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 2**. Intra- and inter-observer error along the *x*, *y*, and *z* axis, averaged across images for each landmark.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Landmark | Standard deviation (mm) | | | | | | | | RMSE (mm) | | | |
| *Observer A* | | | | *Observer B* | | | | *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 3.** **MANOVA on all manual landmark indications to assess manual landmarking error.** MANOVA was performed on the six GPA-aligned manual landmark indications, with individual, observer, individual x observer, and the nested interaction of observer x iteration as predictors.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | DF | SS | MS | R2 | F | Z | Pr(>F) |
| Individual | 40 | 1.1803 | 0.0295 | 0.8491 | 40.7135 | 26.620 | 0.001 |
| Observer | 1 | 0.0244 | 0.0244 | 0.0176 | 33.6563 | 14.568 | 0.001 |
| Individual x Observer | 40 | 0.0492 | 0.0012 | 0.0354 | 1.6963 | 26.292 | 0.001 |
| Observer x Iteration | 4 | 0.0203 | 0.0051 | 0.0146 | 6.9974 | 19.485 | 0.001 |
| Residuals | 160 | 0.1160 | 0.0007 | 0.0834 |  |  |  |
| Total | 245 | 1.3901 |  |  |  |  |  |

**Supplementary Table 4.** 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* | | | | *BML vs. BAuto* | | | |
| *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 5**. Inter-observer error along the *x*, *y*, and *z* axis, averaged across images for each landmark, calculated using both manual landmark observers (AML vs. BML), and by replacing each observer’s manual indications with automatic indications (AAuto vs. BML and AML vs BAuto). The means for each comparison are reported in Table X of the accompanying manuscript.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Landmark | Root mean squared error (mm) | | | | | | | | | | | |
| *AML vs. BML* | | | | *AAuto vs. BML* | | | | *AML vs. BAuto* | | | |
| *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** |