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1 **Growing old – do women and men age differently?**

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26

27

28 **Abstract**

29 **Background**

30 Aging of the head and especially the face have been studied intensively, yet  
31 questions remain about the timing and rates of aging throughout adulthood and  
32 about the extent to which aging differs between men and women. Here we address  
33 these issues by developing statistical models of craniofacial aging to describe and  
34 compare aging through the life course in both sexes.

35 **Methods**

36 We selected cranial surface meshes from 254 females and 252 males, aged from 20  
37 to 90 years from the *Headspace* project, Liverpool, UK. 16 anatomical landmarks  
38 and 59 semilandmarks on curves and surfaces were used to parameterise these.  
39 Modes and degrees of aging throughout adulthood were assessed and compared  
40 among sexes using Procrustes based geometric morphometric methods.

41 **Results**

42 Regression analyses of form through the whole age range indicate that age accounts  
43 for a small proportion of total variance in both sexes, but form is significantly related  
44 to age and males and females age in significantly different ways. Further analyses  
45 indicate that aging differs in character, timing and rates in both sexes between early  
46 and later phases of adulthood. Sexual differences in aging are evident in early and  
47 later phases of adulthood.

48 **Conclusions**

49 The study adds to knowledge of the aging of adult craniofacial form and sexual  
50 dimorphism. It is based on a local population and so the findings are directly  
51 applicable to that population. Further studies are needed to assess generalisability  
52 and to provide better data on population differences to facilitate clinical assessment  
53 and treatment planning.

54 **Key words:** Facial aging; sexual differences; surface scanning; morphometrics

55

56

57 **Introduction**

58 With aging, the form of the head and especially the face transforms in well studied  
59 and recognized ways (Albert et al., 2007; Coleman and Grover, 2006; Farkas et al.,  
60 2013; Pitanguy et al., 2008). Decreased soft tissue elasticity, creasing,  
61 subcutaneous fat redistribution, and skeletal remodelling all contribute to changes in  
62 the three dimensional topography. Coleman et al. (Coleman and Grover, 2006)  
63 describe changes to the upper forehead and periorbital region, that result in ‘fixed  
64 glabellar frown lines, fixed transverse forehead furrows, temporal hollowing, a  
65 skeletonized supraorbital rim, and a relative excess of upper eyelid skin’. In the  
66 midface they note that subcutaneous fullness is lost, giving rise to a deeper and  
67 wider orbit, relative prominence of infraorbital fat pads, development of nasolabial  
68 folds, cheek concavity, chin pad ptosis and depleted malar fullness. Farkas et al.  
69 (Farkas et al., 2013) identify a rotation of the midface relative to the cranial base that  
70 reduces the angle of the pyriform and maxilla. Likewise it has been noted (Matros et  
71 al., 2009) that the malar eminence, infraorbital rim, and piriform aperture become  
72 more retroclined with age. ‘The illusion’ of increased nasal length with age has been  
73 attributed (Coleman and Grover, 2006) to flattening of the medial forehead, this is  
74 accompanied by nasal ptosis and changes in the alar region with narrowing of the  
75 nasolabial angle. The lower face develops a relative excess of loose skin which  
76 blunts the jawline and with redistributed fat deposits, contributes to the development  
77 of jowls (Özdemir et al., 2002). Accompanying this, it has been noted (Coleman and  
78 Grover, 2006) that the chin develops a relative protrusion, attributable to loss of  
79 tissue volume lateral and inferior to the central portion. However, in a geometric  
80 morphometric study of longitudinal radiographs it was found (Pessa et al., 2008) that

81 the mandible continues to grow and develop and so contributes this aspect of aging  
82 of the lower face.

83 Despite an extensive literature, questions remain about the time course of aging and  
84 the extent to which its features are shared among the sexes (Lambros, 2020). Thus,  
85 in an extensive review of facial aging (Albert et al., 2007) it was noted that sexual  
86 differences in patterns of aging have been found by various authors, with the  
87 consensus being that females tend to age faster or earlier than males. Additionally  
88 they point out that features of head and facial aging vary throughout the decades in  
89 both sexes. A geometric morphometric study (Windhager et al., 2019) found that, in  
90 their sample, females and males follow a common pattern of aging until menopause  
91 (albeit slightly faster in females), at which point there is a disruption of this pattern in  
92 females accompanied by an increase in rate of aging. These findings suggest that  
93 aging of the face is a non-linear process, varying in pattern and rate over time and  
94 between the sexes.

95 In this paper we measure the external form of the head and apply state of the art  
96 imaging and statistical methods for the analysis of 3D variation to build statistical  
97 models of whole head surface variation of individuals of both sexes in the UK whose  
98 ages range between 20 years and >80 years, to characterise and compare the  
99 modes and tempos of aging, a term used in this paper to refer specifically to change  
100 in form with time, in both sexes.

101 In particular, we test the hypotheses that: i) males and females each age in a  
102 consistent manner (within sex co-variation with age) and ii) males and females age  
103 in the same ways (between sex co-variation with age). To test hypothesis i),  
104 multivariate regressions of form on age are undertaken, either for the whole sample

105 or for subsamples of age groups, testing the significance of any apparent divergence  
106 of regression vectors between ages. The analyses also provide the opportunity to  
107 identify the detail of any identified differences between the sexes. To test hypothesis  
108 ii), a series of multivariate regressions of form on age are carried out within age  
109 groups, and the significance of any apparent divergence of regression vectors  
110 between sexes is tested. Where significant, the differences are visualized to allow  
111 detailed comparison.

## 112 **Methods**

### 113 ***Ethics approval***

114 Alder-Hey Hospital and The Hull York Medical School granted ethics approval. All  
115 volunteers, or their legal guardian if <18years, gave written informed consent for 3D  
116 photography of their heads and subsequent analyses of variation. We confirm  
117 adherence to the tenets of the Declaration of Helsinki.

### 118 ***Sample***

119 Surface meshes (typically 180K vertices and approx. 360K triangles) stored as  
120 Wavefront™ .obj files were collected from 254 females and 252 males ranging in  
121 age from 20 to 90 years (females) and 20-86 years (males). These came from the  
122 sample of .obj files obtained by the *Headspace* project in Liverpool, UK, from  
123 September 2013 – January 2014 (Dai et al., 2017) using a 3dMD five-camera  
124 system. We excluded individuals who had previous craniofacial surgery, declared  
125 mixed or unknown ethnicity, bulky hair or were missing surface data from the .obj file  
126 to, as far as possible, limit sources of variation to individual differences and age  
127 within the indigenous local population. All participants wore tight fitting, smooth latex

128 caps to flatten the hair against the scalp. Individuals varied in hair mass and so, the  
129 extent to which the cap flattened the hair also inevitably varied.

130 Sampling is uneven in terms of the age distributions of volunteers. Thus, the 20-29  
131 year olds are best sampled with 96 males and 114 females; There are 73 males and  
132 46 females aged 30-39 years, 28 males and 33 females between 40-49 years, 24  
133 males and 25 females between 50 and 59 years, and 31 males and 36 females over  
134 60. The majority of individuals over 60 are younger than 70 years with only 6 older  
135 individuals of either sex.

### 136 ***Digitisation***

137 Anatomically homologous landmarks and curves were manually digitized by the  
138 same person (OAMS) using the Evan Toolbox for geometric morphometrics (Weber  
139 and Bookstein, 2011). This provides tools to trace curves manually, to semi-  
140 automatically locate fixed landmarks for subsequent manual refinement and to  
141 automatically distribute semilandmarks on curves and surfaces. We utilized a  
142 symmetric (Mardia et al., 2000) template comprising 16 landmarks (Table 1) and an  
143 exemplar head surface mesh with traced curves marked up by 59 semilandmarks,  
144 chosen because it represents a young individual with relatively gracile features (Fig.  
145 1).

146 Semi-landmark configurations were used to describe the curves of the right and left  
147 jawlines, the right and left eyebrows and the midline curves, as well as the cranial  
148 surface. No landmarks or semilandmarks are placed on the ears, neck or clothing  
149 and so their apparent deformations in visualisations should be ignored. Using thin  
150 plate splines (Bookstein, 1989), semilandmarks were warped and projected from the  
151 template onto the mesh of each individual. They were then slid along curves and

152 over the surface to minimise bending energy of the thin plate splines with respect to  
153 the fixed landmarks (Bookstein, 1989; Gunz and Mitteroecker, 2013).

154

### 155 ***Statistical analyses***

156 The analyses examined changes in size and shape with age in each sex. Centroid  
157 sizes and shape variables for subsequent analyses were derived from the landmark  
158 and semilandmark coordinates by generalized Procrustes analysis. Analyses of form  
159 (shape and size; Mitteroecker et al., 2013) use the shape coordinates together with  
160 the natural logarithm (ln) of centroid size.

161 Form variation was assessed in preliminary analyses through principal components  
162 analysis (PCA) and modelled in detail using multivariate regressions. These  
163 analyses were carried out using the EVAN Toolbox. Regression vectors were  
164 compared between age groups and sexes using a permutation test on the angles  
165 between them (R Core Team, 2020). Results were visualized in the EVAN Toolbox  
166 by warping the template surface mesh (using thin plate splines) between pairs of  
167 landmark and semilandmark configurations representing forms of interest (e.g. mean  
168 young and old configurations). To facilitate interpretation of these, the target surface  
169 mesh was colour mapped to represent the changes in area of each triangle with  
170 respect to the reference, using the *localmeshdiff* function in the R package, Arothron  
171 (Piras et al., 2020; Profico et al., 2020). The resulting maps represent a key aspect  
172 of form variation; the extent of expansion or contraction of surface regions. The  
173 relative directions of expansion can be visually gauged by comparing warped  
174 surfaces.

175



176 The visualisation of local surface area change is drawn by warping a surface mesh  
177 to fit the mean coordinates and then by warping the coordinates according to the  
178 coefficients of the regression of interest. The surface is warped with the landmarks,  
179 using thin plate splines. Here we use the surface mesh from a young gracile male to  
180 minimise the effect of initial surface choice on the appearance of gender (Fig.1).  
181 Inevitably features such as the form of nose tip, with few landmarks and skin folds  
182 are to some extent retained throughout the warpings so, the original surface is  
183 recognisable, but the interpretation of these diagrams should focus on changes, and  
184 so on the colours displayed in these visualisations rather than on the form of the face  
185 itself. This visualisation is not affected by registration, but it is potentially affected by  
186 where and how the surface mesh cuts through (sections) the deformation field. To  
187 minimise the effects of this, we consistently visualise deformations using the mean  
188 landmark configuration, warped to represent particular ages. From exploratory  
189 experiments, testing the effects of using different configurations (representing the  
190 limits of the ranges of variation on PCs 1 and 2 in Figure 2a) on the visualisation, it is  
191 very stable and fairly represents the average local changes in surface area during  
192 aging.

193

## 194 **Results**

195 There is no significant correlation between centroid size and age, over the entire age  
196 range of the sample, in either sex (males  $r=-0.046$ ,  $p=0.1226$ ; females  $r=0.098$ ,  
197  $p=0.123$ ). However males are significantly larger ( $p<0.001$ ) than females, with mean  
198 centroid size for males of 876mm and for females, 832mm.

199 Figure 2. shows the first three principal components (PCs; 59.6% of total variance)  
200 from a principal components analysis of form (the shape coordinates plus the ln of  
201 centroid size). There is some separation between males and females on PC1 (Fig.  
202 2a) and on the combination of PC2 and PC3 (Fig. 2b) the older individuals tend to  
203 group towards the lower right quadrant of the plot and younger, towards the upper  
204 left.

205 Patterns of covariation with age in each sex are explored further, while taking  
206 account of the whole statistical space (total variance) by multivariate regression of  
207 form and shape on age for the whole sample of each sex (Table 2). In both sexes  
208 the regressions are significant and explain a similar small proportion of the total  
209 variance (3.3-4.5%). The angles between sex specific regression vectors are  
210 significant (form:  $49^\circ$ ,  $p=0.045$ ; shape:  $44^\circ$ ,  $p<0.001$ ; permutation tests with 1000  
211 permutations of sex), Thus, while age accounts for a small proportion of total  
212 variance in both sexes, form and shape are significantly related to age and males  
213 and females age in significantly different ways.

214 Figure 3 presents the regression prediction of form in each sex at 20, 80 and 200  
215 years. The last was drawn to exaggerate differences in the warpings to make them  
216 more visible. The static faces making up the sequence are warpings of a single  
217 surface and therefore share similarities of texture and features such as the nose tip,  
218 which has few landmarks. The reader should focus on the differences between these  
219 rather than the similarities, since it is the differences (changes with age) that concern  
220 us. To make this focus on difference explicit we also show colour maps, indicating  
221 localized changes in surface area between warpings. The distribution of colours  
222 indicating regions of surface expansion and contraction is invariant to registration  
223 and almost invariant (very stable in terms of how colours map to equivalent regions

224 and features) to the form used to visualise them. Because these changes are more  
225 readily seen in the colour map, we visualise them between the more reasonable age  
226 limits, 20 to 80 years.

227 Most aspects of aging appear very similar between sexes. From the warpings  
228 between 20 and 200 years in Figure 3, both sexes show a degree of broadening of  
229 the cheeks, formation of jowls, increase in the size of the nose and lengthening of  
230 the philtrum and upper lip, with the chin and nose coming to lie relatively more  
231 anterior to the lips. The colour maps show that these changes result in the largest  
232 expansion of surface area over the philtrum and nose, and a reduction over the jowls  
233 and supraorbital regions. In detail, semilandmarks on the mid cheek and those on  
234 the jawline come to lie closer together and so reduce the area of the mesh in the  
235 vicinity of the jowls. There are subtle changes over the cranial vault in both sexes  
236 with reduction in surface area locally over the frontal region, particularly in males and  
237 some increase in area locally over the lateral aspects of the vault, especially in  
238 females. These changes may well relate to variations in hair mass with age, as such  
239 we note them but, given the uncertainty over the effects of the hair cap on apparent  
240 vault form, we interpret them no further.

241 Consistent with the significant angle between sex specific regression vectors males  
242 and females show some differences in aging (Figure 3, compare 200 year male and  
243 female trajectory warpings) appear to differ in the greater degree of broadening of  
244 the face in males. Figure 4 visualises the subtle differences in aging using a colour  
245 map of the differences in predicted 80 year old forms. Between 20 and 80 years,  
246 males show greater expansion of the malar region and tip of the nose and chin, with  
247 less expansion of the nasal bridge, anterior chin and central lower lip. Males also

248 show a relatively greater reduction in the area of the periorbital and frontal regions  
249 than females.

250 These comparisons are calculated over the whole age range, so do not account for  
251 possible temporal variation in aging trajectories or rates within in each sex. To  
252 explore these further, mean head form was calculated for each decade and for the  
253 over 60s combined (small sample) and a PCA of form was carried out using these  
254 means. Neither sex specific aging trajectory is linear on the combination of the first  
255 three PCs (Fig. 5). In both, on the combination of PCs1 to 3 there is an  
256 approximately consistent mode of aging (direction of vector between ages) between  
257 20 and 40 years, followed by deviation of the trajectory into the 50s and 60s. This  
258 suggests differences between early (20-40+ years) and late (50+) modes of aging.  
259 The distances between means are variable and these suggest differences in rates of  
260 aging. Note that sample sizes are small, especially in older age groups and  
261 variances are large (see Figure 2). As such, we do not formally test for changes in  
262 aging among these age groups, but instead carry out tests comparing aging between  
263 broader age groups, 'younger' vs 'older' using multivariate regression, as described  
264 below.

265 To investigate rates of aging, these were computed as the Procrustes distances  
266 between the mean shapes from successive years. To account for sampling error  
267 and other sources of variation that affect between year shape differences, the mean  
268 shape in each year was computed as the moving average over 5 years centred on  
269 the year of interest. In Figure 6 the resulting rates of aging are presented for males  
270 and females. The curves overlap between the sexes, however, in both there appear  
271 to be varying rates of aging. In males aging is slow but accelerates slightly between  
272 20 and 40 years, then it shows a dramatic acceleration between 40 and 50 years,

273 before slowing between the mid-fifties and sixties and then accelerating again into  
274 old age. In females the trend is different, with slow aging in the twenties,  
275 accelerating through the mid-thirties, before slowing again until 50 years when aging  
276 accelerates until 60 years before slowing a little between 60 and 70 years and finally  
277 accelerating again into old age.

278 The possibility that modes of aging differ between younger and older age groups, as  
279 indicated by the PCA of Fig 5 was explored through, a series of multivariate  
280 regressions of form on age. Each sex was split into younger and older groups and  
281 the vectors of aging were compared between age groups and sexes. Because it is  
282 not clear (if and) when a change in aging occurs, we explored differences between  
283 20-39 years and 40-90 years and between 20-49 years and 50-90 years, in and  
284 between each sex. Table 3 presents the results of the multivariate regressions of  
285 form on age in each of these age groups for each sex. All are significant, as  
286 assessed by a permutation test (1000 permutations of age) on explained variance,  
287 except in females aged over 50, however the proportion of total variance explained  
288 by these regressions is generally small, indicating that other sources of variation  
289 (error and individual differences) predominate.

290 To assess the extent to which aging differs between younger and older age groups  
291 within and among sexes, vector comparisons were carried out (Table 4). Within each  
292 sex, divergences of aging trajectories between younger and older age groups are  
293 highly significant ( $p < 0.001$ ), 20-39 year old males and females also diverge  
294 significantly ( $P = 0.008$ ), while the divergence between 40-90 year old males and  
295 females is on the borderline of significance ( $p = 0.052$ ). Between 20 and 40 years  
296 (Fig. 7), in both sexes there is expansion of midline facial structures, from nasal  
297 bridge to chin, but the nasal bridge and lateral nose expands to a greater extent in

298 females and the philtrum and chin in males. In males, and more so in females, the  
299 eyebrows medially approximate and lower slightly while the region around the lateral  
300 brow reduces in area. The middle and lateral malar regions expand in males.  
301 Between 40 and 80 years changes appear more marked, but this visualisation spans  
302 twice the age range of that between 20-40 years. In both males and females  
303 changes are more asymmetric than in the younger age group. The jawline and lower  
304 cheek show localized regions of shrinkage due to the formation of jowls and skin  
305 folds, and the upper chin and lower lip reduce in area while the philtrum expands. In  
306 females the whole nose enlarges markedly while in males this is less marked and  
307 more focussed on the nasal tip. In males there are dramatic localized and somewhat  
308 irregular changes in area around the eyes and over the central forehead reflecting  
309 local wrinkling.

310 Finally, to directly compare rates and patterns of aging between age groups and  
311 between the regression analyses of age groups and those of the whole sample, age  
312 changes per 20 years were visualized. The rates of relative expansion and  
313 contraction of facial regions show minor differences between sexes when aging is  
314 modelled by regression of form on age over the whole age range of 20-80 years (Fig.  
315 8, top row), but when the form of age groups 20-40 and 40-80 is separately  
316 regressed on age, localized differences in aging between sexes and age groups  
317 become evident (Fig. 8, bottom row).

## 318 **Discussion**

319 In this study we tested two hypotheses. The first is that males and females each age  
320 in a consistent manner between 20 years and old age and the second is that males  
321 and females age in the same ways. Our analyses indicate that shape rather than

322 size variation characterises aging, and that changes due to age are small relative to  
323 interindividual differences due to other sources, such as sex (Fig. 2). There is clear  
324 evidence that males and females age differently when the sample age range is  
325 considered in its entirety (Table. 2, Fig. 3 and 4). More detailed analysis of changes  
326 in the tempo and mode of aging throughout adulthood (Figure 5) show that mean  
327 head form varies in a somewhat non-linear manner and variable rate with age.  
328 Particularly younger adults of each sex appear to age in ways that are different to  
329 older adults. A major change occurs approximately between 40 and 59 years in  
330 each sex, with some evidence of a slightly earlier change in females. Males and  
331 females age at similar rates when considered over the whole time course, but each  
332 sex appears to show accelerations and relative decelerations of aging throughout  
333 adulthood (Figure 6). Sample sizes are not as large in older age groups as in  
334 younger and variances are large (Figure 2). As such, we must treat this finding with  
335 some caution. However, one other study has similarly examined rates of aging  
336 (Windhager et al., 2019) and in this they noted a peak in female aging rate between  
337 50 and 60 years, which they attributed to menopause. Our estimates of aging rates  
338 follow a very similar pattern but differ in one key respect, we find a very similar  
339 average rate of aging in both sexes, between 40 and 70, whereas the study of  
340 Windhager et al. (Windhager et al., 2019) suggests males age more slowly. This  
341 could be a population difference (UK vs Croatia), and merits further investigation.

342 The visualisations (Fig. 7- 8) of the multivariate regressions of form on age (Table 3)  
343 show that aging differs between younger and older adults and between sexes but  
344 there are commonalities, consistent with the findings of previous workers (Coleman  
345 and Grover, 2006; Lambros, 2020; Özdemir et al., 2002; Pessa et al., 2008; Pitanguy  
346 et al., 2008), in that the eyebrows medially approximate and lower somewhat, the

347 lateral brows droop, the lower lip thins, the chin becomes more prominent and jowls  
348 develop. Expansion (increase in local surface area) but not the rotation evident in the  
349 skeleton of midline facial structures (Farkas et al., 2013; Matros et al., 2009; Pessa,  
350 2000) is common to both sexes but the extent of this varies markedly, with the  
351 philtrum and chin expanding more in males and the nasal bridge and lateral nose  
352 expanding more in females, rather than giving the ‘illusion’ of doing so (Coleman and  
353 Grover, 2006). Indeed, in contrast to a previous study (Otto et al., 2012), in both  
354 sexes age related changes in the form of the nose are among the most prominent  
355 features of aging. Ramaut et al., (2019) compared MR scans of 100 men and women  
356 at two ages, 20-30 and 65-80 demonstrated that the upper lip lengthens in both  
357 sexes as we find here (Figure 7). Lambros, (2020) compared almost 600 3d images  
358 of males and females using a best fit facial averaging method and noted a number of  
359 changes that have been identified in this study, including flattening of the forehead,  
360 orbital enlargement that was more noticeable in men than women, lengthening of the  
361 upper lip, splaying of the alar base and lengthening of the nose due to loss of  
362 support. The overall conclusion however was that men and women aged in the same  
363 way.

364 It is worth considering some limitations of this study. They primarily reflect sampling  
365 and underline the need for very large databases of human facial scans with full life  
366 and medical histories such as has recently been made available for whole body CT  
367 scans (Edgar et al., 2020). Our data were from the headspace dataset (see  
368 Software, tools and data availability) which has ethnicity, age, eye and hair colour  
369 information. This, together with limited sampling of ethnicities other than Caucasians  
370 limited our analyses to assessment of aging without being able to take account of  
371 relevant medical and orthodontic history. A further issue arises since many more



372 young than old people volunteered their images. This has limited the reliability of  
373 results especially with respect to the over 60s, where three decades are represented  
374 by successively fewer individuals. Despite these limitations the data were sufficient  
375 to undertake statistical testing in the analyses presented here, but it has limited our  
376 ability to explore details of age related form changes in the head and covariances  
377 between form, age, medical history and lifestyle factors.

378 The findings of this study falsify both hypotheses in indicating that males and  
379 females vary in rates of age related changes in form throughout adulthood, in  
380 complex ways that differ between the sexes. They provide detailed information on  
381 aging in a specific population and the methods and technologies used in this study  
382 can readily be applied to other populations. Such knowledge can inform patient  
383 expectations of aging and of how surgical intervention might reverse its effects. It will  
384 be of interest in future studies to relate the identified features of aging to the timing  
385 and nature of surgical interventions commonly carried out in each sex.

386

387 **Software, tools and data availability**

388 The Headspace data are available via the project website, [https://www-](https://www-users.cs.york.ac.uk/~nep/research/Headspace/)  
389 [users.cs.york.ac.uk/~nep/research/Headspace/](https://www-users.cs.york.ac.uk/~nep/research/Headspace/). Our VPN for the EVAN toolbox  
390 analyses are distributed via <https://www.evan-society.org/>. The template can be  
391 downloaded from <https://doi.org/10.5281/zenodo.4266290>, together with the data  
392 used in this study. The R tool for the visualisation of differences in meshes are  
393 available on CRAN at <https://CRAN.R-project.org/package=Arothron>, the function is  
394 *localmeshdiff*.

395

396

397 **References**

398 Albert, A.M., Ricanek Jr, K., Patterson, E., 2007. A review of the literature on the  
 399 aging adult skull and face: Implications for forensic science research and  
 400 applications. *Forensic science international* 172, 1–9.

401 Bookstein, F.L., 1989. Principal warps: Thin-plate splines and the decomposition of  
 402 deformations. *IEEE Transactions on Pattern Analysis & Machine Intelligence*  
 403 567–585.

404 Coleman, S.R., Grover, R., 2006. The anatomy of the aging face: volume loss and  
 405 changes in 3-dimensional topography. *Aesthetic surgery journal* 26, S4–S9.

406 Dai, H., Pears, N., Smith, W.A., Duncan, C., 2017. A 3d morphable model of  
 407 craniofacial shape and texture variation, in: *Proceedings of the IEEE*  
 408 *International Conference on Computer Vision*. pp. 3085–3093.

409 Edgar, H., Daneshvari Berry, S., Moes, E., Adolphi, N., Bridges, P., Nolte, K., 2020.  
 410 New Mexico Decedent Image Database. Office of the Medical Investigator,  
 411 University of New Mexico: Albuquerque, NM, USA.

412 Farkas, J.P., Pessa, J.E., Hubbard, B., Rohrich, R.J., 2013. The science and theory  
 413 behind facial aging. *Plastic and Reconstructive Surgery Global Open* 1.

414 Gunz, P., Mitteroecker, P., 2013. Semilandmarks: a method for quantifying curves  
 415 and surfaces. *Hystrix, the Italian Journal of Mammalogy* 24, 103–109.

416 Lambros, V., 2020. Facial Aging: A 54-Year, Three-Dimensional Population Study.  
 417 *Plastic and Reconstructive Surgery* 145, 921–928.

418 Mardia, K.V., Bookstein, F.L., Moreton, I.J., 2000. Statistical assessment of bilateral  
 419 symmetry of shapes. *Biometrika* 285–300.

420 Matros, E., Garcia, J.A., Yaremchuk, M.J., 2009. Changes in Eyebrow Position and  
 421 Shape with Aging. *Plastic and Reconstructive Surgery* 124, 1296–1301.  
 422 <https://doi.org/10.1097/PRS.0b013e3181b455e8>

423 Mitteroecker, P., Gunz, P., Windhager, S., Schaefer, K., 2013. A brief review of  
 424 shape, form, and allometry in geometric morphometrics, with applications to  
 425 human facial morphology. *Hystrix* 24, 59–66. [https://doi.org/10.4404/hystrix-](https://doi.org/10.4404/hystrix-24.1-6369)  
 426 [24.1-6369](https://doi.org/10.4404/hystrix-24.1-6369)

427 Otto, C., Han, H., Jain, A., 2012. How does aging affect facial components?, in:  
 428 *European Conference on Computer Vision*. Springer, pp. 189–198.

429 Özdemir, R., Kiliç, H., Ünlü, E.R., Uysal, Ç.A., Sensöz, O., Baran, N.C., 2002.  
 430 Anatomicohistologic study of the retaining ligaments of the face and use in  
 431 face lift: retaining ligament correction and SMAS plication. *Plastic and*  
 432 *reconstructive surgery* 110, 1134–1147.

433 Pessa, J.E., 2000. An algorithm of facial aging: verification of Lambros’s theory by  
 434 three-dimensional stereolithography, with reference to the pathogenesis of  
 435 midfacial aging, scleral show, and the lateral suborbital trough deformity.  
 436 *Plastic and reconstructive surgery* 106, 479–488.

437 Pessa, J.E., Slice, D.E., Hanz, K.R., Broadbent Jr, T.H., Rohrich, R.J., 2008. Aging  
 438 and the shape of the mandible. *Plastic and reconstructive surgery* 121, 196–  
 439 200.

440 Piras, P., Profico, A., Pandolfi, L., Raia, P., Di Vincenzo, F., Mondanaro, A.,  
 441 Castiglione, S., Varano, V., 2020. Current options for visualization of local  
 442 deformation in modern shape analysis applied to paleobiological case studies.  
 443 *Frontiers in Earth Science* 8, 66.

444 Pitanguy, I., Pamplona, D., Radwanski, H.N., 2008. Facial aging and its mechanics,  
 445 in: *Simplified Facial Rejuvenation*. Springer, pp. 69–76.

446 Profico, A., Buzi, C., Castiglione, S., Melchionna, M., Piras, P., Raia, P., Veneziano,  
447 A., 2020. Arothron: Geometric Morphometric Methods and Virtual  
448 Anthropology Tools.  
449 R Core Team, 2020. R language definition. R foundation for statistical computing.,  
450 Vienna.  
451 Ramaut, L., Tonnard, P., Verpaele, A., Verstraete, K., Blondeel, P., 2019. Aging of  
452 the upper lip: part I: a retrospective analysis of metric changes in soft tissue  
453 on magnetic resonance imaging. *Plastic and Reconstructive Surgery* 143,  
454 440–446.  
455 Weber, G.W., Bookstein, F.L., 2011. *Virtual Anthropology - A Guide for a New*  
456 *Interdisciplinary Field*. Springer-Verlag, Wien.  
457 Windhager, S., Mitteroecker, P., Rupić, I., Lauc, T., Polašek, O., Schaefer, K., 2019.  
458 Facial aging trajectories: A common shape pattern in male and female faces  
459 is disrupted after menopause. *American Journal of Physical Anthropology*  
460 169, 678–688. <https://doi.org/10.1002/ajpa.23878>  
461

462 **Legends for figures**

463 **Figure 1.** a. The male surface used in all subsequent analyses with landmarks  
464 shown in red and digitized curves in white, curve semilandmarks and surface  
465 semilandmarks shown in white. Frontal, b, and lateral, c, screengrabs in the EVAN  
466 Toolbox of the landmark and semilandmark configuration (green).

467 **Figure 2:** a) PC1 (45.32% total variance) vs PC2 (7.22%) and b) PC3 (7.07%) vs  
468 PC2 of form, from a PCA of all individuals aged 20-90 years. Rectangle = male,  
469 circle = female, small symbol = young, large = old

470 **Figure 3:** Predicted form at the ages of 20, 80 and 200 years from the regressions of  
471 form on age of the whole adult samples of each sex. Landmarks and semilandmarks  
472 (see Fig. 1) indicated by red markers. Top row, females, bottom row, males. The last  
473 column shows colour maps that describe the ratios of areas of surface regions  
474 between 20 and 80 years in each sex (indicated by the scale).

475 **Figure 4:** Visualisations of regression predictions of age related form changes in  
476 each sex (left column males, right column, females). The centre column shows the  
477 differences in aging between males and females exaggerated 20 times to facilitate  
478 interpretation. Age related changes are shown as colour maps that indicate the ratios  
479 of areas of craniofacial regions between these ages (left and right columns, colour  
480 map keys below each frontal view) and between the regression prediction of the 80  
481 year old female and 80 year old male means (centre column). The difference is  
482 magnified 20 times in the centre column, relative to the left and right columns.

483 **Figure 5.** Top: PC1 (47.8%) vs PC2 (10.5%). Bottom: PC1 vs PC3 (9.3%) from PCA  
484 of mean head form for decade and over sixty age groups. Rectangle = male, circle =  
485 female, small symbol = young, large = old

486 **Figure 6.** Average rates of aging (shape change as measured by Procrustes  
487 distance per year) in each sex from 23 to 74 years.

488 **Figure 7:** Visualisations of regression predictions of age related form changes in  
489 each sex (females columns 1 and 3; males, 2 and 4) between 20 and 40 years (left  
490 two columns) and between 40 and 80 years (right two columns). Age related  
491 changes are shown as colour maps of the ratios of areas of equivalent craniofacial  
492 regions between these ages as indicated by the key.

493 **Figure 8:** Visualisations of regression predictions of age related form changes in  
494 each sex (females left; males right). Top row: visualisations of regressions between  
495 20-80 years. Bottom: between 20 and 40 years and between 40 and 80 years. Age  
496 related changes are shown as colour maps of the ratios of areas of equivalent  
497 craniofacial regions scaled to represent change per 20 years.

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499 **Legends for Tables**

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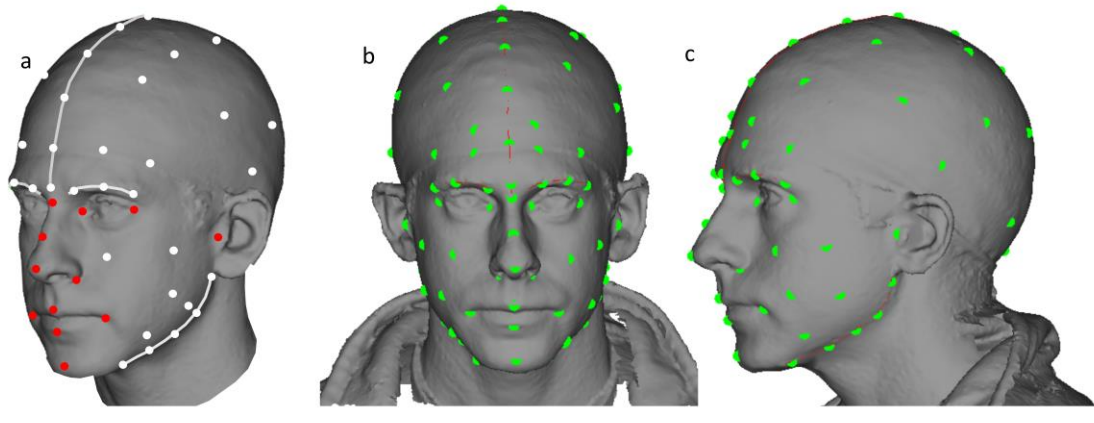
501 **Table 2:** Multivariate regressions of form and shape on age in each sex for the full  
502 sample

503 **Table 3:** Multivariate regressions of form on age in each sex for subsamples of  
504 younger and older individuals in each sex

505

506 **Table 4:** Vector comparisons between multivariate regressions of form on age between age  
507 subgroups and sexes

508

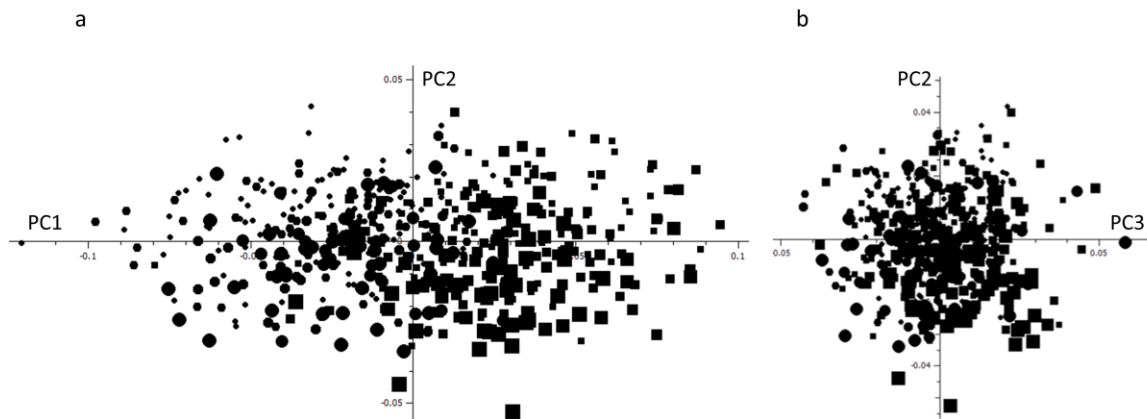


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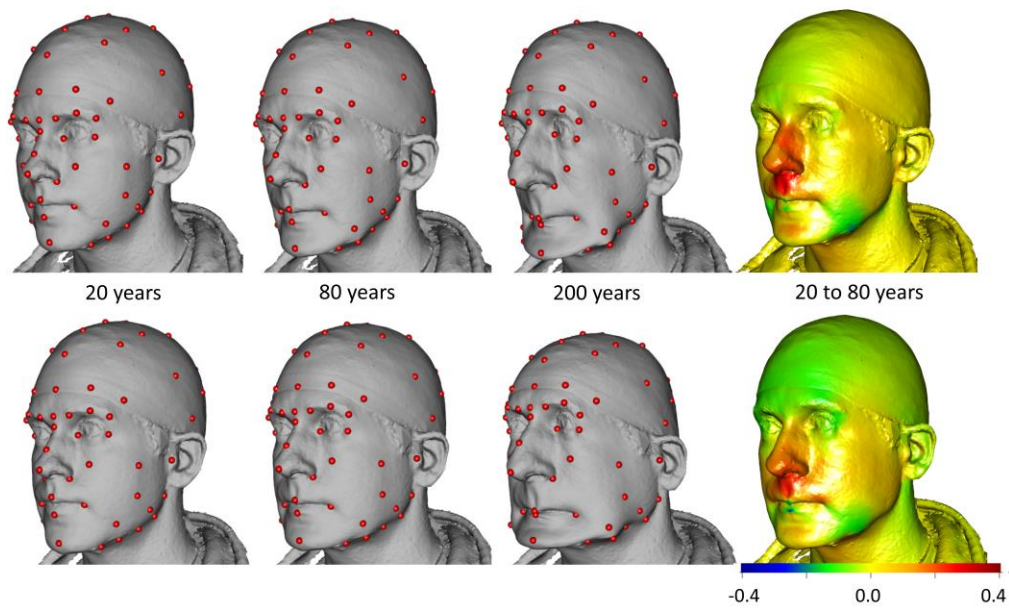




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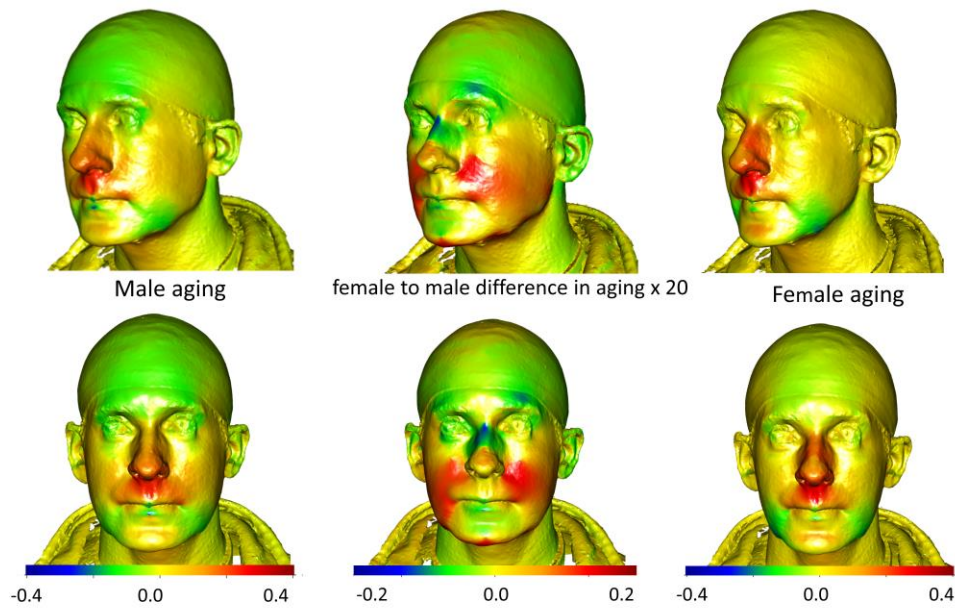
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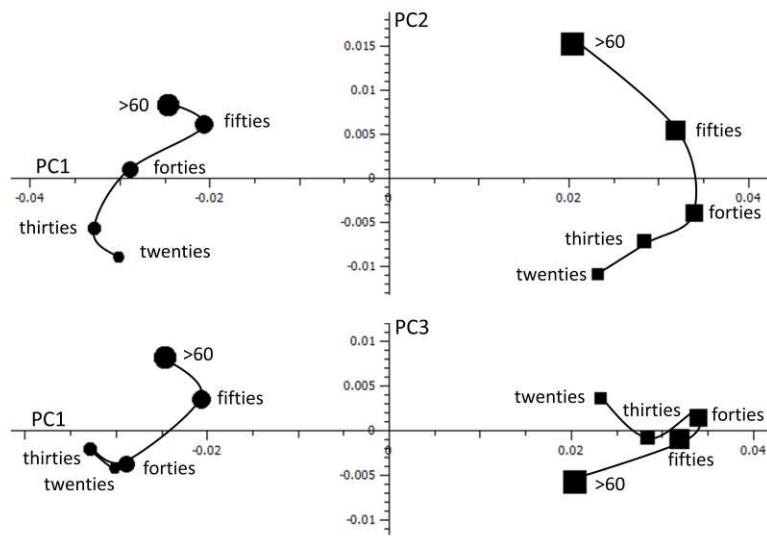
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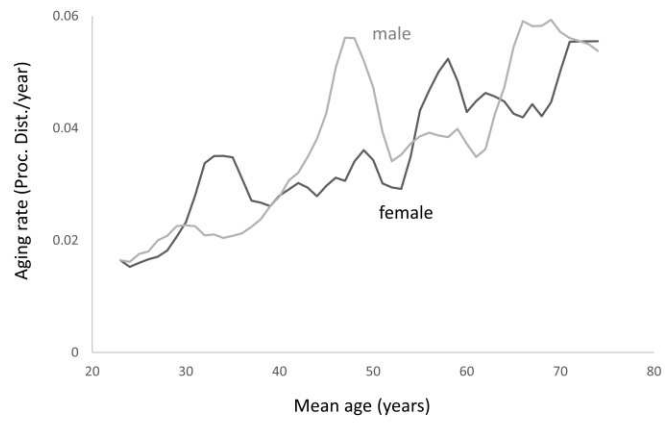
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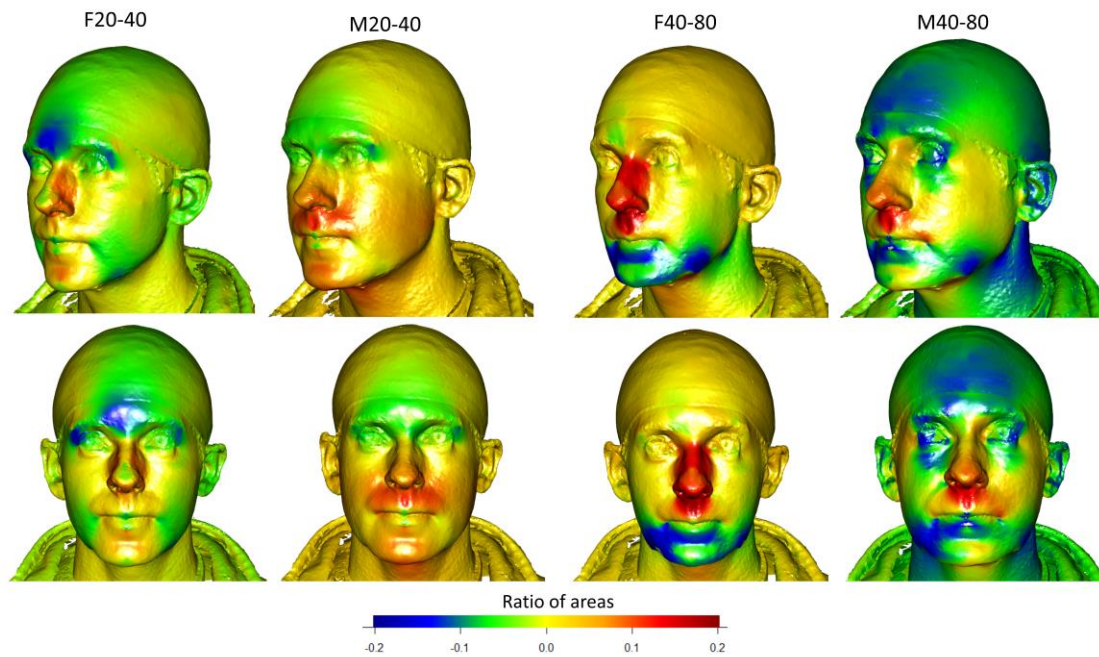
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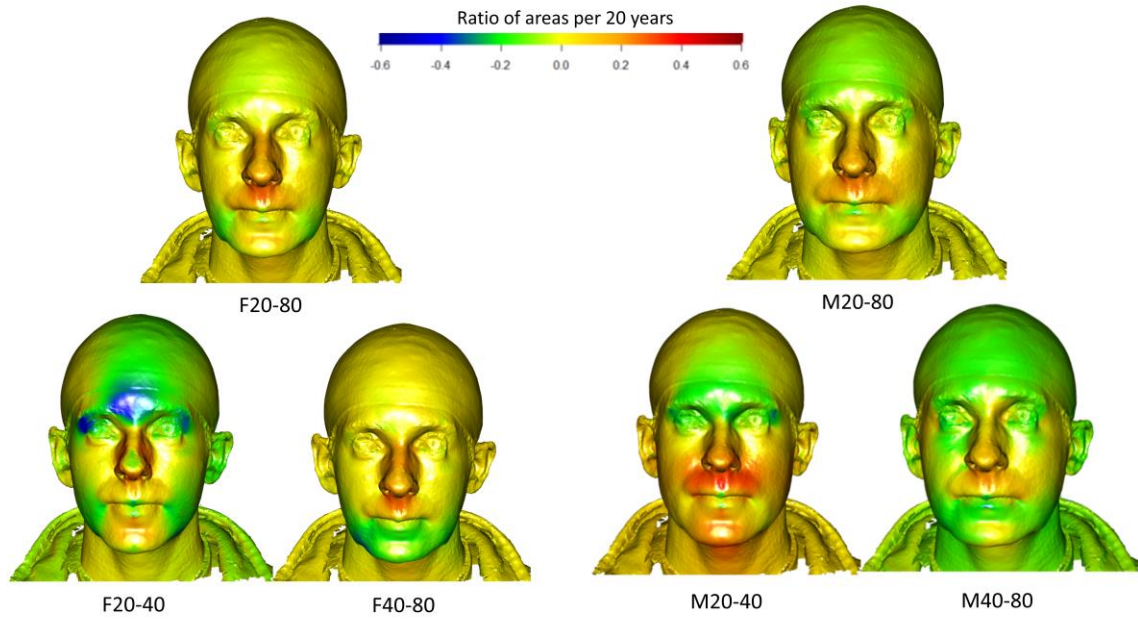
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 557 related changes are shown as colour maps of the ratios of areas of equivalent  
 558 craniofacial regions scaled to represent change per 20 years.

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No.	Landmark description
1 & 3	Medial canthus
2 & 4	Lateral canthus
5	Nasal bridge
6	Middle of nose
7	Tip of nose
8 & 9	Corner of mouth
10	Middle of cupid's bow upper lip
11	Middle of bottom lip
12	Tip of chin
13 & 14	Tragus
15 & 16	Lateral nasal alar rim

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572 **Table 1:** Definitions of fixed facial landmarks.

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Regressions on age	% explained variance ( $R^2$ )	p (1000 permutations)
Form males	3.3%	<0.001
Form females	3.3%	<0.001
Shape males	4.5%	<0.001
Shape females	4.2%	<0.001

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577 **Table 2:** Multivariate regressions of form and shape on age in each sex for the full  
578 sample

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<b>Regression of form on age</b>	<b>R<sup>2</sup></b>	<b>p (1000 permutations)</b>
Males 20-39	0.01607	0.011
Males 20-49	0.01868	0.005
Males 40-90	0.04242	0.002
Males 50-90	0.03619	0.023
Females 20-39	0.0122	0.047
Females 20-49	0.01595	0.007
Females 40-90	0.02322	0.022
Females 50-90	0.01067	0.814

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582 **Table 3:** Multivariate regressions of form on age in each sex for subsamples of  
583 younger and older individuals in each sex

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<b>Form vector comparisons</b>	<b>Angle degrees</b>	<b>p (1000 permutations)</b>
males 20-39 vs males 40-90	94.3	<0.001
males 20-49 vs males 50-90	104.7	<0.001
females 20-39 vs females 40-90	80	<0.001
females 20-49 vs females 50-90	89.5	<0.001
females 20-39 vs males 20-39	81.3	0.008
females 20-49 vs males 20-49	65	0.085
females 40-90 vs males 40-90	85.6	0.052
females 50-90 vs males 50-90	69.2	0.609

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588 **Table 4:** Vector comparisons between multivariate regressions of form on age between age  
589 subgroups and sexes

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