44** | 0.51 | 0.38 | 0.35 | **0.42** |
| Exocanthion right | 0.74 | 0.59 | 0.63 | **0.65** | 0.43 | 0.29 | 0.35 | **0.36** | 0.50 | 0.34 | 0.38 | **0.40** |
| Glabella | 0.56 | 0.87 | 0.30 | **0.58** | 0.45 | 1.17 | 0.44 | **0.69** | 0.59 | 0.98 | 0.36 | **0.64** |
| Labiale inferius | 0.52 | 0.61 | 0.38 | **0.50** | 0.42 | 0.34 | 0.20 | **0.32** | 0.76 | 1.20 | 0.53 | **0.83** |
| Labiale superius | 0.47 | 0.59 | 0.22 | **0.43** | 0.30 | 0.38 | 0.13 | **0.27** | 0.53 | 0.64 | 0.18 | **0.45** |
| Nasion | 0.33 | 0.93 | 0.35 | **0.54** | 0.31 | 0.85 | 0.46 | **0.54** | 0.55 | 1.15 | 0.39 | **0.70** |
| Pogonion | 0.65 | 1.27 | 0.54 | **0.82** | 0.62 | 1.16 | 0.50 | **0.76** | 1.01 | 1.07 | 0.46 | **0.85** |
| Pronasale | 0.42 | 0.71 | 0.25 | **0.46** | 0.30 | 0.44 | 0.21 | **0.32** | 0.41 | 0.70 | 0.30 | **0.47** |
| Subalare left | 0.55 | 0.36 | 0.59 | **0.50** | 0.52 | 0.31 | 0.46 | **0.43** | 0.67 | 0.36 | 0.66 | **0.57** |
| Subalare right | 0.58 | 0.31 | 0.57 | **0.49** | 0.64 | 0.32 | 0.49 | **0.48** | 0.70 | 0.45 | 0.67 | **0.61** |
| Subnasale | 0.38 | 0.65 | 0.32 | **0.45** | 0.33 | 0.72 | 0.35 | **0.47** | 0.25 | 0.78 | 0.44 | **0.49** |
| Mean | **0.59** | **0.65** | **0.50** | **0.58** | **0.45** | **0.49** | **0.37** | **0.44** | **0.60** | **0.64** | **0.44** | **0.56** |

**Supplementary Table X.** Root mean squared error between the manual and automatic landmark indications produced using the average of each observer’s manual indications.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Landmark* | *AML vs. AAuto* | | | | *JML vs. JAuto* | | | |
| *X* | *Y* | *Z* | *Mean* | *X* | *Y* | *Z* | *Mean* |
| *Alar curvature left* | 0.1738 | 0.5427 | 0.5937 | **0.4367** | 0.1890 | 0.6484 | 0.7576 | **0.5320** |
| *Alar curvature right* | 0.1840 | 0.5251 | 0.6682 | **0.4591** | 0.1820 | 0.5800 | 0.6108 | **0.4576** |
| *Chelion left* | 1.2304 | 0.6999 | 0.6364 | **0.8555** | 1.2568 | 0.7390 | 0.6556 | **0.8838** |
| *Chelion right* | 0.9345 | 0.6994 | 0.5269 | **0.7202** | 1.1544 | 0.6472 | 0.6201 | **0.8072** |
| *Crista philtri left* | 0.6893 | 0.8515 | 0.4362 | **0.6590** | 0.8879 | 1.0055 | 0.5080 | **0.8005** |
| *Crista philtri right* | 0.6624 | 0.9461 | 0.5019 | **0.7035** | 1.0002 | 1.1284 | 0.4746 | **0.8677** |
| *Endocanthion left* | 0.8353 | 0.6358 | 0.5323 | **0.6678** | 0.8340 | 0.6163 | 0.4211 | **0.6238** |
| *Endocanthion right* | 1.0501 | 0.7399 | 0.6189 | **0.8030** | 1.0905 | 0.6243 | 0.4504 | **0.7217** |
| *Exocanthion left* | 0.9230 | 0.7840 | 0.9091 | **0.8720** | 0.9669 | 0.7469 | 0.8848 | **0.8662** |
| *Exocanthion right* | 0.9337 | 0.6721 | 0.9314 | **0.8457** | 0.9840 | 0.6763 | 0.9662 | **0.8755** |
| *Glabella* | 0.5223 | 1.4341 | 0.6028 | **0.8531** | 0.5476 | 1.4595 | 0.5938 | **0.8670** |
| *Labiale inferius* | 0.5224 | 0.7514 | 0.5583 | **0.6107** | 0.5005 | 0.7101 | 0.3752 | **0.5286** |
| *Labiale superius* | 0.5726 | 0.7228 | 0.3123 | **0.5359** | 0.5909 | 0.9839 | 0.3669 | **0.6472** |
| *Nasion* | 0.3657 | 1.0978 | 0.5142 | **0.6592** | 0.4198 | 1.0393 | 0.4811 | **0.6467** |
| *Pogonion* | 0.4839 | 1.0824 | 0.4492 | **0.6718** | 0.5419 | 1.1215 | 0.4198 | **0.6944** |
| *Pronasale* | 0.4399 | 0.7148 | 0.3254 | **0.4934** | 0.4515 | 0.5726 | 0.2836 | **0.4359** |
| *Subalare left* | 0.7805 | 0.4699 | 0.5442 | **0.5982** | 0.7855 | 0.4435 | 0.6389 | **0.6226** |
| *Subalare right* | 0.7532 | 0.4566 | 0.7601 | **0.6566** | 0.6724 | 0.5001 | 0.5201 | **0.5642** |
| *Subnasale* | 0.3280 | 0.4606 | 0.3319 | **0.3735** | 0.3528 | 0.6826 | 0.3339 | **0.4564** |
| *Mean* | 0.6518 | 0.7519 | 0.5660 | **0.6566** | 0.7058 | 0.7855 | 0.5454 | **0.6789** |

**Supplementary Table X**. Inter-observer error along the *x*, *y*, and *z* axis, averaged across images for each landmark, calculated using both manual landmark observers (AML vs. JML), and by replacing each observer’s manual indications with automatic indications (AAuto vs. JML and AML vs JAuto). The means for each comparison are reported in Table X of the accompanying manuscript.

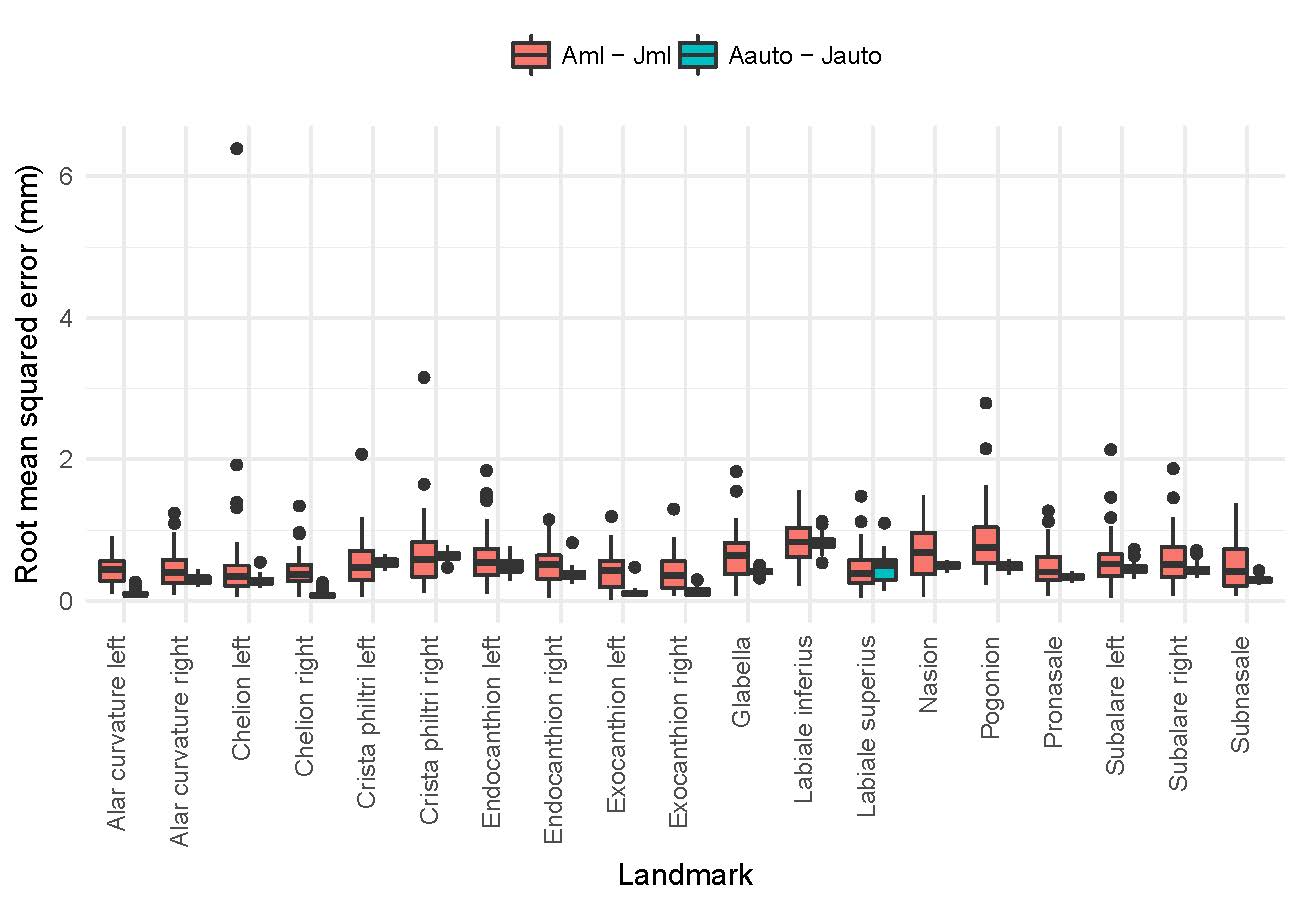
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Landmark | Root mean squared error (mm) | | | | | | | | | | | |
| *AML vs. JML* | | | | *AAuto vs. JML* | | | | *AML vs. JAuto* | | | |
| *X* | *Y* | *Z* | *Mean* | *X* | *Y* | *Z* | *Mean* | *X* | *Y* | *Z* | *Mean* |
| Alar curvature left | 0.17 | 0.53 | 0.60 | **0.43** | 0.17 | 0.55 | 0.59 | **0.44** | 0.18 | 0.64 | 0.74 | **0.52** |
| Alar curvature right | 0.17 | 0.48 | 0.75 | **0.46** | 0.18 | 0.49 | 0.90 | **0.52** | 0.21 | 0.65 | 0.72 | **0.53** |
| Chelion left | 0.84 | 0.42 | 0.51 | **0.59** | 1.19 | 0.76 | 0.71 | **0.89** | 1.37 | 0.70 | 0.65 | **0.91** |
| Chelion right | 0.60 | 0.38 | 0.28 | **0.42** | 0.91 | 0.72 | 0.53 | **0.72** | 1.16 | 0.62 | 0.60 | **0.80** |
| Crista philtri left | 0.73 | 0.65 | 0.27 | **0.55** | 0.92 | 1.12 | 0.50 | **0.85** | 0.95 | 1.03 | 0.50 | **0.83** |
| Crista philtri right | 0.92 | 0.81 | 0.28 | **0.67** | 0.91 | 1.21 | 0.51 | **0.88** | 1.13 | 1.20 | 0.52 | **0.95** |
| Endocanthion left | 0.83 | 0.46 | 0.55 | **0.62** | 1.12 | 0.68 | 0.55 | **0.78** | 0.98 | 0.59 | 0.65 | **0.74** |
| Endocanthion right | 0.68 | 0.38 | 0.47 | **0.51** | 1.19 | 0.80 | 0.72 | **0.90** | 1.13 | 0.56 | 0.49 | **0.73** |
| Exocanthion left | 0.51 | 0.38 | 0.35 | **0.42** | 0.92 | 0.82 | 0.89 | **0.88** | 0.96 | 0.72 | 0.91 | **0.87** |
| Exocanthion right | 0.50 | 0.34 | 0.38 | **0.40** | 0.95 | 0.67 | 0.93 | **0.85** | 0.98 | 0.69 | 0.97 | **0.88** |
| Glabella | 0.59 | 0.98 | 0.36 | **0.64** | 0.64 | 1.42 | 0.65 | **0.90** | 0.66 | 1.56 | 0.57 | **0.93** |
| Labiale inferius | 0.76 | 1.20 | 0.53 | **0.83** | 0.76 | 1.45 | 0.72 | **0.98** | 0.79 | 1.26 | 0.57 | **0.88** |
| Labiale superius | 0.53 | 0.64 | 0.18 | **0.45** | 0.70 | 0.98 | 0.43 | **0.70** | 0.73 | 1.01 | 0.33 | **0.69** |
| Nasion | 0.55 | 1.15 | 0.39 | **0.70** | 0.54 | 1.26 | 0.54 | **0.78** | 0.55 | 1.32 | 0.56 | **0.81** |
| Pogonion | 1.01 | 1.07 | 0.46 | **0.85** | 0.92 | 1.10 | 0.48 | **0.83** | 0.97 | 1.20 | 0.42 | **0.86** |
| Pronasale | 0.41 | 0.70 | 0.30 | **0.47** | 0.52 | 0.80 | 0.42 | **0.58** | 0.51 | 0.74 | 0.27 | **0.51** |
| Subalare left | 0.67 | 0.36 | 0.66 | **0.57** | 0.87 | 0.53 | 0.62 | **0.67** | 0.89 | 0.46 | 0.82 | **0.72** |
| Subalare right | 0.70 | 0.45 | 0.67 | **0.61** | 0.92 | 0.53 | 0.75 | **0.74** | 0.74 | 0.52 | 0.75 | **0.67** |
| Subnasale | 0.25 | 0.78 | 0.44 | **0.49** | 0.35 | 0.67 | 0.34 | **0.45** | 0.35 | 0.76 | 0.40 | **0.51** |
| Mean | **0.60** | **0.64** | **0.44** | **0.56** | **0.77** | **0.87** | **0.62** | **0.75** | **0.80** | **0.85** | **0.60** | **0.75** |

#### Comparison of inter-observer error variance (not sure if I want to keep this)

As an illustration of the low errors involved in the automatic landmark placements, we calculated the inter-observer error between automatic landmark iterations trained using the average of observer AZ’s three landmark iterations and the average of observer JW’s three landmark iterations (Sup Table X). These values can then be compared to the inter-observer error calculated using just the manual landmarks, described in section 2.3.4.1. We additionally performed Levene’s test (Levene, 1960) to determine if the variances of the inter-observer errors calculated using the manual and automatic landmarks were equal (the null hypothesis) or unequal (the alternative hypothesis; Table X).

**Table X. Comparison of inter-observer error variance.** The root mean squared error of average landmark configurations for the manual and automatic landmarks averaged across scans as well as the F value and P value from performing a Levene’s test per landmark.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Landmark* | *Manual (mm)* | *Auto (mm)* | *F value* | *P value* |
| *Alar curvature left* | 0.4337 | 0.1030 | 59.62442 | **2.83 x 10-11** |
| *Alar curvature right* | 0.4648 | 0.3017 | 22.23464 | **1.01 x 10-5** |
| *Chelion left* | 0.5914 | 0.2826 | 4.645328 | **0.0341** |
| *Chelion right* | 0.4220 | 0.0901 | 24.51013 | **4.03 x 10-6** |
| *Crista philtri left* | 0.5488 | 0.5390 | 29.18319 | **6.60 x 10-7** |
| *Crista philtri right* | 0.6699 | 0.6324 | 18.16847 | **5.49 x 10-5** |
| *Endocanthion left* | 0.6168 | 0.4955 | 14.19996 | **3.13 x 10-4** |
| *Endocanthion right* | 0.5102 | 0.3774 | 28.41032 | **8.85 x 10-7** |
| *Exocanthion left* | 0.4166 | 0.1142 | 47.73343 | **1.06 x 10-9** |
| *Exocanthion right* | 0.4038 | 0.1359 | 28.00999 | **1.03 x 10-6** |
| *Glabella* | 0.6423 | 0.4155 | 41.58661 | **7.95 x 10-9** |
| *Labiale inferius* | 0.8283 | 0.8164 | 26.38474 | **1.93 x 10-6** |
| *Labiale superius* | 0.4504 | 0.4651 | 2.421269 | 0.1236 |
| *Nasion* | 0.6983 | 0.4966 | 87.75501 | **1.67 x 10-14** |
| *Pogonion* | 0.8466 | 0.4919 | 23.99269 | **4.95 x 10-6** |
| *Pronasale* | 0.4700 | 0.3360 | 38.24278 | **2.49 x 10-8** |
| *Subalare left* | 0.5664 | 0.4580 | 16.48045 | **1.14 x 10-4** |
| *Subalare right* | 0.6057 | 0.4402 | 25.68186 | **2.54 x 10-6** |
| *Subnasale* | 0.4921 | 0.2930 | 42.64756 | **5.57 x 10-9** |
| *Mean* | 0.5620 | 0.3834 |  |  |



**Figure X. Comparison of inter-observer error variance.** The interobserver error was calculated as described in section 2.3.4.1 and averaged across x, y, and z dimensions to give an average error value per image. We also calculated the inter-observer error of automatic landmarks trained using the three iterations of each observer separately and averaged these values across x, y, and z dimensions to give an average error value per image. For each landmark, Levene’s test was performed to determine if the variances were identical (Table X).

Ability to have up to 50 indications on a single face and then average them is what makes this good. Even though they were done on different faces. Not available on manual . Mapping allowed us to merge