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Longitudinal study of craniofacial growth in five female *Papio anubis*

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Introduction:

The relationship between phylogeny and ontogeny became a popular field of study (Barnes, 2014, Watts, 1986). The study of postnatal growth is important for the field of anthropology (Gavan, 1982). Studies of juvenile and pre-adult hominin fossils can provide valuable information regarding the evolution of body size and proportions and stages of development. But according to Gavan (1982) growth is a dynamic process that is not fossilized, and fossil specimens provide little evidence of "static indication" that does not tell much about the said dynamic process (Gavan, 1982). Therefore to better understand growth processes, it is necessary to study extant non-human primates (Gavan, 1982). Unfortunately, the majority of growth studies are focused on humans and few studies focus on non-human primate studies, despite their valuable contribution in understanding human growth (Watts, 1986).

Human growth shares a lot of similarities with non-human primate growth especially amongst catarrhines, who have a growth curve that is very similar to that of humans (Watts and Gavan, 1982, Watts, 1986). So in order to understand human growth processes, and their evolutionary origins and significance, it is essential to have a good knowledge of growth in non-human primates (Watts, 1986).

One of the major differences that characterizes human growth when compared to non-primate mammals, is the long growth period that goes up to 20 years. The second striking difference is the aspect of the human growth curve, related to changes in postnatal growth velocity. The growth curve in humans is characterized by a peak around the time of birth followed by a phase of slow juvenile growth, and another peak during adolescence (Watts and Gavan, 1982). The latter is called "adolescent growth spurt" and it is not present in non-primate mammals who show a general deceleration of growth during the postnatal period (Watts, 1986). Evidence indicates that these two characteristics of human growth, prolonged pre-adolescent growth period, and the presence of the adolescent growth spurt are related and the first might be responsible for the second (Watts and Gavan, 1982, Watts, 1986).

For mammals, puberty occurs shortly after weaning, and periods of rapid growth are not discernible resulting in a growth curve that has a single inflection point. This is well demonstrated in Fig. 1, where we can see the long juvenile growth phase in humans compared to the general growth curve of domestic mammals and birds (Watts, 1986).

Previous work demonstrated that the trend of prolongation of growth is present in non-human primates. Possible explanations of prolonged somatic development in primates are the complex behaviour and general increase in neural complexity in primates (Watts, 1986). It is argued that the delay in growth and sexual maturity is a selection for a prolonged learning period that is necessary for behavioral and neural complexity (Watts, 1986; Gavan, 1982).

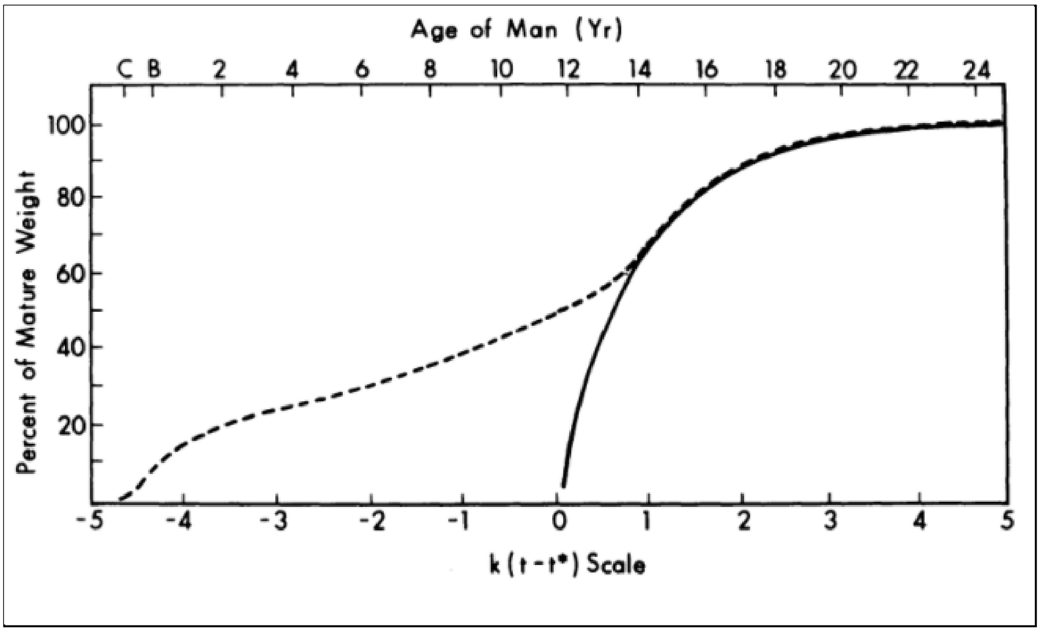

Fig. 1: weight growth of humans (- - -) and other animals (——). Weight, as percentage mature weight, is plotted on an equivalent times scale for human males and for males of various domestic animal species (Watts, 1986).

This would mean that the adolescent growth spurt should be observed in learning animals like cercopithecoid primates (Gavan, 1982). Lawick-Goodall's work showed that chimpanzees have a learning period during their postnatal period (Goodall, 1971). Early possible evidence of an adolescent growth spurt in chimpanzees were derived from cross-sectional data on weight, but the relationship of this spurt with puberty was not clearly established (Gavan, 1953; Grether and Yerkes, 1940; Spence and Yerkes, 1937).

Other studies have shown the presence of the adolescent growth spurt in Chimpanzees but with a very low magnitude (Watts and Gavan 1979). The chimpanzee adolescent spurt is associated with a slow growth period (Gavan, 1982). Other similar results were obtained for *Macaca mulatta* (Gavan, 1982). The presence of the adolescent growth spurts in non-human primates has fueled some debates (Bogin, 1999, Watts and Gavan, 1982). Some authors think that the question should not be if the growth spurt exists in non-human primates but how much it is similar to the human spurt in terms of magnitude? (Gavan, 1982, Watts and Gavan, 1982).

This study aims to investigate if female baboons show growth spurts during puberty (adolescent growth spurts) like in humans. And at what age they occur. In order to investigate the presence of growth spurts in baboons, longitudinal studies of baboon growth must be conducted. This study was done on a sample that is part of a long-term longitudinal study conducted by Sandrine Prat at the CNRs Primatology station at Rousset-sur-Arc (France). The total sample is composed of 35 olive baboons. The purpose of this study is to complete other studies done on non-human primates (Prat, 2014) and to provide more data on craniofacial growth in non-human primates.

State of the Art

I) Longitudinal studies of growth and development

1) Longitudinal studies

In a longitudinal study, repeated observations are made on the same individual over a period of time. Therefore, this type of study allows the detection of different changes during growth, like changes in morphology, shape, and size. There are different types of longitudinal studies: long term, short term, and mixed (Prat, 2014; Caruana *et al*, 2015). The former provides the best datasets allowing the construction of growth velocity curves. As for the latter individuals are not sampled in the same manner, some are sampled repeatedly and others just once (Prat, 2014). Long-term longitudinal studies of growth are hard to put in place due to the financial and time constraints, but also due to the ethical issues related to the use of X-ray radiographs (Prat, 2014; Caruana *et al*, 2015). The main purpose of these studies is to investigate changes in shape and size during growth and investigate growth rates and the presence of “growth spurts" (Prat, 2014).

2) History of growth studies on humans and non-human primates:

The first study on human growth was done by Comte de Montbeillard between 1759 and 1777 on his own child. The data and results were published by Scammon in 1927. The metric measurements of one child were used to plot a growth curve from birth to age 18 (Miller, 2018; Prat, 2014).

“*This article produced one of the most famous images ever to be created in human growth studies”* (Miller, 2018). The growth curve shows the human adolescent growth spurt is at around 13 years of age (Fig. 2) (Miller, 2018).

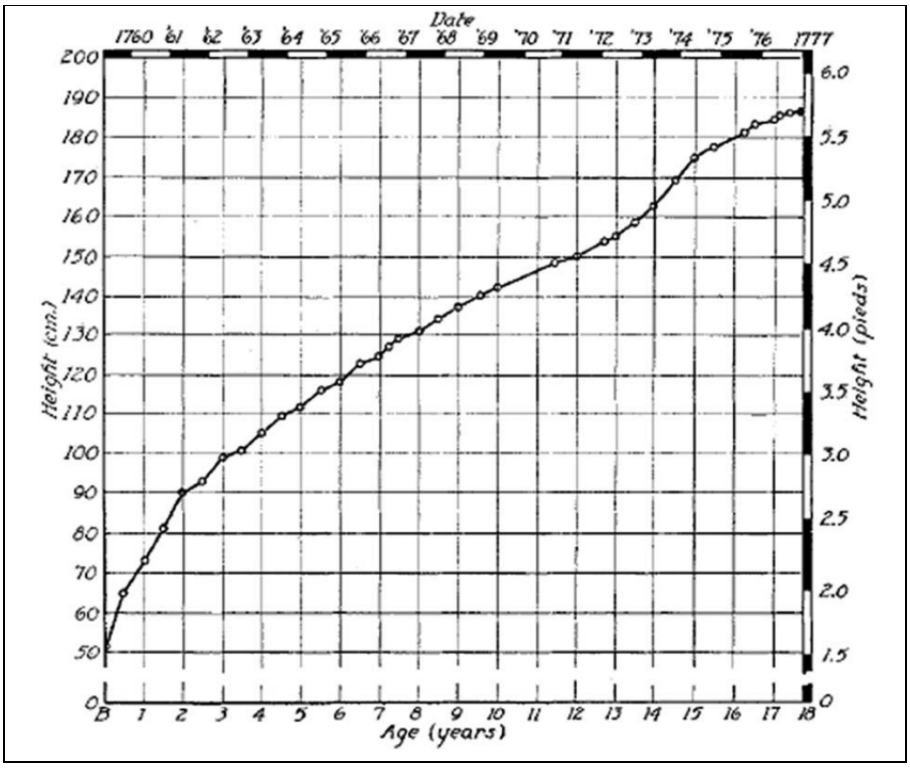

Fig. 2: Figure and caption from "The First Seriatim Study of Human Growth," by Scammon, 1927, American Journal of Physical Anthropology, 10, pp. 329–336. Reproduced with permission from John Wiley and Sons (Miller, 2018)

Growth studies during the 19th century on children documented the growth of child factory workers. The heights of enslaved children in the United States were also recorded. These studies showed that these children had lower mean heights than other modern comparative groups. With the development of anthropometry and statistical analysis studies, growth research increased. Researchers like Adolphe Quetlet, who developed the body mass Index (BMI), and Francis Galton, who helped demonstrate the heritability of height from parents, contributed to growth studies and helped to show the importance of longitudinal studies. Although Galton's contribution was important to growth studies, he had eugenics beliefs (Miller, 2018).

In North America, the first studies on human growth began in 1913. Their goal was to create charts of growth from childhood to adulthood (Garn, 1981; Sherwood *et al,* 2020). In 1930, Broadbent introduced radiographic cephalometry. The advancement of X-ray imaging techniques allowed the production of large datasets of radiographs allowing a better study of skeletal growth (Hans *et al*, 2015; Prat, 2014).

Starting from 1940, the number of growth studies increased, including a wide range of research topics like (body size, nutrition, studies of twins, growth disorders) (Ergun-Longmire *et al*, 2020; Garn, 1981; Sherwood *et al,* 2020). The longest-running longitudinal studies in Europe are the Harpenden Growth study (1948-1971) and the Zurich growth study. They also involved a large number of individuals (Prat, 2014). In the United States of America, the most important growth studies, that largely contributed to clinical and population studies and helped to produce norms and standards of growth, are the Denver growth study, the Fels Longitudinal Study, the Harvard study, and the Brush Foundation study (Garn, 1981; Prat, 2014, Roche, 1992).

Some of the growth studies focused on craniofacial development (Bastir *et al,* 2006; Bastir et Rosas, 2005; Bulgyina *et al*, 2006) and others on dental maturation and development (Anemone *et al*, 1991; Anemone *et al*, 1992; Anemone *et al,* 1996 ; Cheverud, 1981; Conroy and Mahoney, 1991; Dean and Wood, 1981). These studies were really valuable and have contributed to the advancement in the field of physical anthropology and human evolutionary studies like dental development studies by Moorrees (Garn, 1981, Moorrees *et al*, 1963a, b ; Prat, 2014). Studies like the Fels Longitudinal study helped establish growth charts (Prat, 2014; Roche, 1992).

II) Growth studies on non-human primates

A large number of studies focused on non-human primates in biomedical research because of their close phylogenetic proximity with humans (Cacucci et Vargha Khadem, 2019; Estes *et al*, 2018; Leigh, 2009; Nelson et Winslow, 2009; VandeBerg *et al*, 2009). Non-human primates can therefore be used as a model for human development (Nakamura *et al,* 2021, Prat, 2014). Chimpanzees (*Pan troglodytes*) are considered to be the closest species to humans but they are banned from use in invasive biomedical studies along with other great apes like bonobos, gorillas, and orangutans (Johnsen *et al*, 2012 ; Nakamura *et al*, 2021). Although long term longitudinal growth studies on non-human primates are important, they are fewer than human-based studies. Because of the difficulties of implementing such studies and experiments, studies on great apes are often mixed-longitudinal or cross-sectional (Prat, 2014).

Catarrhini (Old World monkeys) that are most used for these studies are baboons (*Papio*) and macaques (*Macaca*). Baboons are often used in these types of research because of their close physiological resemblance to humans (VandeBerg *et al*, 2009 ; Leigh, 2009). Biological characteristics of baboons like pathologies, behavior, reproduction, genetics, and growth and development were studied for decades. These studies can provide reliable models for comparison with humans and allow the investigation of different physiological processes. Baboon studies also largely contributed to the understanding of human and non-human primate ontogeny, allowing the investigation of important growth variables like body mass and growth spurts (Leigh, 2009). Baboons can also be used as an alternative model for human craniofacial evolution (Singleton, 2011).

There are few long-term longitudinal studies that were conducted on baboons, despite the fact that they can provide valuable information and help establish models for growth and development (Prat, 2014).

1) Baboon growth and development

Female and male baboon infants grow at the same rate until 2,5 years of age (6,5 kg). After this age females grow slower than males (VandeBerg *et al*, 2009).

Puberty occurs around 3,5 years for both sexes. Their life expectancy in captivity is between 20 and 30 years (VandeBerg *et al* , 2009).

2) Growth spurts

Growth spurts are defined as an increase in growth rates following postnatal deceleration (quick and sudden growth in a short period of time) (VandeBerg *et al*, 2009). There have been debates about whether or not non-human primates show a growth spurt during adolescence (Bogin, 1999; Watts and Gavan, 1982). Previous studies (Bogin, 1999) suggested that non-human primates do not show growth spurts but these conclusions were based on small samples of macaques and chimpanzees (Leigh, 2009).

Materials and Methods

Materials

The sample consisted of 89 lateral radiographs of 5 lab-reared female *Papio anubis* with known chronological ages. The individuals from "la Station de Primatologie de Rousset (CNRS, UPS 846)" were radiographed from 2007 to 2015 every 3 months after birth and then every 6 months around 3 years of age. The ages range between 2 months and three weeks to 6 years and three months. "Carbone" was first radiographed at the age of 2.3 months until the age of 6 years and two months. "Clara" was first radiographed at the age of 6.1 months until the age of 6 years and 2 months. The first radiograph for "Dictée" was at 4.9 months, and the last one was at the age of 6.3 years. "Dopram" was radiographed between the ages of 5.7 months and 5.4 years. And "Epine" was first radiographed at the age of 3.3 months and the last radiograph was at 6.2 years.

Methods

In order to study growth in baboons, analyze morphological changes in the cranium and face, and identify growth spurts, we have used Geometric Morphometrics methods (GM). These methods are used for the study of morphological shape variation using geometric coordinates instead of traditional linear measurements (Slice, 2007; Metairie, 2014). The difference between Geometric Morphometrics methods and traditional morphometrics is that the first one conserves the geometric information throughout the analysis while the latter is based on linear measures that are strongly correlated to size (Slice, 2007; Metairie, 2014).

In order to compare spatial configurations of objects, anatomical points called "landmarks" are used to represent the shape of the object (Slice, 2007). The landmarks are homologous anatomical points and are quantified as cartesian coordinates. They were classified by Bookstein in 3 types (Bookstein, 1991; Wämländer *et al*, 2019). Type 1 landmarks are points of intersections like intersections of cranial sutures (Bregma, Lambda, Prosthion, Nasion...). Type 2 are points of maximum curvature (Inion, Opisthion, Basion, Nasospinal) and type 3 are extremal points that are taken the farthest from other points (Glabella, Gonion, Gnathion) (Bookstein, 1991; Wämländer *et al*, 2019).

The first step in Geometric Morphometric studies is to choose the landmarks that will help answer the research question, and then proceed with the data collection using a software to digitize the landmarks. The cartesian coordinates are then extracted. Locating and identifying landmarks on radiographs can be challenging even for an expert (Desvignes *et al*, 2000). For this reason, we chose homologous points on the surface of the cranium that can be located easily. For this study, we chose 9 two-dimensional landmarks (Tab. 1) on the surface of the bone. These landmarks represent the outline of the cranium and their study allows us to represent shape changes of the neurocranium and the spatial position of the face during growth (Fig. 3). TpsDIG software (developed by F. James Rohlf, Department of Ecology and Evolution, State University of New York at Stony Brook; © 2001, F. James Rohlf) (Rohlf, 2015) was used to digitize these landmarks. 150 equidistant semilandmarks were digitized as a curve outlining the cranium, starting from landmark number 1 (glabella) to landmark number 5 (opisthion) (Fig. 4). The X, Y coordinates were extracted using Morpho J software.

The second step is the Generalized Procrustes Analysis (GPA). During this step information that is not related to the shape of the object is reduced by transforming the coordinates and removing the effects of orientation, position, and size (Bastir *et al*, 2006). The obtained shape variables called Procrustes residuals can then be used for analysis. Statistical analysis of these variables can be done using the Principal Component Analysis (PCA) which allows for reduction of the variables in a large dataset and allows better interpretation (Jolliffe and Cadima, 2016). This PCA in shape space is also called relative warp analysis (Bulygina *et al*, 2006).

The X, Y coordinates extracted from Morpho J were put into the statistical software PAST. We did a Generalized Procrustes Analysis (GPA) and then Principal Component Analysis (PCA) on the Procrustes residuals. We first did a PCA for each individual separately and then a PCA for all individuals. For this PCA we regrouped the radiographs into 7 age classes (Tab. 2) : 0-6 months, 6 months- 1 year, 1-2 years, 2-3 years, 3-4 years, 4-5 years, 5-6 + years.

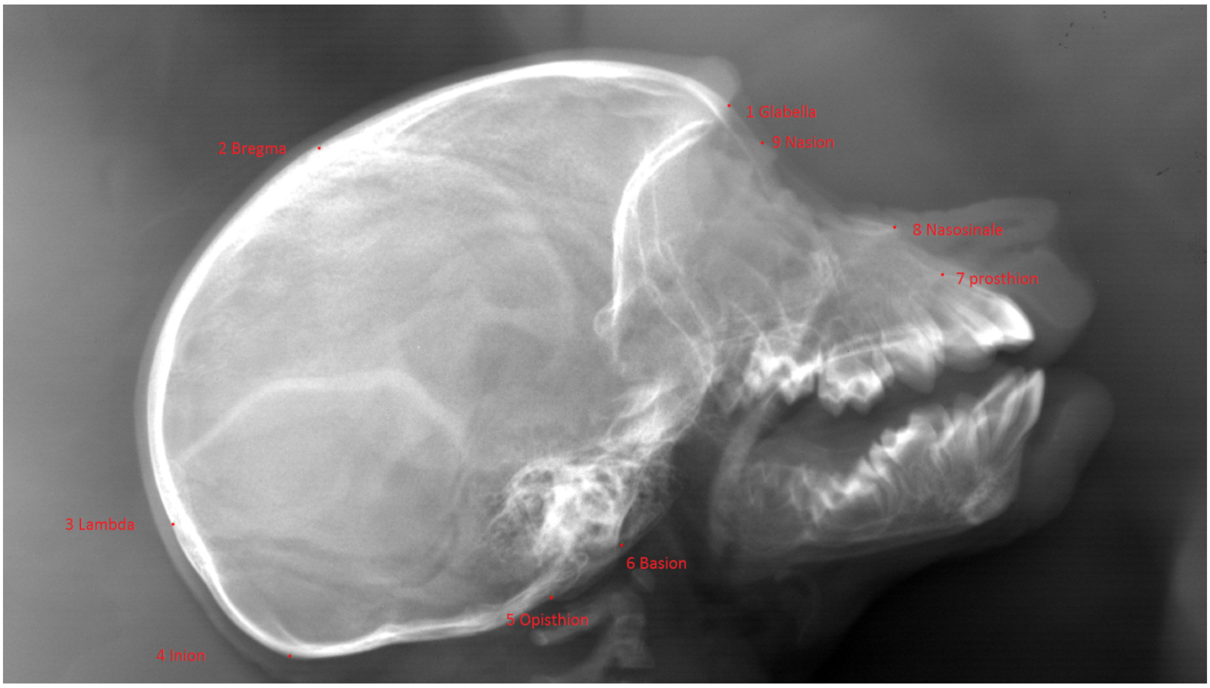

Fig.3: Landmarks.

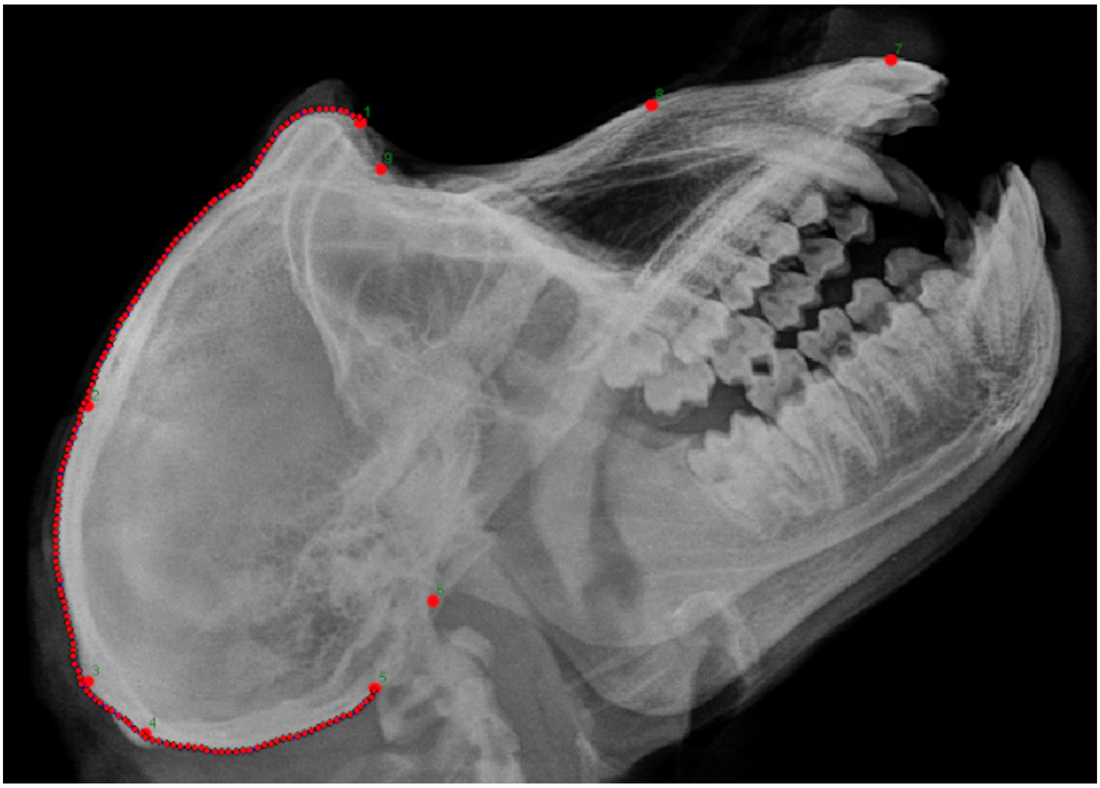

Fig.4: semilandmarks curve from landmark 1 to landmark 5, with 150 equidistant points.

Landmark number	Name
1	Glabella: most anteriorly projecting point in the mid-sagittal plane at the lower margin
2	Bregma: meeting point of coronal and sagittal suture, in the mid-sagittal plane (in case of deviation of the sagittal suture).
3	Lambda: midline bony landmark where the lambdoid sutures and sagittal suture meet, between the occipital and two parietal bones
4	Inion: point at the intersection of the left and right superior nuchal lines (in the mid-sagittal plane)/ most prominent point of the occipital bone in the inferior part of the cranium
5	Opisthion: median point, posterior of the foramen magnum
6	Basion: middle point on the anterior margin of the foramen magnum
7	Prosthion: most anterior point on the alveolar border of the maxilla between the central incisors in the mid-sagittal plane.
8	Nasospinal: lowest point on the inferior margin of the nasal aperture as projected in the mid-sagittal plane.
9	Nasion: point at the intersection of the naso-frontal suture and the midsagittal plane.

Tab. 1: Definition of the Landmarks

Individual:	Carbone	Clara	Dictée	Dopram	Epine
age class	Radiograph number				
0-6 months	1 - 2		1	1	1 - 2
6 months- 1 year	3 - 4	1 - 2	2 - 3	2 - 3	3 - 4
1-2 years	5 - 8	3 - 5	4 - 7	4 - 7	5 - 8
2-3 years	9 - 12	6 - 10	8 - 11	8 - 11	9 - 11
3-4 years	13 - 15	11 - 12	12 - 13	12 - 13	12
4-5 years	16 - 17	13 - 16	14 - 15	14 - 15	13 - 14
5- 6 years	18 - 20	17 - 18	16 - 18	16	15 - 17

Tab. 2: age classes.

In order to study shape changes during growth, we compared average forms between age classes using thin-plate spline (TPS) deformation grids. This allows for a visualization of shape changes from one age class to another. We also did a Principal Component Analysis including all individuals and regrouping them according to age classes to better visualize shape changes at each age stage. To obtain the growth curves for each individual we plotted the centroid size against age. We then calculated the growth rate from these curves which corresponds to the slope between each two points.

Results

1) Thin-plate splines (TPS) deformation grids

To better understand and visualize shape changes during growth and development in female baboons, we compare the differences between TPS deformation grids between age classes for Epine (Fig.5). One major shape change is the enlargement of the face compared to the neurocranium and its projection. During the first year of age (Fig. 5 a) the length of the upper face increases (prostion-nasion), we can see the change of the prosthion position and also the nasospinal. In Fig. 5 b we can see the semilandmarks in the supraorbital torus slightly moving forward and the facial landmarks prosthion and nasospinale projecting more towards the front. The projection of the face is most pronounced around 2 years of age (Fig. 5 c). It is still ongoing in later age stages but is most pronounced between 2 and 3 years.

We can also see the enlargement of the supraorbital torus and the appearance of the nuchal crest around 2-3 year of age (Fig. 5 d).

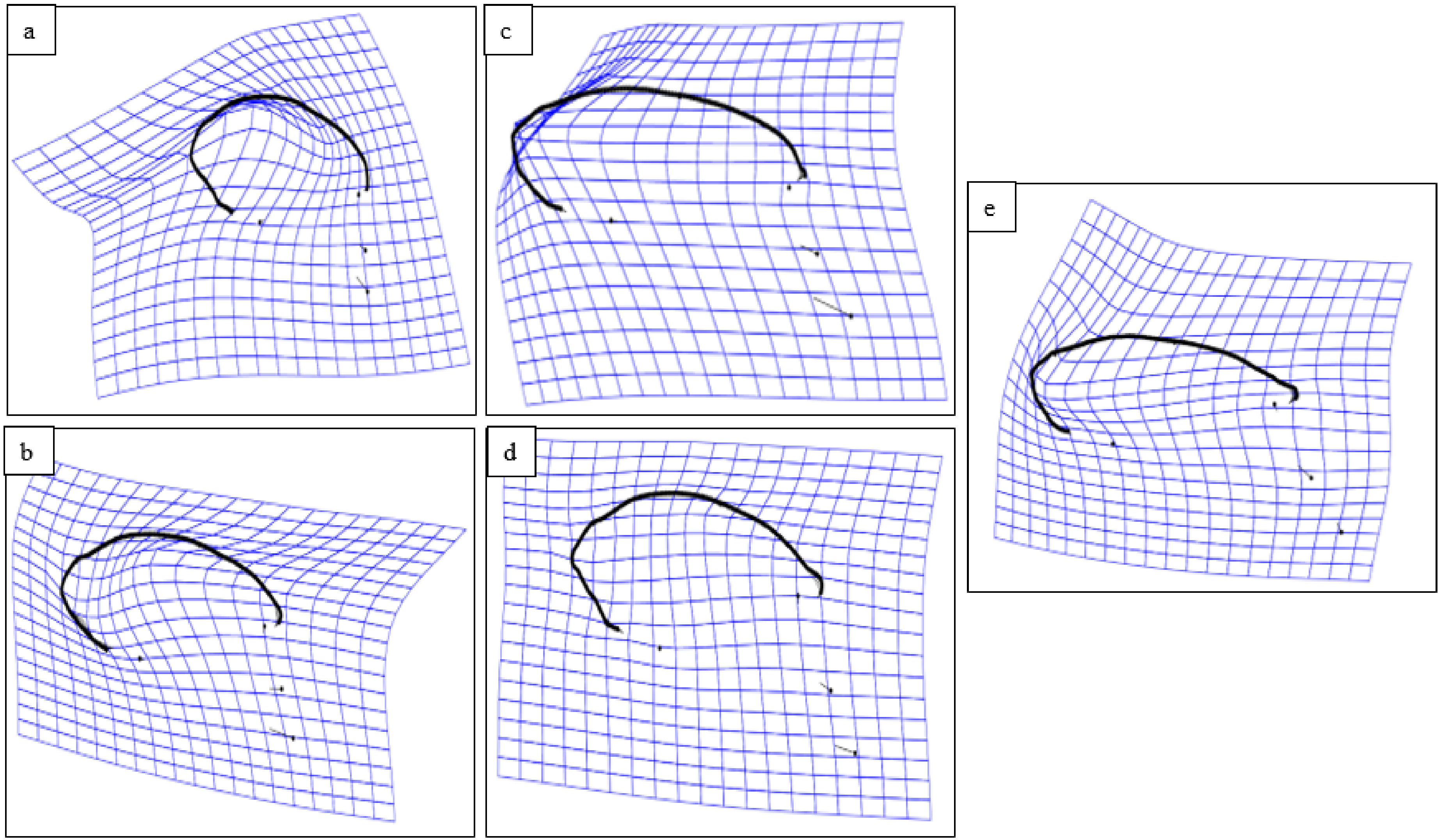

Fig. 5: TPS deformation grids from one age class to its next older for Epine. a) 0 -6 months to 6 months- 1 year, b) 6 months-1 year to 1-2 years,c) 1-2 years to 2-3 years, d) 2-3 years to 3-4 years, e) 3-4 years to 4-5 years.

2) PCA

We present here the results of the Principal Component Analysis done on the procrustes residuals of all individuals. Fig. 6 shows the shape space represented by the first two Principal Components, PC1 and PC2. PC1 explains 73% of the variation and PC2 explains 11.9%. The thin-plate spline grids with expansion factors show the minimum and maximum consensus shape for each PC.

Each point on this PCA represents a radiograph taken at a certain age of one of the five individuals in this study (Carbone, Clara, Dopram, Dictée, Epine). The radiographs were grouped according to 7 age groups (see Tab.2 Materials and methods).

The variation along PC1 is related to variation in the shape of the neurocranium, especially the occipital bone, while the variation along PC2 is correlated to the variation of the face. The individuals from the age group 0-6 months are in the extreme negative values of PC1 and mostly on the negative side of PC2 because they still do not have a pronounced prognathism and developed occipital bone. Individuals from the age group 6 months to 1 year are also mostly on the negative side of PC2 and are on the right side of the first age group. While the age groups 1-2 years, 2-3 years, 3-4 years have points mostly towards positive values on the Y axis (PC2). Which is also coherent with the results from the deformation grid in Fig. 5 where we saw that the facial projection is most pronounced around 2 years of age.

As stated before some radiographs had to be removed due to a scaling problem in the radiographs, the age group 4-5 years had more radiographs initially that could not be represented on this PCA. The age group 5-6+ years was not represented. We could see visually on the radiographs that as the individuals age, they show a more pronounced prognathism, a more pronounced nuchal crest, and a bigger supraorbital torus. Therefore it will be expected that the age groups 5-6+ years should be represented more towards the positive values of PC1 and PC2. In this PCA the individuals from the age group 4-5 years are on the extreme values of PC1 with just two points on the positive side of PC2.

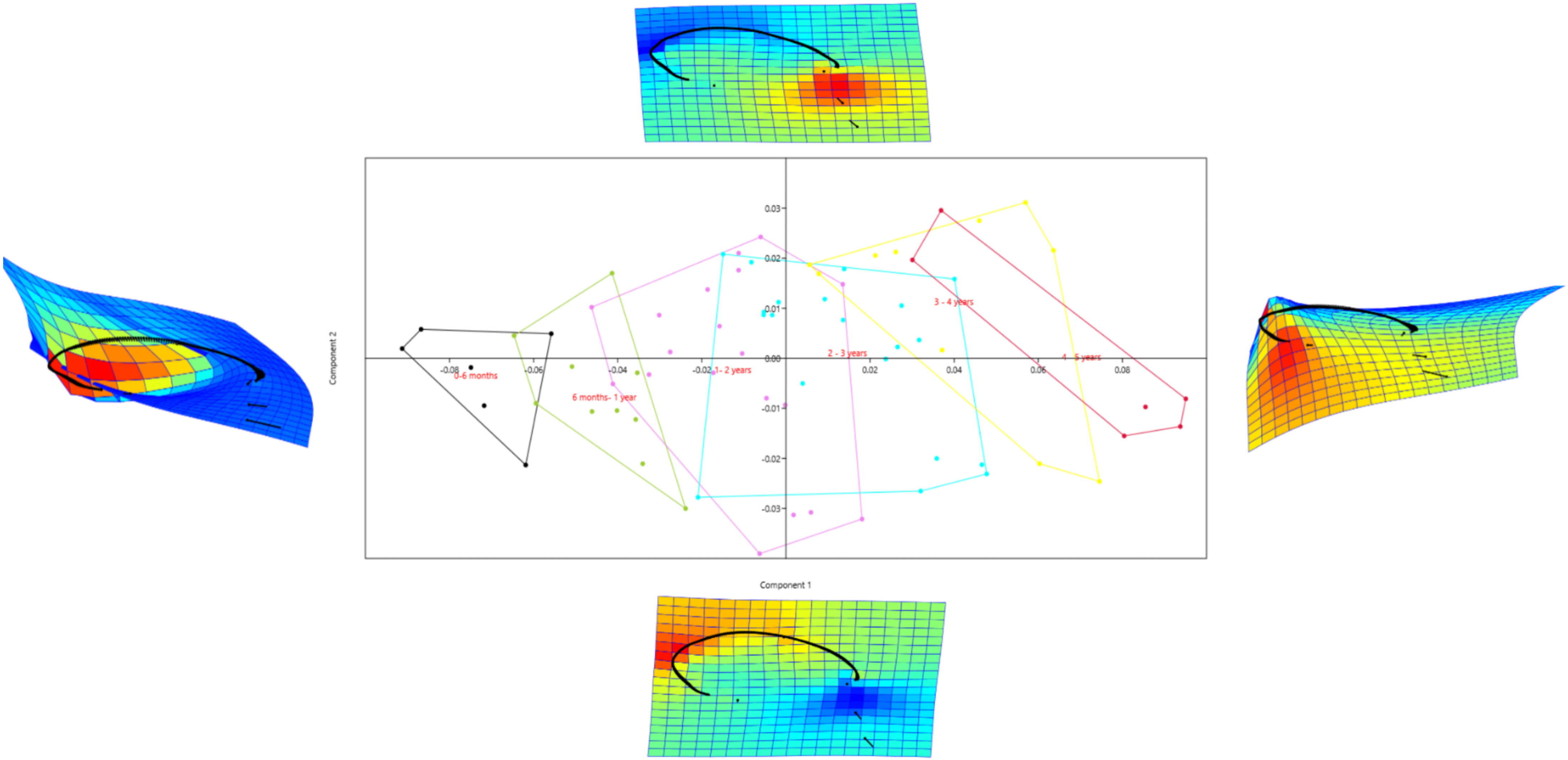

Fig.6: PCA with tps deformation grids for all individuals. PC1 explains 73% of the variation and PC2 explains 11.9%.

3) Growth curves

We plotted centroid size against age in days to obtain growth curves for each individual (Fig. 7, 8 9, 10 and 11). The line connects data points representing the radiographs and it represents the growth trajectory. Odd values were removed. Some radiographs had different resolution or dimensions which resulted in a difference in scale and consequently odd values for centroid size. The radiographs that were removed are 6, 7, 12, 18, 19 and 20 for Carbone; 3, 6 and 18 for Clara; 14 to 18 for Dictée; 14 to 16 for Dopram and 5, 13 to 17 for Epine.

Fig. 7 shows that during the first year of age for Carbone the growth rate is fast (4.5) and then it slows reaching 0,7 (between 1 and 2 years) until the first growth spurt between 2.17 and 2.38 years with a growth rate of 1.8 (between 794 and 870 days) (change of slope/ radiographs 9-10). We can also see two other growth spurts, the first is between 3.11-3.38 years (between 1136 and 1235 days/ radiographs 13-14) and the second between 3.9 and 4.1 years (between 1425 and 1520 days) (radiographs 15-16). The growth rate for these 2 growth spurts is 2.5 and 4.2.

Fig. 8 shows Clara's growth curve. The growth spurts occur between 1.8-2.3 years (638-841 days), 2.93- 3.41 years (1073-1247 days) and 3.66- 4.18 years (1339-1528 days). The growth rate during the first year of age is 3.3 and it slows to reach 0.5 before the first growth spurt. The growth rates for the spurts are 2.1, 3.6 and 3.2. Clara is the only individual for whom we have centroid size data until the age of 5.1 (radiographs 15-17). The growth rate for these are 6.2 between the points 15 and 16 corresponding to 4.7-4.9 years of age, and 3.6 between the points 16 and 17 corresponding to 4.9-5.1 years.

As for the specimen Dictée the growth curve (Fig. 9) shows a change of slope between the points 6 and 9 corresponding to 1.5- 2.29 years with a growth rate of 3.4. There is another growth spurt between 3.04 and 3.29 years (1111-1202 days/points 12-13) with a growth rate of 10.6.

In Fig. 10 we can see two growth spurts for Dopram around 2 years of age. The first is between the points 7 and 8 with a growth rate of 1.9 and corresponding to 1.84-2.11 years and the second between the points 9 and 10 with a growth rate of 2.4 between 2.36 and 2.63 years (862-962 days). We can see another growth spurt between 2.89 and 3.11 years (1057-1137 days) (points 11 and 12) with a growth rate of 3.8.

Fig. 11 shows Epine's growth trajectory with a growth spurt between 1.64 and 1.91 years (600-699 days). The growth rate for this spurt is 4.9. The second growth spurt occurs between 2.69-3.16 years (984-1155 days) with a growth rate of 3.5.

Tab. 3 summarizes the number of growth spurts per individual and the age at which they occur. For the individuals Dopram, Dictée, and Epine and as stated above, data was removed, leaving us with radiographs until the age of 3,29 years for Dictée, 3.36 years for Dopram and 3.16 years for Epine. Therefore, possible growth spurts after these ages (around 1200 months) are missed due to lack of exploitable data. Fig. 12 shows the growth trajectories of all individuals. The general aspect of the growth trajectories is the same. During the first year of age the growth rate is fast and then it decelerates before the first growth spurt occuring around the age of 2 for all individuals.

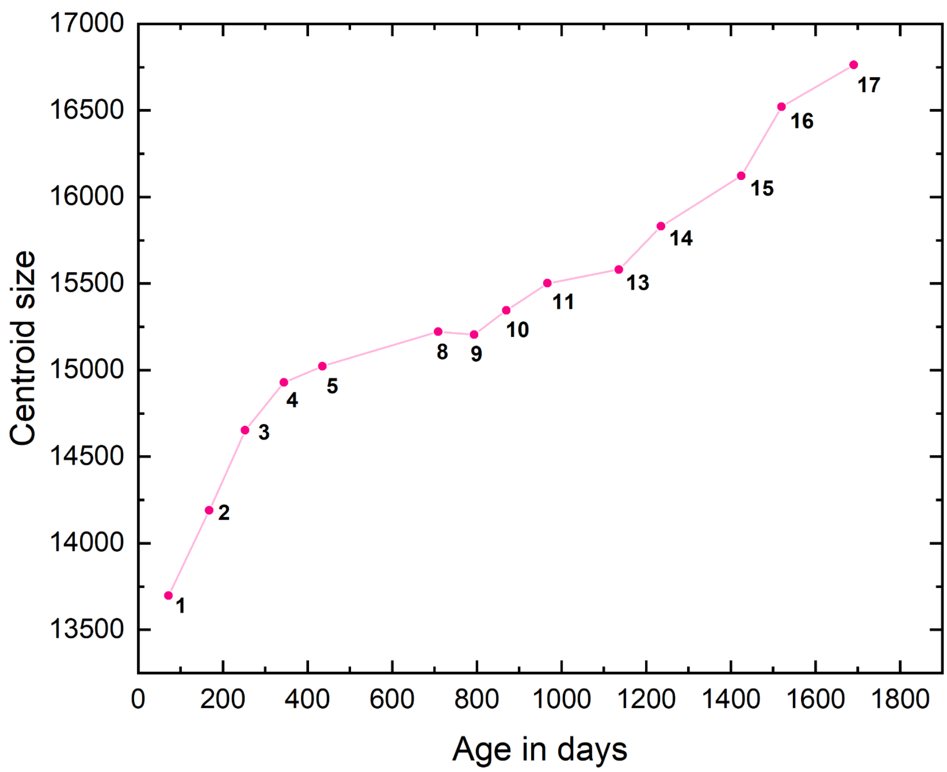

Fig.7: Carbone's growth curve.

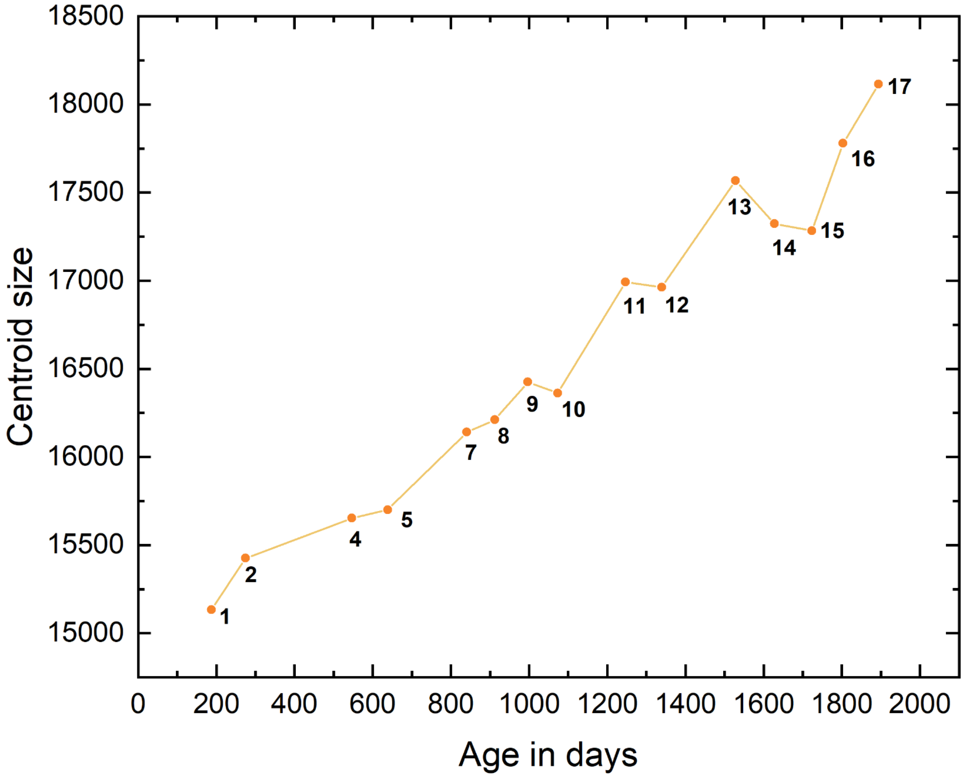

Fig. 8: Clara's growth curve

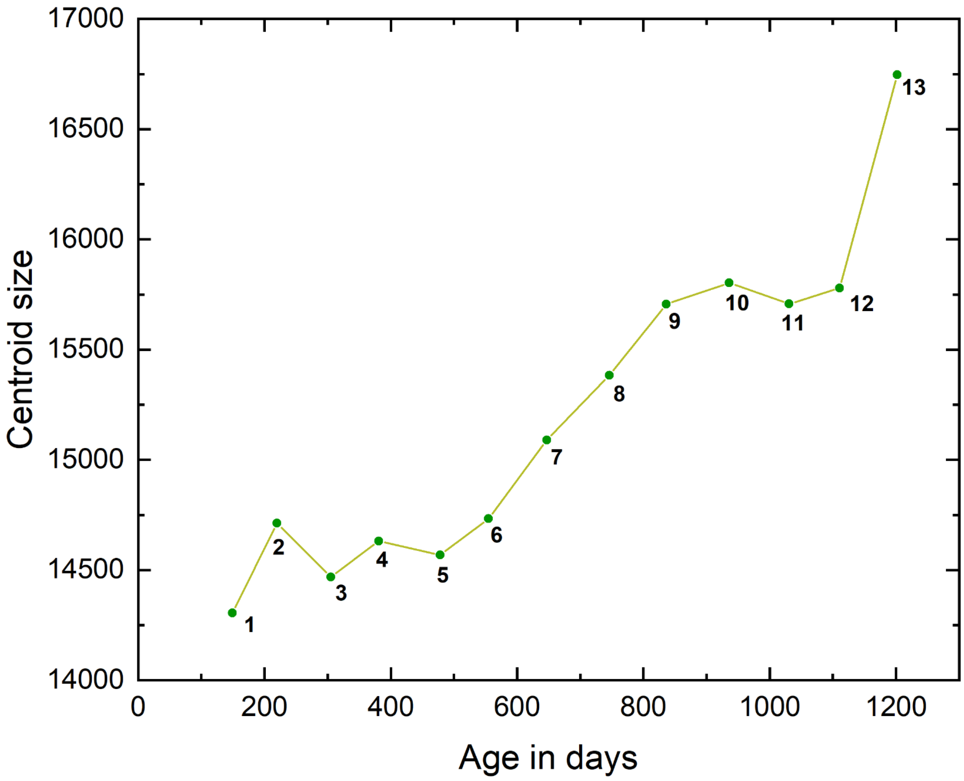

Fig. 9: Dictée's growth curve

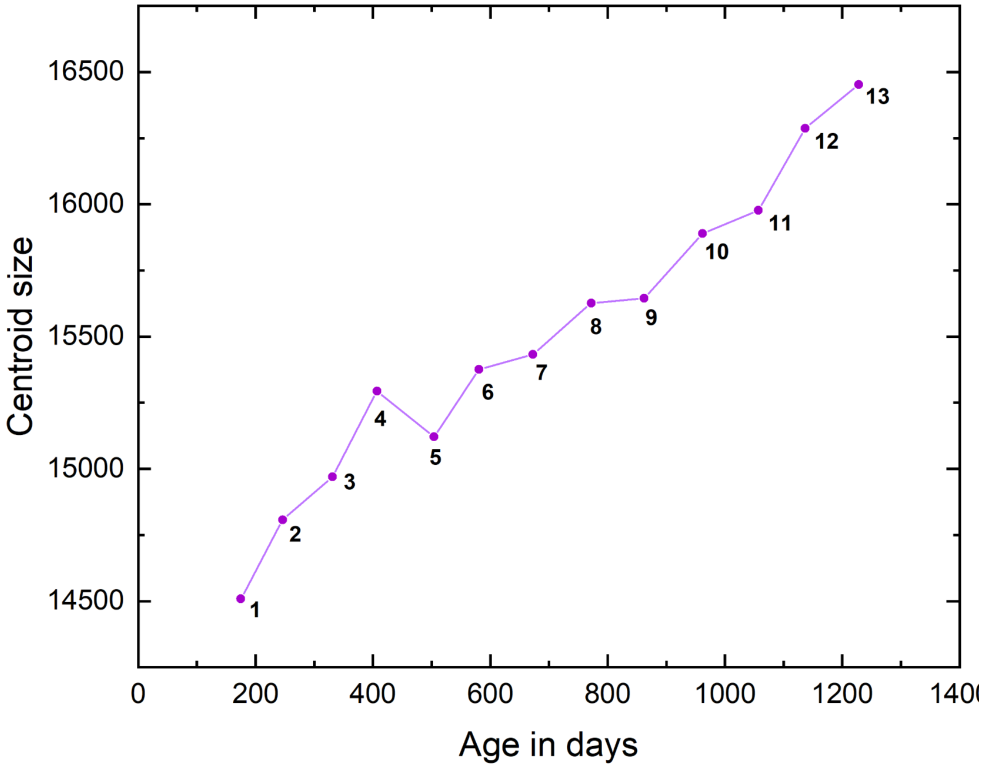

Fig. 10: Dopram's growth curve

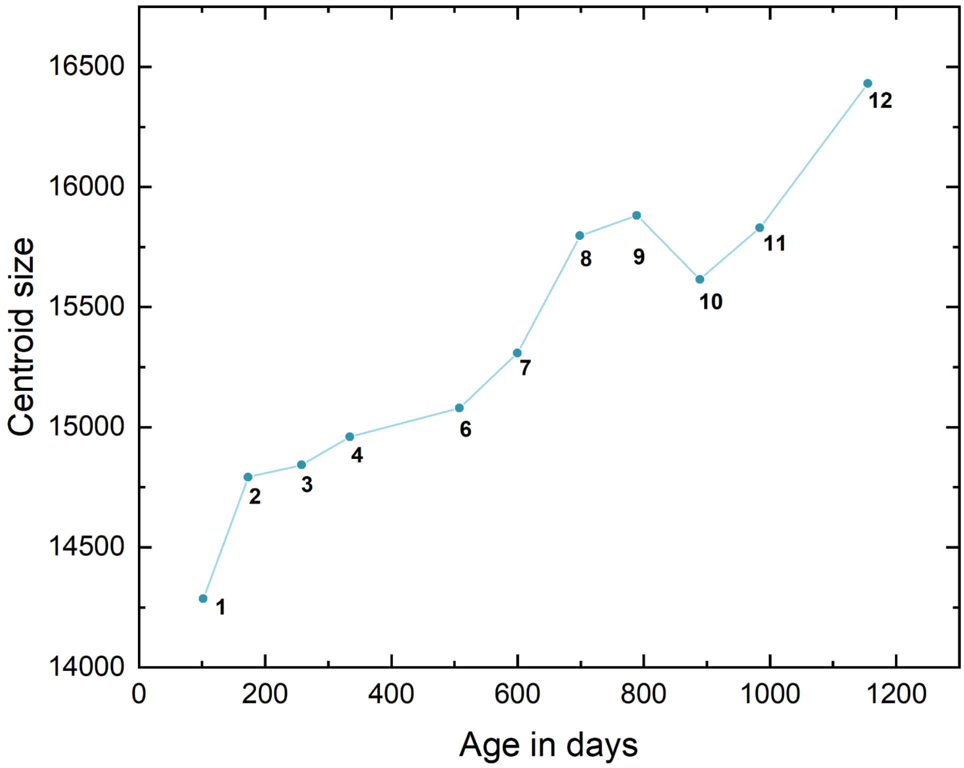

Fig. 11: Epine's growth curve

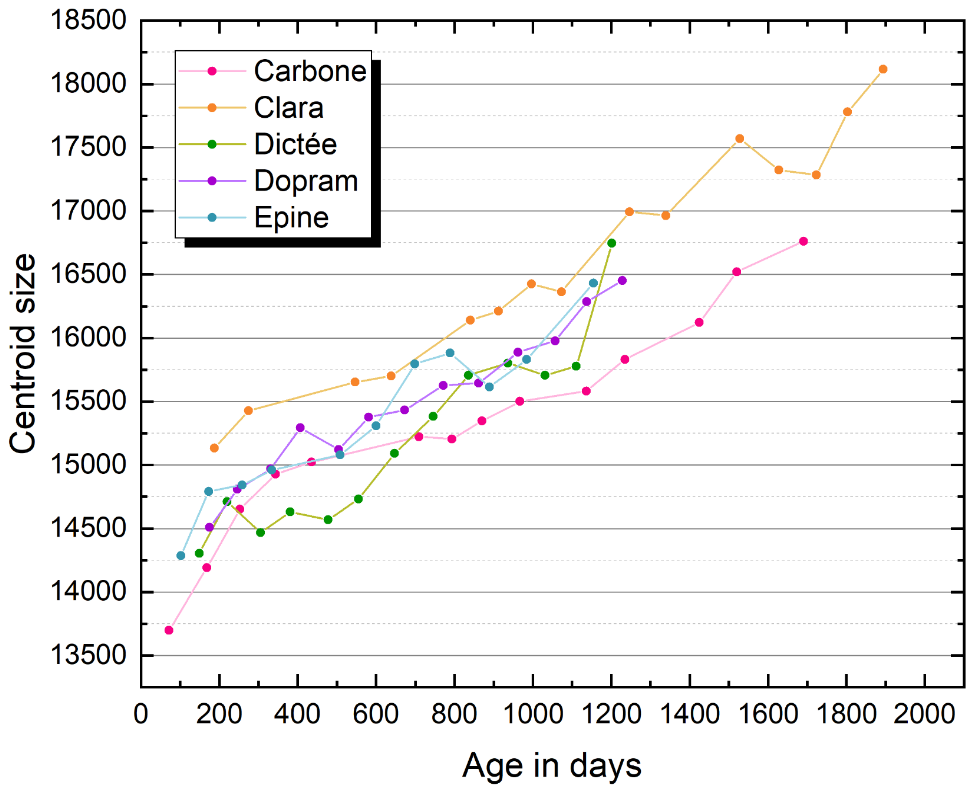

Fig.12: Growth curves for all individuals.

individual	number of growth spurts	age in years
Carbone	3	2.17-2.38/ 3.11-3.38/ 3.9-4.1
Clara	4	1.8-2.3/ 2.93-3.41/3.66-4.18/ 4.7-5.1
Dictée	2	1.5-2.29/ 3.04-3.29
Dopram	3	1.84-2.11/ 2.36-2.63/ 2.89-3.11
Epine	2	1.64-1.91/2.69-3.16

Tab. 3: age and number of growth spurts per individual.

Discussion and Conclusion

The presence of growth spurts in primates was a subject of many debates (Bogin, 1999; Watts and Gavan, 1982). Early possible evidence of an adolescent growth spurt in chimpanzees were derived from cross-sectional data on weight, but the relationship of this spurt with puberty was not clearly established (Gavan, 1953; Grether and Yerkes, 1940; Spence and Yerkes, 1937). Other studies on linear dimensions in lab-reared female rhesus monkeys showed an acceleration of growth during adolescence (Van Wagenen and Catchpole, 1956). This acceleration of growth using weight data was found to be related to menarche in female monkeys. It was observed that female monkeys who had early puberty had an early growth spurt, and those who reached puberty later, had a late growth spurt (Watts, 1986). However, other longitudinal studies on chimpanzees and rhesus monkeys were not successful in locating the adolescent growth spurt (Gavan and Swindler, 1966; Gavan, 1971). In a study done on rhesus monkeys, it was found that females puberty precedes the growth spurt and were not related (Watts and Gavan, 1982).It is possible that the difficulties in precisely locating the growth spurt in primates could be related to the smaller magnitude of the spurt and smaller body size which in turn is responsible for greater measurement errors (Watts, 1986). Recent studies have shown the presence of body mass growth spurts in baboons, as well as a growth spurt in upper facial height (Leigh, 2009)

The present study aimed to provide more evidence to the presence of cranio-facial growth spurts in baboons. TPS deformation grids showed that the biggest deformation in shape occurs around the age of 2 and is related to the change in facial dimensions and prognathism. This is also supported by the growth curves showing growth spurts around 2 years of age for all individuals. In addition, the PCA results show that the groups 1-2 years and 2-3 years are mostly located on the positive side of PC2.

The general shape of the growth curve is the same for all 5 individuals. It shows a fast growth with an important growth rate during the first year of life and then a deceleration followed by an acceleration of growth starting at around 2 years. The peak at 2 years of age is related to the increase in upper facial height and is even observable on the deformation grids.

Some individuals showed only two spurts. This might be due to the lacking data. A way to correct this could be to fix the scaling problem for all radiographs to have more exploitable data.

The first growth spurt occurs around the age of 2 for all individuals in this study. The second growth spurt is observed around the age of 3 for all individuals. And we can see a growth spurt around the age of 4 for Carbone and Clara. For Clara we also have a growth spurt around 5 years of age. Puberty occurs around 3.5 years for both female and male baboons (VanderBerg *et al*, 2009). The growth spurts we observed on the growth curves, occurring around the age of 3 and 4 years are most probably related to puberty.

Previous studies have shown that the length of the upper face (prosthion-nasion) increases until the age of 5 for female baboons (Leigh, 2009). Female baboons show a growth spurt for upper facial height around 2 years of age (Leigh, 2009) which is consistent with what we can see on the TPS deformation grids. The most distinctive skeletal growth spurt in baboons is the upper facial height with a peak of 16mm/ year for male baboons, exceeding even early prenatal velocities. This peak is related to the development of canines, and it occurs at the same time of the eruption of canines (Leigh, 2009). Other skeletal growth spurts in baboons can be very subtle and hard to detect, like spurts in crown rump length, or even lacking in some skeletal measures (Leigh, 2009).

It would be interesting to analyze the data from facial landmarks separately from landmarks and semilandmarks of the neurocranium and see if the peaks of growth occur at the same age and compare them with growth curves for the neurocranium. It would also be interesting to include male individuals in this study, and compare with our results, as it was reported that the growth spurts in females of other species like rhesus monkeys were less marked (Watts and Gavan, 1982).

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Table of figures and tables

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Figures

Summary

Non-human primates share a similar pattern of postnatal growth with humans. Studies of non-human primates are therefore essential to understand human ontogeny and provide valuable data sets for growth comparisons. One characteristic that was thought to be species specific is the presence of an adolescent growth spurt in humans. However studies have provided evidence of an elongated juvenile growth period followed by an acceleration of growth during puberty in non-human primates like chimpanzees. We used longitudinal data from five female *Papio anubis* and geometric morphometrics methods in order to investigate the presence of an adolescent growth spurt. Thin-plate spline deformation grids and Principal component analysis showed that the biggest deformation in shape occurs around the age of 2 years. This was also confirmed by the growth curves showing a rapid growth during the first year of life and a declaration followed by a spurt around the age of 2 that is possibly related to the eruption of canines. Several individuals showed growth spurts around the ages of 3 and 4 which may be related to puberty.