SEXUAL DIMORPHISM IN SOFT TISSUE FACIAL FORM AS CAPTURED BY DIGITAL THREE-DIMENSIONAL PHOTOGRAMMETRY

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Sexual dimorphism in the head and neck area is a particular interest to orthodontists who manipulate the underlying hard tissue in order to alter the overlaying soft tissue. Hard tissue differences between the sexes have been well documented in the literature with the advent of the cephalostat. With the enlightenment of the ‘soft tissue paradigm’, research has been shifted towards revealing differences in the soft tissue. Although overall size difference, with males being larger, has been a commonly recurring theme, elucidating shape differences has been more subtle. A large sample (n=586) of adults with recent European ancestry have been recruited for the study. Five direct anthropometric measurements were taken using calipers while 29 indirect anthropometric measurements were captured using a 3dMD digital stereophotogrammetry system (Atlanta, GA). Seven indices were derived and compared between the sexes. Statistical analysis was performed using a t-test as well as an analysis of covariance (ANCOVA) using height as the covariate measure. Our results confirmed that males were larger than females on all 34 measurements, and 32 of the 34 measurement differences were found to be significant according to the t-test ($p<0.001$). Although the upper and lower vermilion heights were absolutely larger for males, vermilion height in females was proportionally larger relative to the size of the mouth. Once height was factored in, the number of significant findings decreased to 27 of the 34 measurements according to the ANCOVA ($p<0.001$). Measurements such as ‘minimum frontal width’, ‘palpebral fissure length (right)’, ‘palpebral fissure length (left)’,

‘nasal protrusion’, and ‘nasal height’ were found to be non-significant when the effects of body size (height) was controlled. Three of the four index comparisons were significant according to the t-test ($p<0.001$). ‘Upper-middle facial depth index’ was larger in females indicating that they have a more anterior projection of nasion and/or a more posterior projection of subnasale. Females also had a larger ‘middle-lower facial index’ indicating that females have more convexity to their profile shape. Males had a larger ‘nasal index’ suggesting that they have a relatively shorter and wider nose.

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PREFACE

First of all, I would like to mark my appreciation to the University of Pittsburgh, School of Dental Medicine, Department of Orthodontics for the opportunity to pursue this masters research.

I would also like to thank my major advisor, Dr. Weinberg for his dedication and perseverance. And thank you very much Dr. Janet Robison and Dr. Kulkarni in assisting me through this journey. Moreover, I would like to thank Dr. Petrone, select co-residents, and the staff in orthodontics in making this a possibility.

Last but not least, I would like to thank my family and friends for their everlasting love and support.

1.0 INTRODUCTION

Although humans show relatively little sexual dimorphism compared with other primates, males and females still differ (on average) on many physical attributes, such as height and muscle mass. It has also been well documented in the orthodontic, forensic and anthropological literature that various aspects of the craniofacial complex differ between males and females. This observation was stated clearly by Enlow and Hans (2008):

> *"A talented artist can effectively render male versus female faces, and the viewer has no problem recognizing either gender from sketches or portraits of adults. However, many artists, as well as the average citizen, are not really conscious of the actual, specific anatomic differences involved. They just "know." In our mind's eye, we have all subconsciously associated, over the years, the topographic characteristics that relate to facial dimorphism."*

The effects of sex on facial form are of particular relevance to orthodontists. Having an accurate picture of the ways male and female faces differ is particularly important in both treatment planning and outcome assessment, a fact evidenced by the orthodontist's reliance on sex-specific cephalometric norms. Especially in cases where the initial facial state of the patient is drastically altered, such as in craniofacial anomalies, the orthodontist must incorporate facial norms that specifically apply to that case in terms of sex, ethnicity, and age. Dean et al. (1998) highlights this point by stating that the "…use of 'treatment' images of the bony skull are likely to produce the best results when they are averages of a craniofacial imagebase subsampled for sex and ethnicity rather than a grand mean."

The vast majority of studies comparing facial form between males and females have focused on the hard tissue, typically using traditional cephalometrics. Far less has been published on the craniofacial soft tissues. As Proffit et al. (2007) have pointed out, the field of orthodontics is in the process of shifting away from the era of exclusive focus on hard-tissue skeletal relationships and moving into a 'soft-tissue paradigm' where priority is placed on achieving harmony of the soft tissue facial proportions rather than producing an ideal occlusal relationship at the expense of anything else. "Facial appearance is judged largely on soft tissue contours, not hard tissue relationships" (Proffit 2000). "Although at the present time quantitative measurements cannot be rigorously applied for soft tissue assessment, the challenge for the future will be to develop methods for doing so" (Proffit 2000). This altered emphasis has put understanding human variations in facial soft tissues front and center in orthodontics. Recent technological advances in 3D surface imaging have now made it possible to capture large amounts of quantitative data on the soft tissues of the face in a way that is fast, non-invasive, and accurate. Armed with this technology, we are now in an ideal position to improve our understanding of the sex differences in the human face, especially pertaining to the soft tissue.

The purpose of the present study is to provide a detailed quantitative assessment of the sex differences of the craniofacial soft tissue in a large sample of healthy adults based on anthropometric measurements obtained through 3D surface imaging.

2.0 REVIEW OF THE LITERATURE

2.1 SEXUAL DIMORPHISM IN THE HARD TISSUE

Since the advent of the cephalostat, orthodontists have analyzed the human skull. Many studies support the idea that the size and shape of the craniofacial hard tissues, which gives the supporting structure for the face, are different between males and females. The most obvious and consistent finding has been that the male skull is larger than the female skull (Ingerslev and Solow, 1975; Bibby 1979; Miyajima et al. 1996; Rosas and Bastir, 2002; Franklin et al. 2005; Veyre-Goulet et al. 2008; Dayal et al. 2008; Green and Curnoe, 2009). Numerous studies have gone further in specifying the areas of the bony head and face that show the greatest sex differences. Franklin et al. (2005), for example, reported the largest dimorphism in facial width, cranial length, and cranial height. Alternatively, Dayal et al. (2008) found the most significant difference in total face height, bizygomatic breadth, and mandibular ramus height. Researchers have also tried to find an efficient method for discriminating and classifying sex on the basis of skull measurements. Size was a key factor in separating the sexes, and several studies have tried to establish a formula with high predictability based on radiograph analyses. For example, Ceballos and Rentschler (1958) claim 88% accuracy in identifying the sex of the skull. Similarly, Townsend et al. (1982) was able to achieve 80% accuracy, Inoue (1990) 85%, Hsiao et al. (1996) 100%, and Patil and Mody (2005) 99% in identifying the correct sex. Patil and

Mody (2005) identified seven major variables important to their discriminant function: length of cranial base (Ba-N), mastoid height from cranial base (MaHt), total face height (N-M), mastoid width at the level of cranial base (MaWd), middle facial depth (Ba-ANS), perpendicular distance from mastoidale to FH plane (Ma-FH), and maximum length of skull (G-Op), ordered from most to least important. These studies indicate that males and females are clearly distinguishable on the basis of skull radiographs.

In further breaking down the dimorphism into specific regions, males have been found to exhibit some differences in the configuration of the nasal bones. Several studies have reported that males tend to have a more prominent nasal bone (Ingerslev and Solow, 1975; Inoue et al. 1992; Carels 1998; Rosas and Bastir, 2002). In assessing 153 adult Danish dental students, Ingerslev and Solow (1975) concluded that males have a more prominent nasal bone projection. From 100 Japanese skulls, Inoue et al. (1992) also found that the male nasal bone is more developed. Carels (1998) identified the same characteristic among Dutch people, and Rosas and Bastir (2002) observed that males had an increased angulation of the nasal bones among Portuguese adults.

In assessing the upper facial third, which is usually delineated by trichion and soft tissue glabella, the frontal bone shape and projection may also be important sex discriminators. Ingerslev and Solow (1975) concluded that females have a frontal bone that is more prominent than males. Bulygina et al. (2006) also agreed that males have a relatively smaller and flatter frontal bone. Bigoni et al. (2010) had findings that agreed with the flatter frontal bone in males, but concluded that males have a more prominent glabella. Inoue et al. (1992) and Carels (1998) also agreed that males have a more prominent supraorbital ridge, which forms the interface between the viscerocranium and cranial vault. Bigoni et al. (2010) performed a geometric morphometric analysis, and they found that males had a lower, wider, flatter, and vertically oriented upper face while the females had a higher forehead and face that was more convex.

Bastir et al. (2011) studied the airway in 212 adults. Their finding was in line with previous studies that males have a larger airway than females (Bastir et al. 2011; Rosas and Bastir, 2002; Enlow and Hans, 2008). Males still had a larger airway even after adjustments were made for differences in absolute size. This could translate to a larger midfacial dimensions for males in the overall appearance (Bastir et al. 2006; Bulygina et al. 2006). The larger airway was particularly due to a vertically taller choanae according to Bastir et al. (2011). This is also supported by previous studies which state that there are sexual differences in the choanae (Bastir et al. 2009). According to Bastir and co-workers, males had taller piriform apertures, internal nasal cavities, and choanae than females. And even after standardization for size, males still had larger airways than females (Bastir et al. 2011). Bulygina in 2006 concluded that a larger airway manifest itself as a forward projection of the upper nasal area as well as a wider midface (Bulygina et al. 2006). Overall, a larger airway would result in a dimorphic facial form with males having a taller middle third of the face in the sagittal plane as well as a wider midface in the frontal plane.

In the lower third of the face, Schmittbuhl et al. (2001) found that the mandible is significantly different between the sexes via elliptical Fourier analysis of mandibular outlines; his finding are consistent with other studies by Giles (1964), Steyn and Iscan (1998), Iscan and Steyn (1999), and Franklin et al. (2008). Thayer and Dobson (2010) inspected the chin via elliptical Fourier functions analysis and found that, “males tend to have more protruding chins with well-developed lateral tubercles”. This is in accord with previous findings by Bass (1995), Byers (2002), and Schwartz (2007). A more protrusive chin would lead to straighter and more concave profiles as well as the capability to camouflage retrognathia. De Freitas et al. (2007) concluded in their study of 130 lateral cephalograms that "boys have a greater tendency for a vertical pattern of growth than girls", and therefore a greater potential for increased lower face height. Yamauchi et al. (1967) came to a similar conclusion in an adult study that males had a taller lower face height than females. Coquerelle et al. (2011) used 159 CT scans and geometric morphometric analysis to conclude that the mental region is located more inferiorly in males than females, which would again add to the lower third dimension in males.

Although a universal agreement does not exist as to the precise nature of the differences, it is clear that sex differences are present in the craniofacial hard tissues. Therefore the hard tissue differences should manifest themselves in the soft tissue makeup of the sexes. However, in light of Subtleny's (1959) observation, "all parts of the soft tissue profile do not directly follow the underlying skeletal profile", the hard tissue differences may not fully express themselves onto the overlaying soft tissue.

2.2 SEXUAL DIMORPHISM IN THE SOFT TISSUE

In 1931, Broadbent and Hofrath standardized the method in taking lateral cephalograms for analysis, and since then, dentoskeletal analysis was the mainstream method in diagnosis and treatment planning (Fernandez-Riveiro et al. 2002). In 1956, Downs started to utilize the filters in order to capture the soft tissue profile in a lateral cephalogram after realizing that "possible anomalies in the hard tissues could be masked or exaggerated by the soft tissues. In other words, soft tissues did not always follow the underlying dentoskeletal profile" (Fernandez-Riveiro et al. 2002). Subtleny, in 1959, produced a paper on longitudinal soft tissue structures, and concluded that not all of the soft tissues follow the underlying hard tissues equally (Subtleny, 1959). In 1960, Steiner developed the S-line to quantify the position of upper and lower lips (Steiner, 1960). Ricketts, in 1968, developed a similar reference, the E-plane, to create some sort of norms in evaluating the position of upper and lower lips (Ricketts, 1969). Burstone also produced papers in 1958 and 1967 highlighting the importance of the soft tissue profile and lip position in treatment planning (Burstone 1958; 1967). This trend continues into current literature in shifting the focus onto incorporating the soft tissue analyses in diagnosis and treatment planning.

Arnett et al. published an article in 1999 highlighting the difference in soft tissue thickness between the sexes (Arnett et al. 1999). Similarly, Skinazi et al. and Kalha et al. found that soft tissues of the upper lip, lower lip, and chin were all thicker in males than in females (Skinazi et al. 1994, Kalha et al. 2008). In recognition of these differences, Arnett et al. suggested that, “separate values are suggested for male and female patients” (Arnett et al. 1999). Begg and Harkness also pushed for similar standards to be established stating, “age and sexual differences in nasal size and proportions indicate that separate standards are necessary for men and women” (Begg and Harkness, 1995).

Many papers agree that the soft tissue dimensions are significantly larger in men than in women (Budai et al. 2003; Evison et al. 2010; Ferrario et al. 1993, 1994, 1995, 1996, 1998; He et al. 2009; Hennessy et al. 2002; Lundstrom et al. 1992; Scheideman et al. 1980; Starck and Epker, 1996). Ferrario et al. even quantified this measure concluding that, “male faces are 6-7% larger than female faces” (Ferrario et al. 1994). Other studies tried to further dissect this finding by focusing on different parts of the face. For example, Sforza et al. found significant differences in the orbit where males had larger binocular width, intercanthal width, length of the eye fissure, soft tissue orbital area, and inclination of the orbit relative to the true horizontal (Sforza et al. 2009a). In line with Sforza et al.'s findings, Ferrario et al. also concluded that males had larger binocular width, intercanthal width, height and length of the orbits (Ferrario et al. 2001). In the lip, males had significantly larger mouth width, width of the philtrum, total lip height, and lip volumes; however, vermilion height to mouth width ratio was larger in females (Sforza et al. 2010). Differences were also seen in the nose, as males had larger nasal linear dimensions, larger external nasal volume and area, and larger nasal width to height ratios (Sforza et al. 2011). A study from Japan in 1995 separated parts of the face in a frontal photograph in order to identify the sex from the isolated part of the face, and correct identification of sex was made in 68% of the time in assessing the mouth, 65% in assessing the eyes, and 58% in assessing the nose (Inoue et al. 1995). Toma et al. also came to a similar conclusion in that females tended to have more prominent eyes and cheeks while males tended to have more prominent noses and mouths; thus establishing sexual dimorphism in these individual areas that constitute the face (Toma et al. 2008). In the ear, Sforza et al. found differences where males had significantly larger dimensions in all categories they assessed (Sforza et al. 2009b).

Moving beyond linear comparison, criteria such as angular measurements and ratios can be compared. Ferrario and colleagues found that while there was a significant difference in linear measures, there was no difference in angular measures between the sexes (Ferrario et al. 1996, 1999). But a study in 2003 found some significant angular differences in nasofrontal, nasal, vertical nasal, nasal dorsum, and cervicomental angles (Fernandez-Riveiro et al. 2003). Although Begg and Harkness found no differences in nasofrontal or nasolabial angles, there was a significant difference in the nasal dorsum angle where males had a straighter nose while the females had more supratip break angle to their noses (Begg and Harkness, 1995). The supratip break in females has been well documented in various sources. Enlow stated that the male nose tips downwards while the female nose tips upwards (Enlow, 1990). Ferrario et al., via harmonic analysis, found that the male nose is more likely to be straight or convex while the female nose is more concave (Ferrario et al. 1992). Kale-Varlik also found differences in nasofacial angle, middle facial height angle, nasal angle, and nasolabial angle; but found no difference in nasofrontal angle, nasomental angle, labiomental angle, facial angle, and lower facial height angle (Kale-Varlik 2008). He et al., in observing Chinese adults, found that nasal tip angle and nasolabial angle had no significant differences while the nasofrontal angle was more acute in men possibly owing to a more prominent supraorbital ridge (He et al. 2009).

In looking at proportionality, Ferrario et al. concluded that males had a longer lower 1/3 of the face while females had a longer middle 1/3 of the face (Ferrario et al. 1996). In the sagittal plane, Skinazi et al. observed that the percentage contribution of the lips were the same in both sexes; key difference was that the female nose ratio to profile was higher resulting in a more convex profile, while in men, the chin contribution was larger resulting in a straighter profile (Skinazi et al. 1994). He et al. and Sforza et al. noted that men had a larger base to height ratio of the nose (He et al. 2009, Sforza et al. 2011).

Size as well as shape can both contribute to differences in morphology. With size being a consistent sexually dimorphic finding as stated above, several articles focused on taking size out of the equation by comparing male and female faces scaled to the same size. However, the findings were not consistent. Ferrario et al. in 1994 used Euclidean distance matrix analysis and found that there was no significant sexual dimorphism in 3-dimensional facial shape (Ferrario et al. 1994). Starck and Epker in 1996 also came to similar conclusions via ratio comparisons (Starck and Epker, 1996). Ferrario et al. took a different approach by using mesh diagrams in

1998 and 1999 and found that the differences were very limited. But small findings included that males had a lower gonia and more posterior cheeks than females; the lower facial third was larger, more anterior, and more inferior in males; females had more anterior cheeks; and females had more anteriorly positioned forehead/trichion (Ferrario et al. 1998, 1999). Halazonetis, via morphometric analysis, came to a similar conclusion in that "sex differences in shape were small" (Halazonetis 2007). In using the Fourier analysis to assess the soft tissue, Ferrario et al. concluded that, "the present 3-dimensional study did not find a significant sex difference in the shape of the soft tissue facial contour" (Ferrario et al. 1995). Contrastingly, in 1993 Ferrario et al. concluded that there are sexual differences in size and shape according to Euclidean distance matrix analysis (Ferrario et al. 1993). Moreover, Hennessy and co-workers explores this question using a geometric morphometric approach and concluded that there was strong evidence of sexual dimorphism in their assessment of 131 individuals; they stated "our findings are that among females: the face is wider and, as seen from the side flatter; in the upper face the eyes are more lateral and anterior, and nasion is posterior; the nose is smaller, narrower and less protrusive; the distance between the lower and upper margins of the lips is greater, and the upper lip is located more posteriorly, as is the chin" (Hennessy et al. 2002). Hennessy et al. expanded on their earlier finding by describing the following features that make a face feminine: "greater posterior and superior displacement of the upper lip and philtrum; more reduced anterior projection of the nose; more outwardly displaced malar regions; increased superior and posterior displacement of the chin along with medial displacement of the gonial angle; increased medial displacement of the inferior ear attachment point and inferior displacement of the superior ear attachment point; and increased superior and posterior displacement of the superior medial orbital margins and lateral displacement of the superior lateral orbital margins" (Hennessy et al.

2005). Size differences were removed with analyses such as Euclidean distance matrix analysis, ratio comparisons, mesh diagrams, geometric morphometric analysis, and Fourier analysis. As the underlying sexual dimorphism was revealed, the soft tissue facial morphology differences seem to be very subtle.

3.0 PURPOSE OF THE PRESENT INVESTIGATION

It is clear that there is ample evidence of sexual dimorphism in the human craniofacial complex. Prior studies have generally either focused on hard tissue or soft tissue craniofacial measurements. Assessment of the literature revealed that the findings are perhaps more pronounced and more consistent for measures of the skull, compared with the soft-tissue findings. This was particularly true when body size differences were taken into account during the analysis. Given the contrasting results in recent studies examining soft-tissue craniofacial dimorphism, the principal aim of this project is to help elucidate which sex differences, if any, are present in the soft tissues face in a large sample of healthy adults.

4.0 MATERIALS AND METHODS

4.1 SAMPLE DESCRIPTION

The sample used for this study was comprised of 586 craniofacially healthy adults (over the age of 18 years). There were 197 males and 389 females in the sample. The mean age of the male sample was 27.2 years (sd = 5.69; range = 18-40). The mean age for female sample was 27.7 years (sd = 5.47; range = 18-40). Age was not found to be significantly different between the two sexes ($t = -0.988$; $p = 0.342$). The boxplot in Figure 1 shows the age comparison between males and females.

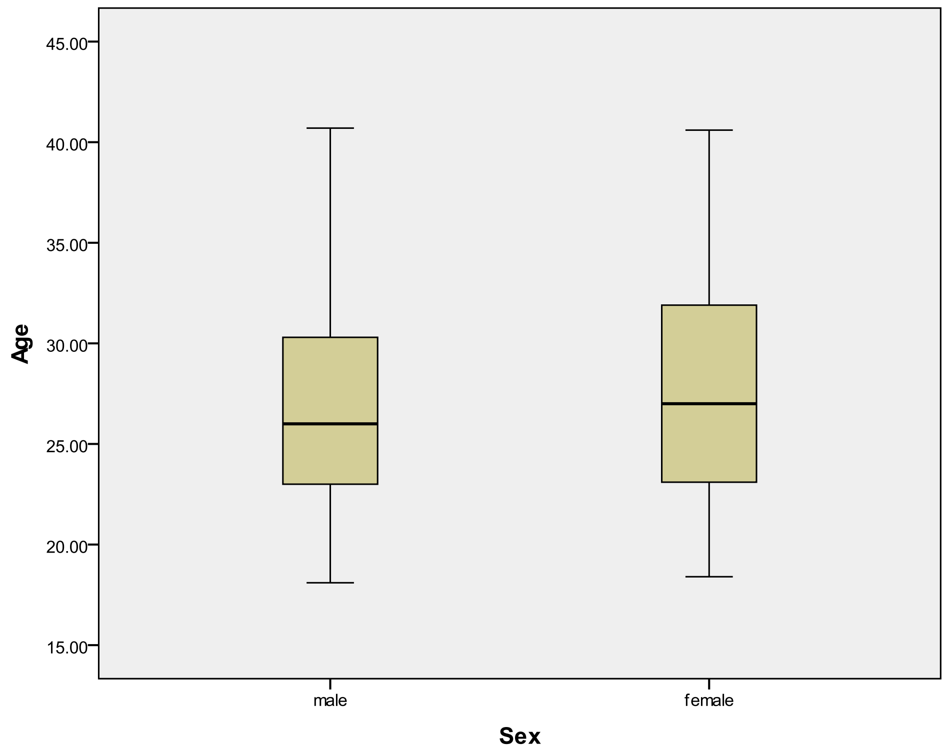

Figure 1: Boxplot showing the mean age of males and females in the present sample

Subjects were recruited at three US locations: Pittsburgh, PA (University of Pittsburgh), Seattle, WA (Seattle Children's Research Institute) and Houston, TX (University of Texas Health Sciences Center at Houston). Recruitment was accomplished primarily through a combination of targeted advertisement, word-of-mouth, research registries, and on-site recruitment in public venues. To participate in the study individuals had to be of recent European ancestry (all four grandparents) and could not have any personal history of facial trauma, facial reconstructive or aesthetic plastic surgery, orthographic surgery, or any other medical condition that might affect the structural integrity of the head and face. In addition, there could be no personal of family history of any craniofacial anomalies or syndromes that involve the craniofacial complex. All individuals were screened on these criteria prior to enrollment in the study. IRB approval was obtained at each site prior to recruitment.

4.2 DATA ACQUISITION

Following informed consent, each participant completed a short demographic interview to gather information on age, height, weight and ancestry/ethnicity. Then, using direct anthropometry, a series of five standard craniofacial measurements (Kolar and Salter, 1997) was taken on each participants head and face with spreading calipers (GPM, Switzerland); these measurements are listed in Table 1 and Table 2.

Table 1: Direct anthropometric measurements used in the present study (Kolar and Salter, 1997)

Measurement	Description
Maximum cranial width	eu-eu (euryon = the most lateral point on the head, located in the parietal region)
Minimum frontal width	ft-ft (frontotemporale = the medial point on the temporal crest of the frontal bone)
Maximum cranial length	g-op (glabella = the more prominent point in the median sagittal plane between the supraorbital ridges, identified by palpation; opisthocranion = the most prominent posterior point of the occiput, the point which produces the greatest length of the head from glabella)
Maximum facial width	zy-zy (zygion = the most lateral point on the zygomatic arch)
Mandibular width	go-go (gonion = the most lateral point at the angle of the mandible)

Table 2: Indirect anthropometric measurements used in the present study (Kolar and Salter, 1997)

Measurement	Description
Maximum cranial width	eu-eu (euryon = the most lateral point on the head, located in the parietal region)
Minimum frontal width	ft-ft (frontotemporale = the medial point on the temporal crest of the frontal bone)
Maximum cranial length	g-op (glabella = the more prominent point in the median sagittal plane between the supraorbital ridges, identified by palpation; opisthocranion = the most prominent posterior point of the occiput, the point which produces the greatest length of the head from glabella)
Maximum facial width	zy-zy (zygion = the most lateral point on the zygomatic arch)
Mandibular width	go-go (gonion = the most lateral point at the angle of the mandible)
Cranial base width	t-t (tragion = located at the notch above the tragus of the ear, the cartilaginous projection in front of the external auditory canal, where the upper edge of the cartilage disappears into the skin of the face)
Upper facial depth (Right)	n-t (nasion = midpoint of the nasofrontal suture; tragion)
Upper facial depth (Left)	(same as above)
Middle facial depth (Right)	sn-t (subnasale = the junction between the lower border of the nasal septum, the partition which divides the nostrils, and the cutaneous portion of the upper lip in the midline; tragion)
Middle facial depth (Left)	(same as above)
Lower facial depth (Right)	gn-t (gnathion = lowest point in the midline on the lower border of the chin, a bony landmark; tragion)
Lower facial depth (Left)	(same as above)
Morphological facial height	n-gn (nasion; gnathion)
Upper facial height	n-sto (nasion; stomion = the midpoint of the labial fissure when the lips are closed naturally)
Lower facial height	sn-gn (subnasale; gnathion)
Intercanthal width	en-en (endocanthion = the inner corner of the eye fissure where the eyelids meet, not the caruncles)
Outercanthal width (Biocular width)	ex-ex (exocanthion = the outer corner of the eye fissure where the eyelids meet)
Palpebral fissure length (Right)	en-ex (endocanthion; exocanthion)

Table 2: (continued)

Palpebral fissure length (Left)	(same as above)
Nasal width	al-al (alare = the most lateral point on the nasal ala)
Subnasal width	sbal-sbal (subalare = the point on the lower margin of the base of the nasal ala where the ala disappears into the upper lip skin)
Nasal protrusion	sn-prn (subnasale; pronasale = the most protruded point of the nasal tip)
Nasal ala length (Right)	ac-prn (alar curvature point = the most posterolateral point of the curvature of the base of the nasal alae, the lateral flaring walls of the nostrils; pronasale)
Nasal ala length (Left)	(same as above)
Nasal height	n-sn (nasion; subnasale)
Nasal Bridge Length	n-prn (nasion; pronasale)
Labial fissure width	ch-ch (cheilion = the outer corner of the mouth where the outer edges of the upper and lower vermilions meet)
Philtrum width	cph-cph (crista philtri = the point on the crest of the philtrum, the vertical groove in the median portion of the upper lip, just above the vermilion border)
Philtrum length	sn-ls (subnasale; labiale superius = the midpoint of the vermilion border of the upper lip)
Upper lip height	sn-sto (subnasale; stomion)
Lower lip height	sto-sl (stomion; sublabiale = midpoint along the inferior margin of the cutaneous lower lip, labiomental sulcus)
Upper vermilion height	ls-sto (labiale superius; stomion)
Lower vermilion height	sto-li (stomion; labiale inferius = the midpoint of the vermilion border of the lower lip)
Cutaneuous lower lip height	li-sl (labiale inferius; sublabiale)

Next, each subject had a 3D image acquired of their facial surface using a 3dMD digital stereophotogrammetry system (Atlanta, GA). 3D stereophotogrammetry is a totally non-invasive method for acquiring human facial surface data, with capture speeds well under one second. The 3dMD system captures geometry of the human face as a point cloud, typically containing over 25000 individual points. These points can then be connected creating a 3D mesh and rendered with color, texture and shading to deliver a geometrically accurate facial representation. The 3dMD system has been shown previously to be accurate at the sub-millimeter level (Weinberg et al. 2006). An example of a facial surface is shown in Figure 2 without color and texture to preserve anonymity.

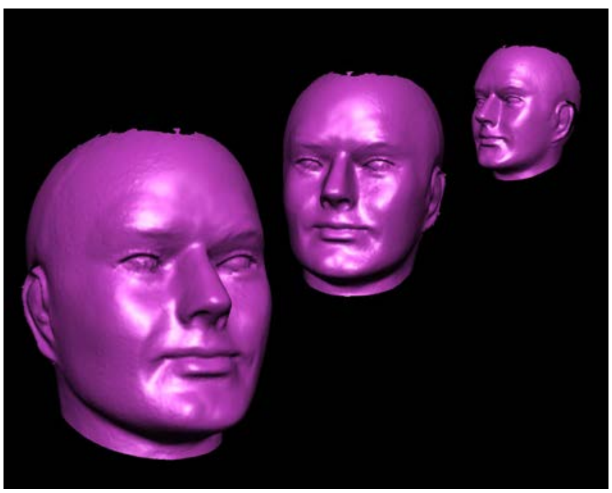

Figure 2: Example of 3D mesh obtained via stereophotogrammetry

A series of 26 anatomical surface landmarks were then collected from each participant's 3D facial scan, and the corresponding *x,y,z* coordinates saved. From these landmark coordinates, a set of 29 simple linear distances were calculated using simple Euclidean geometry. These 29 distances are equivalent to standard facial anthropometric measurements (Farkas 1994; Kolar and Salter, 1997) and are shown above in Table 1 and Table 2.

In addition to simple linear distance measures, seven commonly used anthropometric indices were calculated from these distances (shown below in Table 3). These proportions provide a rudimentary way of capturing shape information on the face (Farkas and Munro, 1987).

Table 3: List of craniofacial indices used in the present study

Index	Definition	Interpretation
Cephalic	Maximum head width x 100 / Maximum head length	Higher values indicate more brachycephalic head shape
Facial	Morphological face height x 100 / Maximum face width	Higher values indicate relatively longer and/or narrower face
Upper Facial	Upper face height x 100 / Maximum face width	Higher values indicate relatively longer and/or narrower upper face
Upper-middle face depth	Upper facial depth x 100 / Middle facial depth	Higher values indicate relatively protruded upper face and/or retruded middle face
Middle-lower face depth	Middle facial depth x 100 / Lower facial depth	Higher values indicate greater increased maxillary projection and/or mandibular retrusion
Intercanthal	Intercanthal width x 100 / Outercanthal width	Higher values indicate greater relative hypertelorism
Nasal	Nasal width x 100 / Nasal height	Higher values indicate a relatively shorter and/or wider nose

4.3 STATISTICAL METHODS

Simple univariate statistics were run to compare males and females across the entire set of 41 craniofacial measurements and indices (5 distances from direct anthropometry; 29 distances from 3D photogrammetry; and 7 indices). Tests were run two different ways: (1) independent samples t-tests were performed and (2) analysis of covariance (ANCOVA) was carried out on the same variables, with the subject's height included as a covariate. The second set of tests was performed to assess whether any craniofacial measures were significantly different even after adjusting for the effects of overall body size, since it is well known that males are larger on average. Comparing height in our dataset revealed this same pattern, with males showing a mean height increase of 15.4 cm over females ($p < 0.001$). To adjust for multiple comparisons, a Bonferonni correction was applied to the p-value and the threshold for statistical significance was set to 0.001 (.05/41).

5.0 RESULTS

The descriptive statistics of the five direct anthropometric measurements and 29 3D surface-derived measurements are presented in Table 4. Of note, the positive mean difference values were all signed positive, indicating that all 34 dimensions were larger in our male sample. The inferential statistics are presented in Table 5. The t-tests showed that mean difference between males and females was significant for 32 of the 34 measurements at the $p < 0.001$ level. Only two of the 34 measurements were found to be non-significant, and these were upper vermilion height ($p = 0.109$) and lower vermilion height ($p = 0.046$), both relating to the vermillion segment of the lips. When the means were adjusted for the covariate 'height', the analysis of covariance (ANCOVA) still revealed significant differences for 27 of the 34 measurements at the $p < 0.001$ level. Five of the 34 measurements were no longer found to be statistically significant, and these were minimum frontal width ($p = 0.011$), palpebral fissure length (right) ($p = 0.203$), palpebral fissure length (left) ($p = 0.277$), nasal protrusion ($p = 0.01$), and nasal height ($p = 0.014$). Both upper vermilion height ($p = 0.940$) and lower vermilion height ($p = 0.202$) remained non-significant.

Table 6 summarizes the seven calculated craniofacial indices as well as the results of the accompanying t-tests. Males were found to have larger facial, intercanthal, and nasal indices while females were found to have larger cephalic, upper facial, upper-middle facial depth, and middle-lower facial depth indices. Of the 7 indices calculated, four were found to be non-significant, and these were the cephalic ($p = 0.103$), facial ($p = 0.094$), upper facial ($p = 0.082$), and intercanthal ($p = 0.444$) indices. Conversely, the remaining three indices (upper-middle facial depth, middle-lower facial depth, and nasal) were found to be significant at the $p < 0.001$ level.

Table 4: Descriptive statistics on all 34 craniofacial measurements (mm)

	Males		Females		
Measurement	**Mean**	**sd**	**Mean**	**sd**	**Mean diff**
Maximum cranial width	153.67	7.05	145.75	5.80	7.92
Minimum frontal width	107.84	8.47	102.84	7.57	5.00
Maximum cranial length	197.80	9.24	186.85	7.33	10.95
Maximum facial width	138.63	6.90	129.76	5.95	8.88
Mandibular width	106.16	7.11	97.48	6.43	8.68
Cranial base width	148.67	6.58	138.68	4.62	9.98
Upper facial depth (Right)	127.97	4.98	119.75	3.92	8.22
Upper facial depth (Left)	128.11	5.01	119.88	4.00	8.23
Middle facial depth (Right)	133.90	5.21	124.16	4.02	9.74
Middle facial depth (Left)	133.60	5.24	124.11	4.07	9.49
Lower facial depth (Right)	152.84	6.72	139.76	5.45	13.07
Lower facial depth (Left)	152.11	6.89	139.55	5.41	12.56
Morphological facial height	128.42	6.10	119.02	5.94	9.40
Upper facial height	79.50	3.98	75.14	4.08	4.37
Lower facial height	73.44	5.13	66.34	4.99	7.11
Intercanthal width	33.64	2.84	32.14	2.63	1.49
Outercanthal width	88.61	4.31	84.94	3.66	3.67
Palpebral fissure length (Right)	28.19	1.81	27.10	1.68	1.09
Palpebral fissure length (Left)	27.87	1.77	26.93	1.77	0.94
Nasal width	36.54	2.72	32.81	2.19	3.73

Table 4: (continued)

Subnasal width	19.93	2.34	17.74	2.09	2.18
Nasal protrusion	20.98	1.88	19.93	1.67	1.05
Nasal ala length (Right)	35.44	2.35	31.52	1.97	3.91
Nasal ala length (Left)	35.44	2.36	31.64	1.94	3.79
Nasal Height	57.46	3.47	55.13	3.44	2.33
Nasal Bridge Length	50.30	3.69	47.80	3.35	2.50
Labial fissure width	50.42	4.12	47.61	3.22	2.80
Philtrum width	13.07	1.76	11.73	1.65	1.34
Philtrum length	16.91	2.34	14.81	2.26	2.10
Upper lip height	23.24	2.28	21.04	2.33	2.20
Lower lip height	19.65	2.77	17.57	2.33	2.09
Upper vermilion height	7.65	1.75	7.42	1.43	0.23
Lower vermilion height	8.78	2.28	8.39	2.09	0.39
Cutaneuous lower lip height	13.14	2.48	11.05	1.98	2.10

Table 5: Results of t-test and ANCOVA for all variables

	t-test		ANCOVA[1]	
Measurement	**t-value**	**p**	**F-value**	**p**
Maximum cranial width	13.603	< 0.001*	67.109	< 0.001*
Minimum frontal width	7.255	< 0.001*	6.448	0.011
Maximum cranial length	15.615	< 0.001*	65.528	< 0.001*
Maximum facial width	15.383	< 0.001*	89.652	< 0.001*
Mandibular width	14.629	< 0.001*	55.989	< 0.001*
Cranial base width	18.822	< 0.001*	165.955	< 0.001*
Upper facial depth (Right)	19.992	< 0.001*	166.703	< 0.001*
Upper facial depth (Left)	19.911	< 0.001*	161.302	< 0.001*
Middle facial depth (Right)	22.746	< 0.001*	224.486	< 0.001*
Middle facial depth (Left)	22.072	< 0.001*	209.567	< 0.001*
Lower facial depth (Right)	23.128	< 0.001*	186.729	< 0.001*
Lower facial depth (Left)	21.937	< 0.001*	163.630	< 0.001*
Morphological facial height	17.751	< 0.001*	69.892	< 0.001*
Upper facial height	12.320	< 0.001*	26.990	< 0.001*
Lower facial height	15.972	< 0.001*	72.847	< 0.001*
Intercanthal width	6.304	< 0.001*	12.274	< 0.001*
Outercanthal width	10.033	< 0.001*	14.454	< 0.001*
Palpebral fissure length (Right)	7.108	< 0.001*	1.627	0.203
Palpebral fissure length (Left)	5.967	< 0.001*	1.182	0.277
Nasal width	16.676	< 0.001*	120.693	< 0.001*

Table 5: (continued)

Subnasal width	11.466	< 0.001*	32.960	< 0.001*
Nasal protrusion	6.885	< 0.001*	6.646	0.01
Nasal ala length (Right)	21.195	< 0.001*	163.339	< 0.001*
Nasal ala length (Left)	19.430	< 0.001*	155.991	< 0.001*
Nasal Height	7.716	< 0.001*	6.109	0.014
Nasal Bridge Length	8.237	< 0.001*	11.978	0.001*
Labial fissure width	8.336	< 0.001*	27.438	< 0.001*
Philtrum width	9.102	< 0.001*	22.852	< 0.001*
Philtrum length	10.500	< 0.001*	44.732	< 0.001*
Upper lip height	10.872	< 0.001*	38.200	< 0.001*
Lower lip height	8.997	< 0.001*	29.896	< 0.001*
Upper vermilion height	1.608	0.109	0.006	0.940
Lower vermilion height	2.059	0.046	1.692	0.202
Cutaneuous lower lip height	10.218	< 0.001*	67.241	< 0.001*

[1] results adjusted for height

*** significant after correction for multiple testing**

Table 6: Descriptive statistics and t-test results for the seven anthropometric indices

	Males		**Females**		
Index	**Mean**	**sd**	**Mean**	**sd**	**p**
Cephalic	77.47	3.72	77.97	3.04	0.103
Facial	92.60	5.73	91.77	5.58	0.094
Upper facial	57.38	3.87	57.97	3.85	0.082
Upper-middle facial depth	95.75	1.95	96.53	2.04	< 0.001*
Middle-lower facial depth	87.88	2.48	88.94	2.47	< 0.001*
Intercanthal	37.98	2.41	37.81	2.50	0.444
Nasal	63.88	6.05	59.74	5.55	< 0.001*

*** significant after correction for multiple testing**

6.0 DISCUSSION

All 34 facial measurements were found to be larger in males compared to females. Moreover, all of these differences were found to be statistically significant, even after adjusting for multiple testing, except for the upper and lower vermilion heights. The overall larger dimensions of the face and the cranium are in line with previous findings in the hard tissue (Ingerslev and Solow, 1975; Bibby, 1979; Miyajima et al. 1996; Rosas and Bastir, 2002; Franklin et al. 2005; Veyre-Goulet et al. 2008; Dayal et al. 2008; Green and Curnoe, 2009) as well as the soft tissue (Budai et al. 2003; Evison et al. 2010; Ferrario et al. 1993, 1994, 1995, 1996, 1998; He et al. 2009; Hennessy et al. 2002; Lundstrom et al. 1992; Scheideman et al. 1980; Starck and Epker, 1996).

In the orbital region, significant differences in outercanthal width, intercanthal width, and palpebral fissure length are consistent with conclusions drawn by Sforza et al. and Ferrario et al. where males have larger dimensions (Sforza et al. 2009a, Ferrario et al. 2001). In both the oral and nasal regions, the overall larger dimensions in males also agree with the findings of Sforza et al. (2011). The only non-significant findings were that of the upper and lower vermilion heights. Sforza et al. (2010) investigated the vermilion to mouth width ratio and found that females had a longer vermilion in comparison to the mouth width. Our derived ratios of vermilion height to mouth width (males: 0.3259, females: 0.3321) were in accord with that of Sforza et al.'s in that females had a larger total vermilion height in relation to the mouth width. Although the upper and lower vermilion heights were absolutely larger for males, vermilion height in females was proportionally larger relative to the size of the mouth.

It could be the case that all of the craniofacial differences described above were simply due to difference in body size, since males are on average larger than females. However, when the effects of body size (height) were controlled for, all measurements were still found to be larger in males than females and most of these differences (27/34) remained statistically significant. This indicates that even after body size differences were taken into account, males still had larger heads for virtually every dimension and feature. This finding suggests that the craniofacial sexual dimorphism that we observe in human adults cannot simply be accounted by differences in general somatic growth. It is interesting to note that minimum frontal width, both palpebral fissure lengths, nasal protrusion, and nasal height differences between the sexes were no longer a significant finding once height was factored in. This may be consistent with Toma et al.'s finding that females tended to have more prominent eyes (Toma et al. 2008). Minimum frontal width is measured from frontotemporale (left) to frontotemporale (right) which are located on the temporal crest of the frontal bone where it is the most medial and superior to the superior orbital rims (Kolar and Salter 1997). Palpebral fissure length, in effect, measures the size of the globe. Therefore, it may be the case that since females have more prominent eyes, the minimum frontal width and both palpebral fissure lengths have lost their significance once height was factored in. Nasal protrusion is measured from the base of the nose to the tip of the nose, and nasal protrusion may have lost its significance in the ANCOVA because the male nose tends to tip downwards while the female nose tends to tip upwards (Enlow 1990, Ferrario et al. 1992). In the nose, He et al. and Sforza et al. concluded that males have a wider and shorter nose than females (He et al. 2009, Sforza et al. 2011), and nasal height may have also lost its significance once height was accounted for.

Ratio measurements are useful because that can provide at least rudimentary information about shape, by comparing dimensions within the same face. In considering the seven ratios calculated here, three were found to be larger in males, while four were larger in females. Moreover, according to the T-test, cephalic, facial, upper facial, and intercanthal indices were found to be non-significant, while upper-middle facial depth, middle-lower facial depth, and nasal indices were significant at the $p < 0.001$ level. Although non-significant, the larger cephalic index observed in females indicated a slight tendency toward brachycephaly compared with males. Males had a larger facial index while the females had a larger upper facial index which means that males tend to have a longer and/or narrower faces overall while the females tend to have longer and/or narrower upper faces, although these differences were not statistically significant. In dissecting the facial and upper facial indices, the result may be due to the fact that males tend to be longer in the lower face (de Freitas et al. 2007, Yamauchi et al. 1967, Ferrario et al. 1996) which would increase the total face height, thus making the facial index larger in males. Once the lower face was detracted in the upper facial index, females had a larger value than males. This may be due to the fact that males have a wider face, as proposed by Bigoni et al. via the geometric morphometric analysis which also equalizes size in comparing the shape (Bigoni et al. 2010). Wider faces in males would produce a lower upper facial index in males as observed in our data. In reconsidering the facial index, the wider facial dimension may be overpowered by such a long face height, owing to the longer lower third, that it produced a larger mean than in females. Hennessy et al. (2002) via geometric morphometric analysis came to a different conclusion of females having a wider face, which is in direct contradiction to Bigoni et al. (2010). Bulygina et al. (2006) agreed with Hennessy et al. (2002) that males have a wider face owing to a larger airway. Bastir et al. (2011) agreed with Bulygina and Bigoni as well. But Bastir et al. (2011) added that males have a larger airway and have taller piriform rims, may help to offset the increase in the width dimension by increasing the height dimension and therefore maintaining the ratio. The equivocality in the facial width dimension may be why the cephalic, facial, and upper facial index differences between the sexes were found to be insignificant. Lastly, the intercanthal index tells us that although males had a higher mean and hence an increased tendency for relative hypertelorism, this difference was also found to be non-significant.

Our findings revealed that upper-middle facial depth, middle-lower face depth, and nasal indices showed significant sexual dimorphism ($p < 0.001$). Upper-middle facial depth index was greater in females, indicating that females have a more anterior projection of nasion and/or a more posterior projection of subnasale in relation to tragion compared to males. A more posterior projection of subnasale is consistent with Bulygina et al.'s (2006) evaluation of the hard tissue as well as Hennessy et al.'s (2002, 2005) evaluation of the soft tissue. However, a more anterior projection of nasion is inconsistent with a more posterior and less prominent nasal bone finding in females (Ingerslev and Solow, 1975; Inoue et al. 1992; Carels 1998; Rosas and Bastir, 2002) as well as Hennessy et al.'s (2002, 2005) more posterior location of nasion in females. This may be explained in two ways. Firstly, tragion's position may vary vertically and hence disturb the ratio. Secondly, the posterior projection of subnasale in females may far outweigh the anterior projection of nasion resulting in a ratio greater in women than in men. In considering the middle-lower facial index, females had a statistically greater value than males inferring that females have a greater maxillary projection and/or mandibular retrusion. This is consistent to the previous hard tissue findings that males have a flatter upper face while females have a more convex face (Bigoni et al. 2010). Moreover, males were found to have a more prominent chin (Thayer and Dobson, 2010; Bass 1995; Byers 2002; Schwartz 2007). Hennessy et al. (2002, 2005) reverberates this notion that the female chin is displaced superiorly and posteriorly. In the soft tissue, this is also in accord with the finding that the females have a more convex facial profile while the males have a straighter profile (Skinazi et al. 1994). In terms of facial convexity, which is defined by glabella, subnasale, and soft tissue pogonion, a more posteriorly placed chin would give males a straighter and even concave profile while in females it would give them a more convex profile. Lastly, the nasal index was found to be larger in males suggesting that males have a relatively shorter and wider nose. This confirms Sforza et al.'s (2011) previous finding that the male nose has a larger width to height ratio.

There are many different intrinsic and extrinsic factors that might explain why male and females faces differ in size and shape. First and foremost, one effect of having Y-chromosome is a vastly different hormonal profile in males. Although the effects of hormones on bone development are complex, the presence of excess androgens does generally have an osteo-inductive effect, particularly on the mandible (Fujita et al, 2004). Functional matrix effects may also be at work. The larger masticatory muscles in males affect both the structure and robustness of the underlying craniofacial skeleton as well as the appearance of the facial surface. Capsular matrices as well such as the brain, eyes and tongue may also exert influences on head size via secondary displacement forces as they attain their full growth. Brain growth, for example, largely drives cranial vault growth and males have been shown to have relatively and absolutely larger brains compared to females (Goldstein et al. 2001).

Some of the findings here may have implications for the orthodontist. Although males had larger overall craniofacial dimensions, conspicuously there were no differences found in the upper and lower lip vermillion portion of the lips. Therefore orthodontists may opt for more vermilion show in females as opposed to males. In considering the ratios, females had a more anteriorly placed upper face in relation to the lower face. Moreover, the middle-lower face depth ratio adds to the evidence that females have a more anteriorly placed midface and/or a more posteriorly placed lower face. Therefore, orthodontists may choose to finish their female patients with a profile that is more convex as opposed to concave. According to the nasal index, males tended to have a wider and a shorter nose. Therefore in orthognathic cases, the team may consider an alar cinch in maxillary LeFort I advancement cases to minimize flaring of the alae especially in female patients.

Compared with the relatively straightforward size differences reported here, shape differences between males and females, as revealed by craniofacial indices, were far more subtle. The next logical step would be to complete a more comprehensive assessment of the craniofacial shape differences between males and females. The type of three dimensional landmark data used for the present study can be subjected to a variety of sophisticated multivariate shape analyses, such as geometric morphometrics. Another fundamental question not addressed in the present study relates to the ontology of these sex differences in facial form. When during development do they arise? Which facial components show evidence of dimorphism the earliest? These questions are beyond the scope of the present thesis, but are possible with large normative data repositories like the one used in the current analysis.

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