Submitted, accepted and published by Elsevier: HOMO 67(3): 188–202 (2016).
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TITLE PAGE

Variation of mandibular sexual dimorphism across human facial patterns

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Abbreviated title: Mandibular sexual dimorphism

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ABSTRACT

This study analyzed how sex-specific features differed in male and female adult mandibles throughout the spectrum of vertical facial patterns (i.e., meso-, dolicho- and brachy-facial) and sagittal variations (the so-called skeletal classes I, II and III; normal maxillo-mandibular relationship, maxillary prognathism vs. mandibular retrognathism, and maxillary retrognathism vs. mandibular prognathism, respectively). Specifically, we test the hypothesis that sexual dimorphism in the mandible is independent of such facial vertical and sagittal patterns. A sample of 187 European adults (92 males, 95 females; age range, 20–30 years; mean age, 25.6 ± 4.2 years) from Granada (southern Spain) were randomly selected and grouped according to the standard cephalometric criteria of the sagittal and vertical patterns. Geometric morphometrics were used to analyse the size (centroid size) and shape (principal components analysis, mean shape comparisons) of the mandible. The patterns of sexual dimorphism were evaluated with a Generalised Linear Model with interaction term. We found that sagittal and vertical facial patterns are associated with different mandibular morphologies (size and shape) Also, sexual dimorphism was present in all comparisons. The hypothesis was rejected only for vertical facial patterns. That is, the nature of sexual dimorphism was similar among the skeletal classes but different (e.g., distribution of dimorphic variables, interaction term) in meso-, dolicho-, and brachyfacial mandibles. In conclusion, sex-specific mandibular traits behave in a different way across vertical facial patterns. These results imply that an assessment of the vertical facial pattern of the individual is required before a sexual diagnosis of the mandible is proposed.

Introduction

A marked sexual dimorphism has frequently been reported in the human face and mandible, both in size and shape (Bulygina et al., 2006; Giles, 1964; Humphrey, 1998; Loth and Henneberg, 1996; Oettle et al., 2009; Rosas and Bastir, 2002; Ursi et al., 1993). The pattern of sexual dimorphism in the mandible (e.g., distribution of sexually dimorphic measurements) is, nevertheless, extremely variable, both between and within species. Within humans, the degree and pattern of sexual dimorphism is frequently recognized as highly population-specific (Bejdova et al., 2013; Frayer and Wolpoff, 1985; Hall, 1978; Iscan, 2005; MacLaughlin and Bruce, 1986; Ross et al., 2011; Wells, 2007), which has given rise to a number of studies directed to typify the population-specific pattern of sexual dimorphism of the skull and mandible (e.g., Franklin et al., 2008; Green and Curnoe, 2009; Kharoshah et al., 2010; Steyn and Iscan, 1998). Even more, Bulygina et al. (2006) detected changes in the pattern of facial shape differences between sexes along ontogeny, something already appreciated in mandibles along the adult life by Hunter and Garn (1972), who suggested the desirability of age specific discriminant function analysis. In this context, Coquerelle et al. (2011) found that males are characterised by a continuation of allometric shape changes from puberty to adulthood. In contrast, the shape of the female mandible continues to change even after the size has ceased to increase. As a consequence, adult dimorphism is concentrated at the ramus and mental region, during the earliest ontogenetic stages and again at adulthood. At age 20 in males, the coronoid process is positioned more backward and upward; the gonion is pointed more downward; and the basal symphysis is oriented more downward than in females. Rosas and Bastir (2002) found a dimorphic superoinferior positioning of the mental region, upward in females versus downward in males; In their study, they extracted three features potentially useful for sexual diagnosis in the mandible: the curvature of the anterior symphysis, the development of the preangular notch, and the flexion of the ramus. Thayer and Dobson (2010) examined patterns of quantitative variation in modern human chin shape in order to evaluate different hypotheses about the functional significance of the chin. They found significant differences in chin shape between sexes, and the male mandibular symphyses tending to be taller and the mentum osseum more protrusive than females. These authors concluded that any hypotheses for the function of the human chin must take into account sexual dimorphism in chin shape.

On the other hand, some specific features are identified as sexually dimorphic in one population whereas the very same features are not necessarily valid for the sexual diagnosis in another population (Bejdova et al., 2013; Garvin and Ruff, 2012). Simultaneously, there are also some variables in the mandible that are more sexually diagnostic across population, like height of the ramus (Humphrey et al., 1999; Hunter and Garn, 1972).

Sexual dimorphism of the adult mandible has also been confirmed, although to a lesser extent, in malocclusive groups (Baccetti et al. 2005; Battagel 1993; Wellens et al. 2013). Nevertheless, Riesmeijer et al. (2004) and Generoso et al. (2010) did not find differences in mandibular lengths between adolescent males and females with skeletal Class II malocclusion (i.e., maxillary prognathism vs. mandibular retrognathism).

In this context, knowing the factors that determine the variation in the pattern of sexual dimorphism of the mandible is relevant in biological anthropology, the implications of which disseminate also in paleoanthropology, paleodemography, forensics or orthodontics.

Explanations for the sexual dimorphism pattern in the mandible and its large variation are diverse, but the biological determinants by which differences between males and females are reached remains elusive. Bejdova et al. (2013) proposed that sexual dimorphism of mandible size could be influenced by the environment, and especially by diet and nutrition, while others maintain that the different degree of sexual dimorphism of shape between samples could be related to differences in sexual selection (Swaddle and Reierson, 2002; Thayer and Dobson, 2010). Hormones, nutritional stress and population-specific activity pattern have also been proposed as determinants for the mandible sexual dimorphism (Bejdova et al., 2013; Loth and Henneberg, 1996; Oettle et al., 2009; Suazo et al., 2008). Genetic correlation or morphological integration with other organism-level factors must be also involved in the expression of sexual dimorphism in the human mandible. In this context, Alarcon et al. (2014) have recently demonstrated a different pattern of morphological integration between the craniofacial complex and the mandible among vertical facial patterns.

In light of the difficulty of directly assessing this complex matter, a way to approach the analyses of the disparity in the distribution of sexually dimorphic features across populations has been to evaluate the association of the sexual dimorphism in the mandible with other factors of variation affecting the craniofacial system. Thus, this study analyzed how sex-specific features differed in male and female adult mandibles throughout the spectrum of vertical facial patterns (i.e., meso-, dolicho- and brachy-facial) and sagittal variations (the so-called skeletal classes I, II and III; normal maxillo-mandibular relationship, maxillary prognathism vs. mandibular retrognathism, and maxillary retrognathism vs. mandibular prognathism, respectively). Specifically, we test the hypothesis that sexual dimorphism in the mandible is independent of facial vertical and sagittal patterns. Consequently, if the nature of the sex differences is independent of the facial patterns, it could be expected that the distribution of sexual differences would be the same in different subgroups of the same population. That is, the differences that help to distinguish males and females might be the same in the meso-, dolicho-, and the brachy-facial within-population subgroups. The same applies for the sagittal patterns (skeletal classes I, II and III).

We next approach these aspects by means of 2D GM methods in a large modern human sample, previously exploring the basics of size and shape mandibular variation across sagittal and vertical variation facial patterns.

Material and methods

Data sample

This study included 187 European adult subjects (92 males, 95 females; age range, 20–30 years; mean, 25.6 ± 4.2 years) from Granada (southern Spain) who were randomly selected from a private dental office. Exclusion criteria included craniofacial anomalies; congenitally missing, supernumerary, or extracted teeth; and previous or current orthopedic or orthodontic treatment.

For all subjects, standard lateral cephalometric radiographs (with the teeth in centric occlusion and with the head oriented horizontally with the Frankfort plane) were taken with a cephalostat in accordance with standard cephalometric procedures (Alpern, 1984). The same digital x-ray device (Planmeca PM-2002 EC Proline Dental Pan X-Ray Machine, Helsinki, Finland), technician, focus-median (150 cm) plane distance, and film-median (10 cm) plane distance were used for all radiographs. A reference ruler was shown on the cephalostat for exact measurement of the magnification factor. Prior to analyses all cephalograms were anonymized in order to comply with the Helsinki protocol (Goodyear et al., 2007).

Sagittal facial patterns (skeletal classes I, II and III) and vertical facial patterns (meso-, dolicho-, and brachi-facial) were distinguished following standard orthodontic criteria (ANB angle and FMA angle, respectively) (Proffit et al., 2007; Riolo et al., 1974; Steiner, 1953).

Skeletal classes refer to sagittal maxillo-mandibular relationship, according to the ANB angle. ANB angle measures the relative sagittal position of the maxilla to mandible; it can be measured or calculated from the formula: ANB = SNA - SNB. SNA is the angle between Sella, Nasion, and Point A (deepest point on the anterior surface of the maxilla between anterior nasal spine and Prosthion). SNB is the angle between Sella, Nasion, and Point B (deepest point on the anterior surface of the mandibular symphysis between Infradentale and Pogonion). Class I (ANB angle between 0° and 3°) refers to an adequate maxillo-mandibular relationship, while Class II (ANB angle >3°; i.e., relatively protruded maxilla and retruded mandible) and Class III (ANB angle <0°; i.e., relatively retruded maxilla and protruded mandible) refer to sagittal jaw discrepancies.

Vertical facial patterns were determined according to the FMA angle. FMA angle is the angle between Frankfort Horizontal, a line connecting Porion to Orbitale, and Mandibular Plane, a line connecting Gonion to Menton. FMA angle between 20° and 28° correspond to mesofacial, FMA angle >28° to dolichofacial, and FMA angle <20° to brachyfacial pattern.

From the total sample (n=187, 92 males, 95 females), 88 (40 males; 48 females) subjects presented Class I, 54 (26 males; 28 females) Class II, and 45 (23 males; 22 females) Class III, and 97 (46 males; 51 females) subjects presented mesofacial, 49 (26 males; 23 females) dolichofacial, and 41 (21 males; 20 females) brachyfacial pattern.

All cephalograms were imported into the tpsDIG 2.12 software (tpsSeries, J.F. Rohlf, SUNY Stony Brook; http://life.bio.sunysb.edu/morph/) to digitise 17 landmarks (2D) representing the morphology of the mandible and 31 semi-landmarks representing the morphology of the lower surface of the mandibular body and the contour of the bony chin-symphysis (Table and Fig. 1). All of these localisations were performed by the same examiner (J.A.A.). Paired bilateral landmarks were digitised by averaging the left and right sides, when there was not an exact match between both sides.

Measurement errors were evaluated by multivariate analysis of variance (MANOVA) by repeated data recordings of 10 randomly selected subjects on 4 different days. No significant differences were found between the repeated samples (Wilks lambda 5 0.00; F 5 1.69; df1, 2 5 138, 6, 47; P 5 0.2), indicating that the measurement errors were smaller than the sample variations.

Geometric morphometrics and statistical analyses

The landmark data were superimposed using Generalised Procrustes registration. During the superimposition, the semilandmarks were reslid iteratively so as to minimize the bending energy between each specimen and the Procrustes average (Bookstein, 1997). The size (centroid size) and shape (Procrustes shape coordinates) were analysed separately. Shape analyses (principal components analysis, mean shape comparisons, and permutation tests) and shape visualisations were conducted in MorphoJ software (Klingenberg, 2011). Parametric statistical analyses (ANOVAs for mean centroid size comparisons, Generalised Linear Models) were performed in Statistika (STATSOFT, 1999).

First, groups of sagittal and vertical facial patterns were determined using the standard orthodontic procedures mentioned above. Then, principal components analyses were conducted to explore overall variation, and group differences among sagittal and vertical facial patterns were assessed with shape comparisons and permutation analyses of group membership (N=1000) of Procrustes distances for hypothesis testing.

Finally, we tested the hypothesis that different patterns of sexual dimorphism are present across different sagittal and vertical facial patterns, using a Generalised Linear Model with an interaction term (Sex* sagittal patterns, and Sex* vertical patterns) on the first 20 PC scores, which accounted for more than 95% of the total shape variance.

Results

Size analysis

Mean comparisons of centroid size are given in Table 2. ANOVAs were significant for sagittal facial patterns and no interaction was observed between sagittal and vertical facial patterns. Bonferroni post-hoc comparisons of mean centroid size across sagittal patterns revealed significant differences between skeletal Class III (mean size 240.83) and Class I (mean size 231.22) and between Class III and II (mean size 225.04) (Table 3). The mean sex differences were also significant in all comparisons (Table 4).

Shape analysis

The first two principal components capture approximately 40% of total variance (Figs. 2,3). These analyses show a major component of shape variation (PC1) that is not associated with sagittal facial patterns (Fig. 2a,b), but, in turn is very clearly linked to vertical facial patterns (Fig 2c,d). The loadings of the second principal component show a clear signal of sexual dimorphism with female loadings towards the negative extreme and males towards the positive extreme. This is also evident from the associated shape changes. PC1 of Figure 3 shows clearly variation according to the dolicho- versus brachyfacial spectrum (hyper- versus hypodivergent mandibles), while PC2 reflects general features of sexual dimorphism.

Quantitative analyses of mean shape showed significant differences between all sub-groups of sagittal (Fig. 4) and vertical (Fig. 5) facial patterns (Table 5) and sex (Table and Fig. 6):

The smallest differences in mandible shape were found between Class I and Class II, and the greatest differences between Class II and Class III. Class II mandibles exhibited a wider ramus and corpus and were more squared-shaped. The coronoid process of class II mandibles is also located forward and slightly upward; the condyle is also located forward but downward; the posterior border of the ramus is shorter and had a posterior flexion; and the gonion is located downward and backward. The gonial angle is more closed; the basal border is concave; and the anterior corpus is antero-rotated. The alveolar process is elongated, and the anterior part antero-rotated. The symphysis is wider and taller, and the upper part is elongated and proclinated. In contrast, Class III mandibles exhibit an elongated and posteriorly rotated ramus which gives rise to a more hyper-divergent shape; a very slight anterior flexure; and an upper and backward elongated condyle. This configuration results in an anteroposterior elongation of the mandible along the condyleon-Pogonion axis (Co-Pg)(Fig. 4).

Differences between dolicho- and brachyfacial shapes are manifested in all mandibular traits. In dolichofacial mandibles, the mandible is hyper-divergent; the ramus is narrow and posteriorly-orientated; the coronoid process is positioned backward and upward; the condyle is relatively narrow and positioned backward and downward; the posterior ramus border exhibits a posterior flexion; the gonial angle is open (open corpus-ramus angle); the pre-angular notch is pronounced; the corpus height is relatively decreased with a rounded inferior basal border; the anterior mandibular corpus and chin are postero-rotated with a decreased projection of the chin; the symphysis is narrow, elongated, and vertically projected; and the alveolar process is higher. Brachyfacial mandibles display the opposite morphology: hypo-divergent square-shape; a relatively wider condyle; a wider and anteriorly-oriented ramus; the posterior ramus border has an anterior flexion; the gonial angle is positioned more downward; the anterior mandibular corpus and chin are rotated anteriorly leading to an upward and forward projection of the chin; and the corpus and symphysis thickness is greater (Fig. 5).

Sexual dimorphism is clearly expressed among the sagittal and vertical facial patterns. Among Class II mandibles, female mandibles are more open angled; the ramus is relatively shorter and wider; the coronoid process is located forward and downward; the condyle is oriented backward and downward; the posterior border of the ramus is shorter and has a marked posterior flexion due to a posterior inclination of the condyle; the gonion is located upward and backward; the preangular notch is smoother and the basal border is flatter; the symphysis is anteriorly inclinated; and, therefore, the dentoalveolar process becomes longer. Even more relevant sexual differences can be seen in Class III. Female mandibles have a relatively shorter and narrower ramus, a pronounced concavity in the anterior border, and a marked posterior flexion in the posterior border; the coronoid process is located further down; the condyle is located downward and backward and is posteriorly inclinated; the corpus is narrower, especially the posterior part; the symphysis is markedly shorter, narrower, and the upper part anteriorly inclinated; and the alveolar process longer. In both Class II and Class III, female mandibles are relatively shorter antero-posteriorly. According to vertical facial patterns, in dolichofacial males, the ramus and corpus are narrower and more open angled. This shape increases the gonial angle. The symphysis is thinner, and the chin is less prominent than in females. In females, the posterior ramus flexure is more pronounced. In brachyfacials, the posterior ramus flexure difference is very pronounced. In males, the anterior flexion increases. In females, the posterior flexion also increases. The corpus is relatively narrower in females (especially the posterior part), and the alveolar height is also reduced (mainly the posterior region). The antero-rotation of the anterior corpus and chin increases in females resulting in a remarkable reduction in the symphysis height (Fig. 6).

The Generalised Linear Model analysis showed further that the pattern of sexual dimorphism in shape was the same in all sagittal facial patterns (Table 7) but was significantly different (interaction term) in the vertical facial patterns (Table 8, Fig. 7). Therefore, the hypothesis was rejected only for vertical facial patterns.

Discussion

This study aimed to explore mandibular variation in principal sagittal and vertical facial patterns and tested the hypothesis that sexual dimorphism and facial patterns are independent factors in the spectrum of craniofacial variation (Enlow, 1990).

In short, we have found that sagittal and vertical facial patterns are associated with different mandibular morphologies (size and shape) Also, sexual dimorphism was present in all comparisons. The hypothesis that sex-specific mandibular variability patterns are independent across standard sagittal and vertical facial patterns was rejected only for vertical facial patterns. That is, the nature of sexual dimorphism was similar among the three skeletal classes (sagittal facial patterns) but different (e.g., distribution of dimorphic variables, interaction term) in meso-, dolicho-, and brachyfacial mandibles (vertical facial patterns).

Shape evaluation of the mandible revealed specific and significantly different shape characteristics associated with every sagittal and vertical facial pattern. Regarding sagittal facial patterns, the greatest differences were found between Class II and Class III skeletal classes, which represent the limits of the sagittal maxillo-mandibular relationship, in reference to the anterior cranial base (ANB angle). Class II subjects present a more squared shape and wider corpus and ramus than Class III subjects. Class III mandibles show relatively elongated and posteriorly-rotated ramus and upper and backward elongated condyles which result in an anteroposterior elongation of the total mandible along the condyleon-pogonion axis. Due to its specific shape configuration, the Class III mandible is more pronounced antero-posteriorly, and that, together with its larger size, contributes to a more prognathic profile. In contrast, Class II mandible is less pronounced antero-posteriorly, mainly due to a thinner symphysis and to a thinner and lower condyle process; this morphologic configuration contribute to a more retrognathic profile. A remarkable finding of the present study is the posterior flexion of the posterior ramus border in the Class II mandible, which, to our knowledge has not been previously described in the literature.

Regarding vertical facial patterns, significant differences were found in mandibular shape between the three groups (meso- vs. dolichofacials, meso- vs. brachyfacials, and dolicho- vs. brachyfacials). Mean shape comparisons also indicate greater shape distances between dolicho- versus brachyfacial mandibles than between meso- vs. dolichofacials, and meso- vs. brachyfacials (Table 5). Dolicho- and brachyfacial mandibles present the previously described shape characteristics of long- and short-faces, respectively (Bastir and Rosas, 2004; Bhat and Enlow, 1985; Enlow et al., 1982; Lieberman et al., 2000). Due to its specific shape configuration, dolichofacial mandibles are less pronounced antero-posteriorly. This configuration, together with its smaller size, contributes to a more retrognathic profile. On the other hand, brachyfacial mandibles are more pronounced antero-posterioly. The shape range variability is greater among the vertical than between the sagittal facial patterns (i.e., the shape range variability) (Procrustes distances, Table 5) between dolicho- and brachyfacial mandibles is greater than between Class II and Class III mandibles.

Mandible sexual dimorphism discrepancy among populations

Sexual dimorphism is clearly expressed in the mandible size and shape. Differences in mandible size were expected, reflecting differences in body size and body composition between males and females.

Our findings of mandible shape analysis match with those reported by Rosas and Bastir (2002) in the mandible condyle, gonion, and development of the preangular notch. However, we found in males a slight anterior flexion of the posterior border of the ramus, while Rosas and Bastir

(2002) found that males presented a marked curvature of the posterior border, and, even more striking, in our study, females presented a pronounced posterior flexion of the ramus. Although related to vertical facial pattern, this feature could be extracted for sexual diagnosis in our population. The posterior mandibular ramus flexure has also been considered a significant qualitative feature for sex discrimination in other populations. Loth and Henneberg (1996) described the mandibular ramus flexure as an easily applied, highly reliable method for sex identification in their African and American samples. According to their research, distinct angulation (flexure) of the posterior ramus border at the level of the occlusal plane is present in adult male mandibles. Adult female mandibles are not flexed at this point and have straighter posterior borders. These findings are contrary to those found in our population and have been discussed by other studies that found much less dimorphism using this approach (Donnelly et al., 1998; Hill, 2000; Rosas et al., 2002).

Our results on sexual dimorphism of the mandibular symphysis differ from Coquerelle et al. (2011) and Bastir and Rosas (2002). We did not find the dimorphic superoinferior positioning of the mental region (upward in females versus downward in males). In our sample, the whole symphysis had a more forward location in females, which is in agreement with Rosas and Bastir (2002), however, its superoinferior position was similar in both sexes in the overall sample. Nevertheless, when separated by sagittal and vertical facial patterns, these differences between males and females appear in skeletal Class III and in brachyfacial adults. Thayer and Dobson (2010) also demonstrated dimorphism between the sexes (the male mandibular symphysis tends to be taller, and the mentum osseum is more protrusive than in females). These features are different from our sample most likely because these authors analysed a pooled sample of individuals from diverse geographic regions.

Sex and facial pattern interaction

Sexual dimorphism is significantly expressed in sagittal and vertical facial patterns and affects all mandibular traits. As noted before, visual analysis indicates more differences between male and female mandibles in the vertical dimension (dolicho- vs. brachyfacials) than in the sagittal dimension (Class II vs. Class III).

As stated in the introduction, we were expecting that if the nature of the sex differences is independent of the facial pattern, the distribution of sexual differences would be the same in the within-population subgroups, both sagittal and vertical patterns. Interestingly, we found a composite of results. On the one hand, the pattern of sexual dimorphism in shape was similar among the three sagittal facial patterns, which is indicated by the non-significant interaction term between sexual dimorphism and skeletal class I, II and III. However, on the other hand, a significant interaction term was detected for vertical facial patterns, reflecting differences in the pattern of sexual dimorphism between meso-, dolicho-, and brachyfacial mandibles.

The interaction term found for vertical facial patterns was a reasonable and expected finding according to our previous studies. Human skull sexual dimorphism was previously verified in the nasopharyngeal skeleton among different populations, and males have relatively and absolutely larger airways than females (Bastir and Rosas, 2013; Rosas and Bastir, 2002). A proposed explanation for these sexual differences is that males have higher daily energy expenditure, greater respiratory air consumption, and differences in body composition. Thus, respiratory function and energy expenditures may play an important role in sexual dimorphism of the skeletal morphology in the midface (Bastir et al., 2011; Holton et al., 2014). We also found that morphological integration between the craniofacial complex and mandible differed among vertical facial patterns. In other words, dolicho- and brachyfacial subjects showed specific and different craniofacial complex and associated mandible configurations (Alarcon et al., 2014). The present study illustrates that, besides their morphologic specific differences, dolicho- and brachyfacial patterns also shows specific patterns of sexual dimorphism. The different nature of sexual dimorphism found between dolicho- and brachyfacial patterns would most likely be an expression of the different physiological demands of males and females in a given structural context (Bastir and Rosas, 2013; Bastir et al., 2011). Morphologically, the interaction term found for vertical facial patterns is particularly well reflected in the morphological features of the ramus. In dolichofacial individuals males and females differ in both ramus breadth and flexion of the posterior ramus, while in brachyfacial patterns, sexual dimorphism has almost no effect on the ramus breadth. This is also recorded in the principal components analysis (Fig. 2 c,d) where within the dolichofacial patterns a clear separation of males and females can be observed, with females plotting at the negative PC2 extremes and males towards the positive PC2 extremes. In the brachyfacial group no such differences can be observed (Fig. 2 c,d). Additionally, relative mandibular corpus height at the molar level in brachyfacial patterns is higher in males, while in dolichofacial individuals, it is higher in females. However, orientation features at the gonion-coronoid axis (coronoid orientation) and the symphysis are shared. In conclusion, sex-specific traits behave in a different way across vertical facial patterns.

Conversely, the nature of sex differences remains stables across skeletal classes. If the physiological explanation and size of nasal cavity holds, it follows that size and volume of the nasal cavity does not affect the morphogenesis of the mandible, and consequently no effect on sexual dimorphism is expressed. This is fully consistent with our previous results in which we found indistinguishable covariation pattern between mandible and craniofacial complex across sagittal facial patterns (skeletal classes) (Alarcon et al., 2014).

Quantity of growth is clearly involved in size and allometric shape correlations, for instance higher ramus (Rosas and Bastir, 2002). At the same time, specific craniofacial growth patterns have an effect on the mode sexual differences are expressed in the mandible, hypothetically mediated by the adjustment of differential nasal cavity volume on basic long or short skeletal faces.

To summarize, sex-specific mandibular traits behave in a different way across vertical facial patterns. As a practical corollary, these results imply that an assessment of the vertical facial pattern (e.g., dolicho- brachyfacial) of the individual is required before a sexual diagnosis of the mandible is proposed.

Acknowledgments

We would like to thank the extremely useful comments and suggestions by the editor and referees during the review process. This research was funded by the Spanish Ministry of Economy and Competitiveness: Projects CGL2012-36682 and CGL2012-37279

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Figures Legends

Figure 1. Lateral cephalometric radiograph showing the localisation of the landmarks and semi-landmarks.

Figure 2. Scatterplots of PC1 and PC2 by sex and by sagittal facial patterns (a,b) and by vertical facial pattern (c,d). Upper row shows females, lower row males. Females and males are plotted into the same range of PC scores so as to indicate sexual dimorphism. Note that PC1 (22.35% of total variance) does not order the data according to sagittal facial patterns (a,b), while it orders the data very well according to vertical facial patterns (c,d). PC2 (17.7% of total variance) reflects general sexual dimorphism. Note that sexual dimorphism is clearer in dolichofacial patterns than in brachyfacial patterns (c,d).

Figure 3. Shapes associated to PC1 and PC2 (natural range of variation); A negative scores, B positive scores. PC1 (upper row) shows variation related to vertical facial patterns and contrasts hyperdivergent (dolichofacial) and hypodivergent (brachyfacial) mandibles. PC2 reflects variation related to sexual dimorphism (ramus height, chin inclination, gonial profile, posterior ramus flexion).

Figure 4. Morphological comparisons of mandibles from the different sagittal facial patterns (skeletal classes) (differences magnified 3x). The first named is illustrated with dashed line.

Figure 5. Morphological comparisons of mandibles from the different vertical facial patterns (differences magnified 3x). The first named is illustrated with dashed line.

Figure 6. Comparisons of morphological sexual differences in the sagittal, and vertical facial patterns (differences magnified 3x). The first named is illustrated with dashed line.

Figure 7. Complete representative lateral cephalometric radiographs of males and females belonging to vertical facial patterns (dolicho- and brachyfacial patterns) (differences magnified 3x). A: Female-Dolichofacial; B: Male-Dolichofacial; C: Female-Brachyfacial; D: Male-Brachyfacial

Table 1. Landmarks and semi-landmarks

1	Infradentale (Id)	Anterosuperior point of mandibular alveolus
2	Supramentale (point B)	Deepest point of the anterior surface of the symphyseal outline of the mandible
3	Pogonion (Pg)	The most anterior point on the contour of the bony chin
4	Gnathion (Gn)	The most antero-inferior point on the contour of the bony chin symphysis
5	Menton (M)	Most inferior point on the mandibular symphysis
6	Symphysis point (Symp)	The most posterior point on the contour of the bony chin
7	Internal infradentale (LIB)	Most anterosuperior point on the lingual aspect of the mandibular alveolus
8	Antegonial Notch (Ag)	The deepest point of the curvature of the lower surface of the mandibular body in the gonial region
9-23	Slm	Semi-landmarks describing basal border of the mandible
24	Gonion (Go)	Point at the infero-posterior aspect of the angle of the mandible
25	Ramal Posterior (Rp)	Point of deepest concavity on the posterior border of the ramus
26	Articulare Posterior (Arp)	Posterior intersection of the condylar head and the posterior cranial base
27	Condylion (Co)	Point at the apex of the head of the mandibular condyle
28	Articulare Anterior (Ara)	Anterior intersection of the condylar head and the posterior cranial base
29	Sigmoid Notch (No)	Most inferior point between condylar head and coronoid process
30	Coronoid Tip (Ct)	Apex of coronoid process
31	Ramal Anterior (Ra)	Anterior Ramus Point. Most posterior point on the anterior border of the ramus
32	Mesioocclusal7- (L2M)	Mandibular second molar mesial cusp tip
33-48	Slm	Semi-landmarks describing internal symphysis profile

Table 2. Mean comparisons (ANOVAs) of centroid size among sagittal and vertical facial patterns.

	SS	**Degr. of - Freedom**	**MS**	**F**	**P**
Intercept	7564258	1	7564258	16330.87	0.0000
Sagittal facial patterns (skeletal classes)	3610	2	1805	3.90	0.0221
Vertical facial patterns	1849	2	925	2.00	0.1388
sagittal*vertical facial patterns	541	4	135	0.29	0.8828
Error	82447	178	463		

Table 3. Bonferroni post-hoc comparisons of mean centroid size across sagittal facial patterns (skeletal classes) ordered by magnitude of mean sizes.

Between MSE = 455.98, df = 182.00				
	Sagittal facial patterns (skeletal classes)	Class II**- 225.04**	Class I**- 231.22**	Class III**- 240.83**
1	Class II		0.2872	0.0009
2	Class I	0.2872		0.0449
3	Class III	0.0009	0.0449	

Table 4. Mean size comparisons, total sample, sagittal (skeletal classes) and vertical facial patterns. Student's t-tests and comparisons of variances between males and females.

Centroid Size	Male (Mean)	Female (Mean)	t-value	df	*P*
Total sample	242.19	221.63	7.1551	185	0.0000
Class I	241.55	222.60	3.4517	86	0.0008
Class II	236.96	218.02	5.7223	52	0.0000
Class III	246.26	227.45	4.9745	43	0.0000
Mesofacial	242.71	224.63	6.8505	95	0.0000
Dolichofacial	240.72	215.78	2.6149	47	0.0119
Brachyfacial	242.32	223.61	4.5784	39	0.0000

Table 5. Procrustes distances between means.

	Class I (d)	***p***	**Class II (d)**	***p***
Class II (d)	0.0176	0.014		
Class III (d)	0.0253	<.0001	0.0362	<.0001
	Brachyfacial (d)	***p***	**Dolichofacial (d)**	***p***
Dolichofacial (d)	0.0626	<.0001		
Mesofacial (d)	0.035	<.0001	0.0312	<.0001

Table 6. Mean shape comparison between males and females (1000 permutations).

	Procrustes distance	*p*
Total sample	0.0388	<.0001
Class I	0.0344	<.0001
Class II	0.0323	0.003
Class III	0.0395	0.001
Mesofacial	0.0364	<.0001
Dolichofacial	0.0462	<.0001
Brachyfacial	0.0351	0.004

Table 7. Sagittal facial patterns (skeletal classes) vs. sex (GLM)

	Test	Value	F	Effect - df	Error - df	*P*
Intercept	Wilks lambda	0.9905	0.0793	20	165	1
Sagittal facial patterns*Sex	Wilks lambda	0.7969	0.9919	40	330	0.489

Table 8. Vertical facial pattern vs. Sex (GLM)

	Test	Value	F	Effect - df	Error - df	*P*
Intercept	Wilks lambda	0.9821	0.1509	20	165	0.999
Vertical facial patterns*Sex	Wilks lambda	0.6546	1.9471	40	330	<.0001

Fig. 1

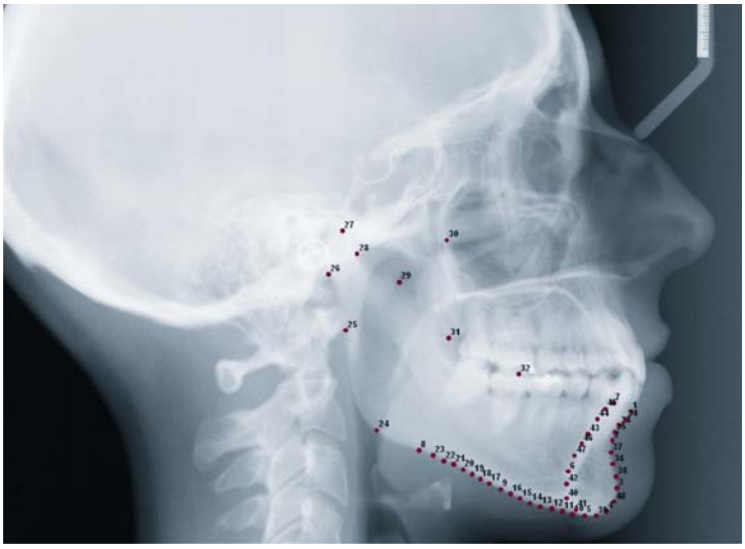
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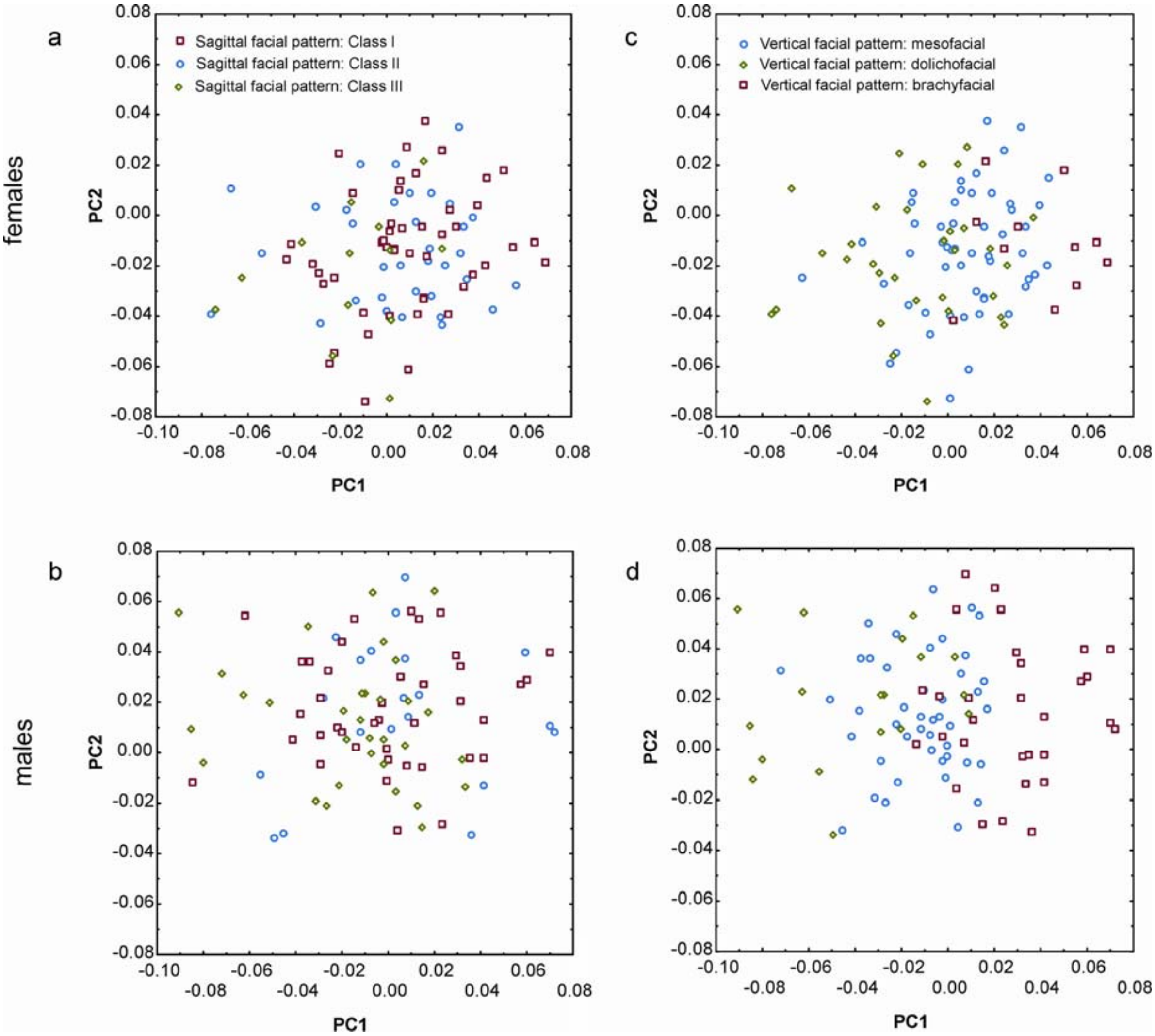
Fig. 2



a
b
c
d
females
males
Sagittal facial pattern: Class I
Sagittal facial pattern: Class II
Sagittal facial pattern: Class III
Vertical facial pattern: mesofacial
Vertical facial pattern: dolichofacial
Vertical facial pattern: brachyfacial
PC1
PC2
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10

Fig. 3

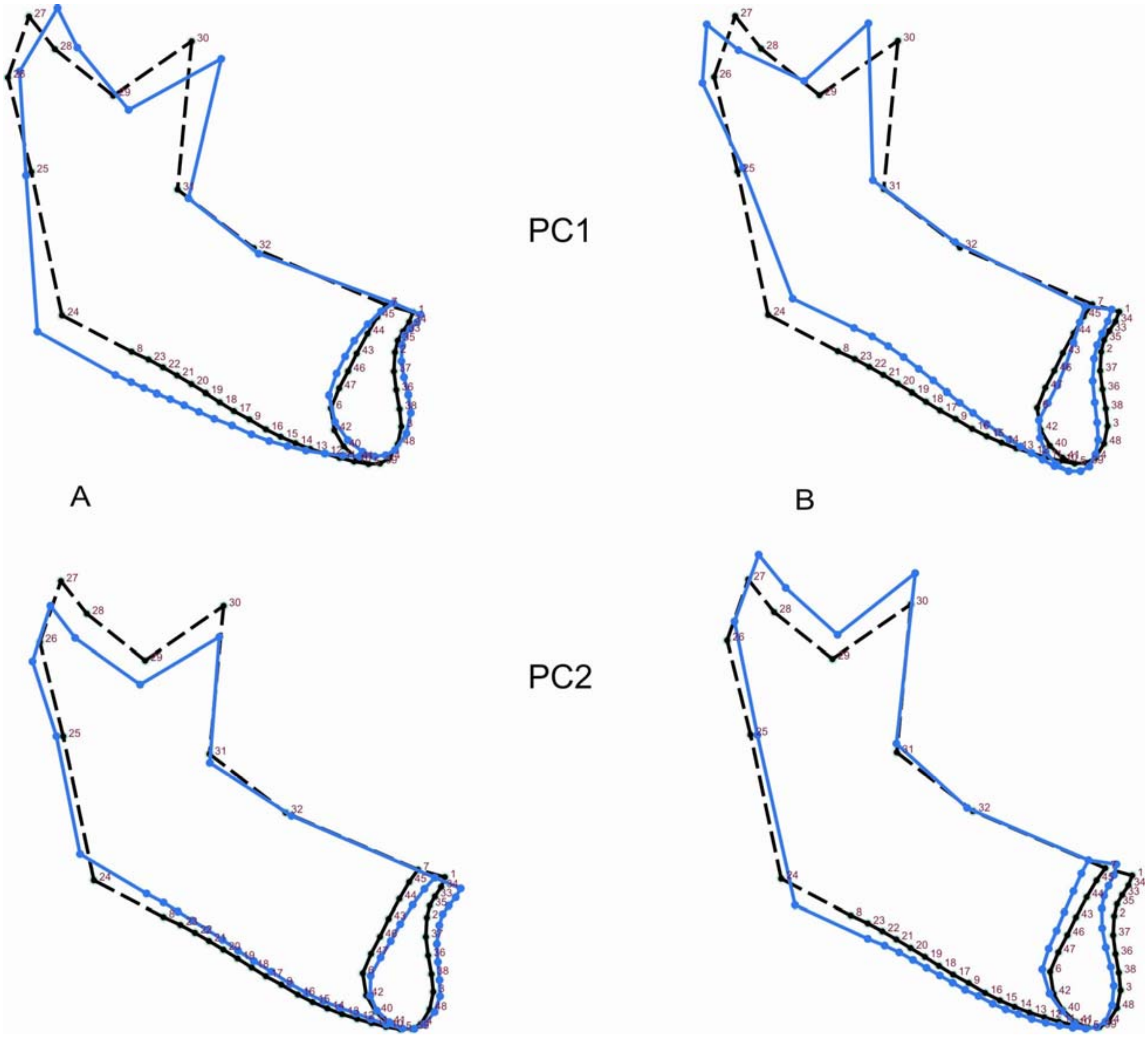


Fig. 4

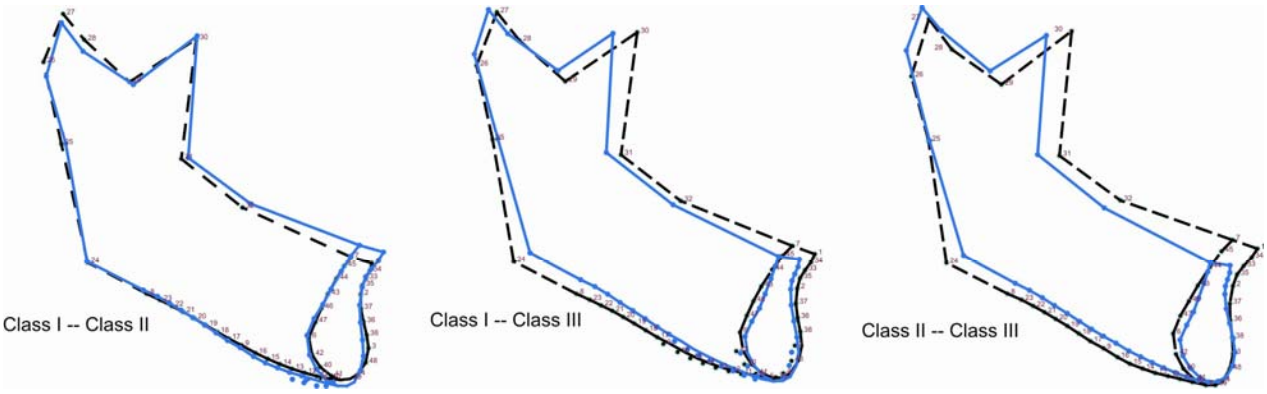


Fig. 5

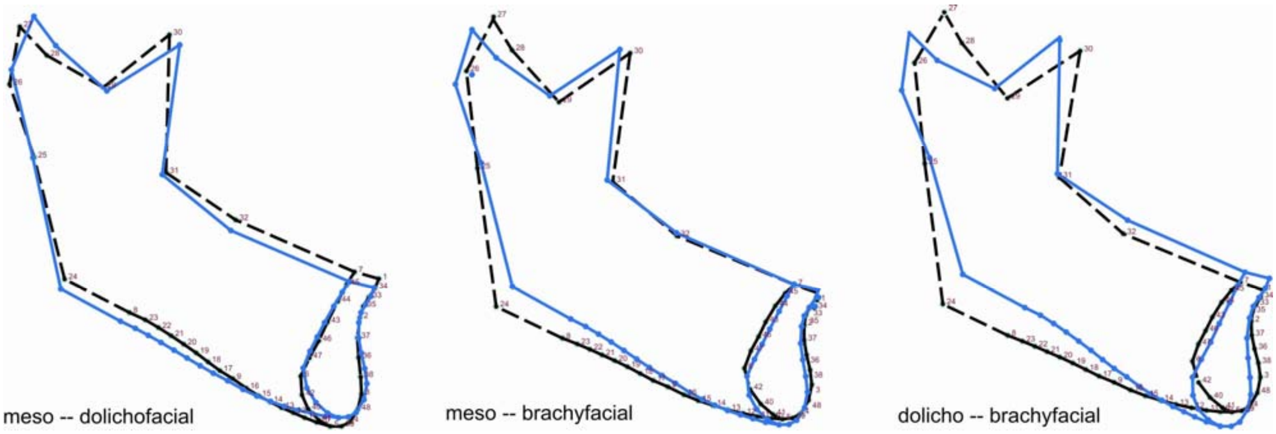

meso -- dolichofacial
meso -- brachyfacial
dolicho -- brachyfacial

Fig. 6

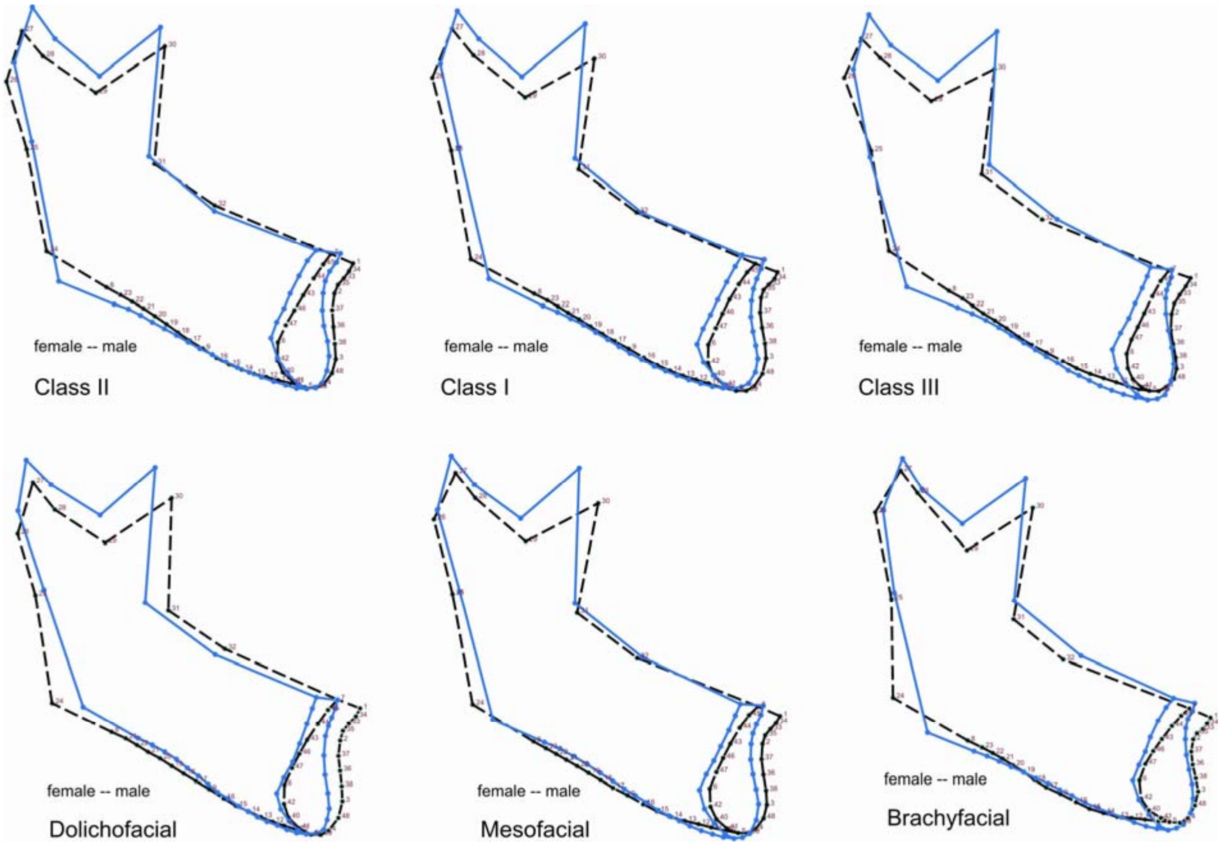

female -- male
Class II
female -- male
Class I
female -- male
Class III
female -- male
Dolichofacial
female -- male
Mesofacial
female -- male
Brachyfacial

Fig. 7