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Female adolescent craniofacial growth spurts: real or fiction?

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SUMMARY The purpose of the study is to determine whether the various aspects of the craniofacial complex exhibit female adolescent growth spurts. Multilevel polynomial models were used to estimate the growth curves of a mixed-longitudinal sample of 111 untreated females 10–15 years of age. To evaluate the horizontal and vertical movements of the individual landmarks relative to stable structures, the tracings were superimposed on the natural reference structures in the anterior cranial base. The horizontal and vertical growth changes of four landmarks and the changes of three traditional linear measurements were evaluated. Posterior nasal spine (PNS) moved posteriorly at a constant rate of approximately 0.12 mm/year. Five measures showed changes in growth velocity (i.e. quadratic growth curves) but not adolescent growth spurts, including the anterior movements of anterior nasal spine (ANS) and pogonion (Pg), the inferior movements of gonion (Go), and the increases in ANS–PNS and condylion to pogonion (Co–Pg). Five measurements, including the inferior movements of ANS, PNS and Pg, the posterior movements of Go, and the increases of Go–Pg exhibited adolescent growth spurts. Peak growth velocities were attained between 11.4 and 12.8 years of age, approximately 0.7–1.4 years earlier in the maxilla than mandible. While the vertical aspects of craniofacial growth exhibit distinct female adolescent growth spurts, with peak rates occurring earlier in the maxilla than mandible, most horizontal aspects of craniofacial growth do not exhibit an adolescent spurt.

Introduction

Because treatments are often planned to correct profiles or prevent profiles from worsening, understanding the antero-posterior (AP) maxillary and mandibular growth is important. AP growth patterns are especially relevant during adolescence when children undergo growth spurts (i.e. dramatic increases in growth rates until a peak is attained, followed by decreases in growth rates). Adolescence is widely considered to be an optimal time for treating orthodontic individuals with AP mandibular deficiencies due to the spurts that occur (Bambha, 1961; Thompson *et al*., 1976; Lewis et al., 1985; Hunter *et al*., 2007).

The AP position of the maxilla, as determined by the SNA angle, does not appear to exhibit an adolescent spurt (Jamison *et al*., 1982; Reyes *et al*., 2006). Growth spurts have been reported for maxillary lengths, based on changes in the distances of A-point–Ptm and from condylion to A-point (Jamison *et al*., 1982; Alexander *et al*., 2009). Others have not been able to identify a spurt for condylion–A-point (Baccetti *et al*., 2000). Adolescent growth spurts have also been reported for overall mandibular length (Tracy and Savara, 1966; Savara and Tracy, 1967; Thompson *et al*., 1976; Bishara *et al*., 1981; Franchi *et al*., 2000; Hunter *et al*., 2007; Alexander *et al*., 2009), corpus length (Nanda, 1955; Tracy and Savara, 1966; Savara and Tracy, 1967), and ramus height (Nanda, 1955; Tracy and Savara, 1966; Savara and Tracy, 1967). However, growth spurts do not occur for the AP position of the mandible, based on the SNB and SNPg angles, or pogonion to nasion perpendicular (Bishara *et al*., 1981; Chvatal *et al*., 2005; Alexander *et al*., 2009). Using 3 point smoothing procedures, Bhatia and Leighton reported that adolescent spurts usually occur in boys but not in girls (Bhatia and Leighton, 1993).

Assuming that an adolescent spurt actually exists, whether or not it can be accurately identified depends on how the growth velocities are calculated. Typically, growth spurts and peak rates of craniofacial growth have been evaluated using yearly velocities, which are calculated based on the changes that occur between two successive observations (e.g. the growth velocity of Co–Pg between 10 and 11 years is calculated by subtracting $Co–Pg_{10\ years}$ from $Co–Pg_{11\ years}$). The problem with this approach is that successive velocities are serially correlated to each other, resulting in a sequential dependency among velocities (Kowalski and Guire, 1974). Errors in yearly data are negatively correlated and produce an irregular, up and down, growth curve with peaks that could be mistakenly interpreted as spurts. Curve fitting addresses this problem by smoothing out such errors (Goldstein, 1979).

The second methodological problem with previous studies pertains to the measures that have been evaluated. Most previous studies have evaluated linear or angular

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measurements, which are defined by two or more landmarks. When measures are defined by more than one landmark, it is difficult to determine what is actually happening at any given landmark (i.e. which landmark is actually changing). For example, SNA might not be expected to exhibit a spurt if both nasion and A-point spurt simultaneously.

The purpose of this study was to test whether there is a female adolescent spurt in various aspects of craniofacial growth based on a large sample of females 10–15 years of age. Multilevel modeling procedures were used to statistically determine the presence of a spurt. Unlike previous studies evaluating distances between landmarks this study also evaluated the growth changes of individual landmarks.

Materials and methods

Annual cephalometric radiographs were obtained from a French–Canadian sample, which was collected by the Human Growth Research Center, University of Montreal, Canada (Demirjian *et al.*, 1971). They were drawn from three randomly selected school districts representing the socioeconomic background of the larger French–Canadian population (Demirjian *et al.*, 1971). Within each of the districts, the individuals had been chosen at random from 107 schools, which had also been randomly chosen. This non-orthodontic sample is therefore considered to be representative of the larger population, including individuals with normal occlusion and malocclusion. The present study is based on a mixed-longitudinal sample of 111 untreated female adolescents between 10 and 15 years of age. Each subject included had at least four of the six possible annual radiographs available within that age range (Table 1). None of the subjects had been treated orthodontically or surgically.

Data collection and analysis

Lateral cephalograms (total $n = 625$) were taken within ± 12 days of the subjects' birthdays. The cephalograms were traced on acetate paper, and the landmarks were digitized by a single operator. Based on seven landmarks identified on each tracing (Figure 1), 11 measurements were computed. Three linear measurements were computed in order to make comparisons with published growth changes, including Co–Pg, Go–Pg, and ANS–PNS.

To evaluate the horizontal and vertical movements of the individual landmarks relative to stable structures, the tracings were superimposed on the natural reference structures in the anterior cranial base (Björk and Skieller, 1983). In order to quantify growth changes at the anterior and posterior aspects of the maxilla and mandible, the horizontal and vertical changes of four landmarks were evaluated relative to a stable-structure reference plane. The initial sella (S) served as the origin and the initial S–N plane minus 7 degree was used for orientation of the reference plane. Following each cranial base superimposition, the reference plane was transferred to the tracing and used for orientation of the horizontal and vertical movements of the anterior nasal spine (ANS–H & ANS–V), posterior nasal spine (PNS–H & PNS–V), gonion (Go–H & Go–V), and pogonion (Pg–H & Pg–V) were computed (Figure 1).

Table 1 Summary of the collected data from females from 10 to 15 years of age.

Total number of patients	111
Total number of acquired radiographs	625
Missing radiographs (%)	6.15
Total number of measurements	6,875
Missing measurements (%)	7.01

Based on 120 replicate superimpositions, method errors [$\sqrt{(\sum \text{differences}^2/2n)}$ ranged from 0.25 to 0.41 mm. Replicate analyses of 112 randomly chosen cephalograms produced method errors of the landmarks ranging between 0.15 and 0.73 mm. There were no statistically significant systematic differences between the replicate measurements.

Statistical analysis

Curve fitting procedures were used to obtain a mathematical function that 'best fit' of the subjects' mixed-longitudinal data points. Multilevel procedures were used to derive polynomials based on generalized least squares (Strenio *et al.*, 1983; Goldstein, 1987). Polynomial regression was used to model the mixed-longitudinal growth changes that occurred. The polynomial is a multiple linear equation that quantifies the form of the growth curve, making no assumptions about the shape of the actual curve. Multilevel estimates of repeated growth measures have been shown to be more stable and meaningful than estimates based on ordinary least squares (Tanguay *et al.*, 1993). These models are also more flexible than traditional approaches because they can estimate growth changes for subjects with unadjusted series of measurements and for subjects with missing data.

The models estimated each of the 11 measurements as a function of chronological age. The shape of the average growth curve (i.e. the relationship between the measurements and age) was determined by the order of the polynomial, which was estimated by the fixed part of the model. The terms of the polynomials provide information about the average size of each measure at 12 years of age (intercept or constant term), yearly growth velocity (linear term), growth acceleration or deceleration (quadratic term), and changes in acceleration or deceleration (cubic term). The order of each polynomial was determined statistically. A fifth-order polynomial was first fitted; the highest order term was sequentially eliminated if it was not statistically significant. This continued until statistical significance was attained. Using the polynomial models, yearly growth velocities were estimated and presented in the figures and tables.

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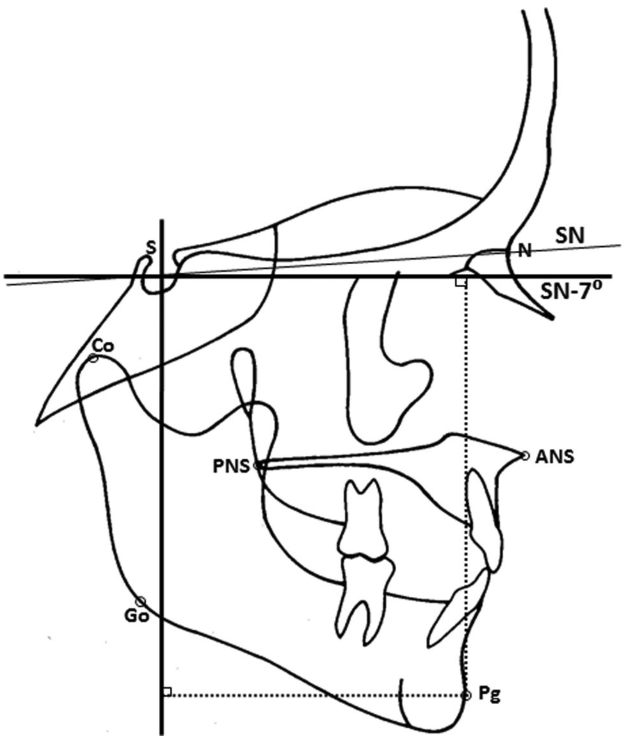

Figure 1 Cephalometric landmarks digitized; (S) sella, (N) nasion, (PNS) posterior nasal spine, (ANS) anterior nasal spine, (Co) condylion, (Go) gonion, (Pg) pogonion. Horizontal and vertical measurements were obtained by registering on sella (S) and orienting on S–N minus 7 degree. The dotted lines indicate the perpendicular and parallel projection of the landmark Pg related to S–N minus 7 degrees.

The random part of the model estimated variation between subjects at the higher level and between ages, nested within subjects, at the lower level. Multilevel models are well suited for assessing mixed-longitudinal data (Gilthorpe and Cunningham, 2000) and have been applied to various measures of craniofacial growth (Buschang *et al*., 1988; Hoeksma and van der Beek, 1991; Chvatal *et al*., 2005; Van Diepenbeek *et al*., 2009; Arboleda *et al*., 2011).

Results

The models explained between 89.3 and 77.0% of the variation in the horizontal, vertical, and linear changes that occurred over time. Five of the 11 measures followed third-order, or cubic, polynomials (Table 2), indicating that growth velocities increased initially and then decreased (i.e. there was a peak velocity and a growth spurt).

All of the linear measures increased in size between 10 and 15 years of age (Figure 2). Co–Pg, Go–Pg, and ANS–PNS increased 9.6 ± 2.1, 6.0 ± 1.4, 3.3 ± 1.5 mm, respectively, between 10 and 15 years of age. Of the three measures, only Go–Pg showed an adolescent growth spurt. With the exception of Go–V, all of the vertical measures also showed growth spurts (Figure 3; Table 3). Pg–V showed the highest growth rates, ranging from 1.5–2.5 mm/yr. The vertical growth changes of the two maxillary landmarks showed the lowest growth rates after 12 years of age.

There was approximately 1.4 years between the average ages at which the earliest and latest peak velocities occurred. The vertical changes of ANS and PNS peaked at 11.53 and 11.43 years of age, respectively (Figure 3). They peaked more than 6 months before Go–Pg and Pg–V. Go–H was the last measure to peak, at 12.83 years of age.

The five measures showing quadratic growth patterns did not exhibit a spurt. All had growth rates that decreased regularly over time (Figure 4). Go–V and Co–Pg showed growth rates that were substantially higher than the other measures. Rates of anterior movement of ANS and Pg were similar

Table 2 Polynomial models describing the growth changes (mm) between 10 and 15 years of the horizontal, vertical, and linear measures, with the constant, linear, quadratic, and cubic terms indicating size, growth velocity, acceleration or deceleration, and changes in acceleration or deceleration, respectively, at 12 years of age (the horizontal and vertical changes were evaluated relative to the initial stable structure reference plane, which had an origin at sella and was oriented along S–N minus 7º).

	Variable	Constant (at 12 yrs)		Linear		Quadratic		Cubic	
		Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Linear	Co–Pg	97.5350	0.3983	2.0323	0.0342	−0.0949	0.0197		
	Go–Pg	64.5530	0.3234	1.4245	0.0483	0.0251	0.0196	−0.0374	0.01
	ANS–PNS	47.3780	0.2431	0.7165	0.0265	−0.0339	0.0154		
Horizontal	ANS	65.6420	0.3129	0.5993	0.0237	−0.0481	13.7020		
	PNS	18.2940	0.2075	−0.1173	0.0181				
	Go	21.4580	0.3557	1.1642	0.0665	0.0827	0.0270	−0.0337	0.0138
	Pg	51.7410	0.5081	0.4366	0.0463	−0.0850	0.0267		
Vertical	ANS	39.0450	0.2258	1.1825	0.0437	−0.0305	0.0172	−0.0215	0.0091
	PNS	37.5750	0.1845	0.8767	0.0306	−0.0303	0.0125	−0.0176	0.0064
	Go	59.6170	0.3489	1.2815	0.0353	−0.0508	0.0204		
	Pg	90.4720	0.4915	2.2534	0.0852	0.0403	0.0347	−0.0507	0.0177

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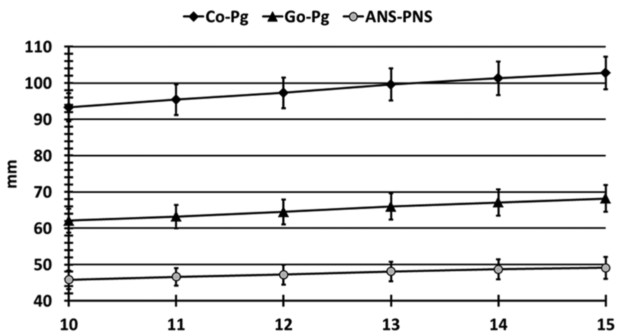

Figure 2 Growth changes of the three linear measurements showing size increases in females between 10 and 15 years of age.

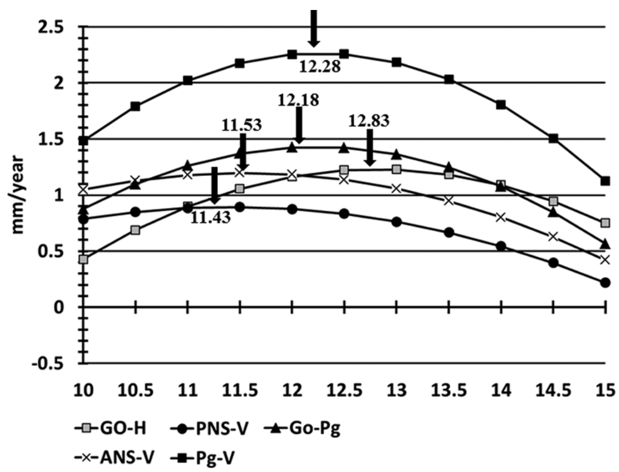

Figure 3 Rates of growth of measurements exhibiting spurts in females 10–15 years of age.

initially, but rates decreased faster for Pg than ANS, resulting in greater anterior repositioning of ANS. PNS moved posteriorly at a constant rate of 0.12 mm/year (Table 3); it also did not exhibit an adolescent spurt.

Discussion

The vertical aspects of maxillary growth underwent an adolescent spurt, with peak velocities occurring at approximately 11.5 years of age. Rates of growth were slightly greater for ANS than PNS. A spurt has been previously reported for upper face height (N–ANS) of class I females (Alexander *et al.*, 2009). The present study, based on a larger sample and evaluating pure vertical changes of individual landmarks, is the first to show that both the anterior and posterior maxilla undergo spurts and attain peak adolescent velocities at approximately the same time. The maxillary spurt may be related to nasal septal cartilage, which is under hormonal influence (Vetter *et al.*, 1986), plays a role in midfacial displacements (Kvinnsland, 1974; Sarnat, 2008), and continues to display growth activity during adolescence (Vetter, 1983).

The vertical changes of the anterior mandible (Pg) showed the most pronounced adolescent growth spurt, whereas the vertical changes at gonion did not exhibit a spurt. Peak growth velocity of Pg–V occurred at 12.3 years of age, with average rates of growth approaching 2.3 mm/year. Lower anterior face height of females has been previously shown to exhibit a growth spurt at approximately 12 years of age (Reyes *et al.*, 2006; Alexander *et al.*, 2009; Baccetti *et al.*, 2011). The timing of the adolescent spurt for lower face height—which includes both jaws—might be expected to be earlier than the mandibular spurt and later than the maxillary spurt. Growth of lower face height measured from ANS might also be expected to underestimate the actual vertical growth changes of the anterior mandible because the maxilla also undergoes a vertical growth spurt. The lack of a vertical growth spurt for gonion probably reflects resorption along the lower mandibular border (Enlow and Harris,

Table 3 Growth velocities (mm/yr) of horizontal, vertical, and linear measures in females 10 to 15 years of age (negative velocities indicate posterior rates of growth; the horizontal and vertical changes were evaluated relative to the initial stable structure reference plane, which had an origin at sella and was oriented along S−N minus 7º).

		Age (years)									
		10.5		11.5		12.5		13.5		14.5	
	Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Linear	Co−Pg	2.32	0.14	2.13	0.13	1.94	0.13	1.75	0.15	1.56	0.11
	Go−P	1.10	0.09	1.37	0.08	1.42	0.08	1.25	0.10	0.85	0.09
	ANS−PNS	0.82	0.11	0.75	0.11	0.68	0.11	0.61	0.13	0.55	0.11
Horizontal	ANS	0.74	0.10	0.65	0.09	0.55	0.10	0.45	0.11	0.36	0.10
	PNS	−0.12	0.09	−0.12	0.08	−0.12	0.08	−0.12	0.09	−0.12	0.07
	Go	0.69	0.13	1.06	0.11	1.22	0.11	1.18	0.09	0.95	0.08
	Pg	0.69	1.98	0.52	0.18	0.35	0.15	0.18	0.13	0.01	0.13
Vertical	ANS	1.13	0.07	1.20	0.07	1.14	0.06	0.95	0.08	0.63	0.07
	PNS	0.85	0.06	0.89	0.05	0.83	0.06	0.67	0.06	0.40	0.06
	Go	1.43	0.22	1.33	0.18	1.23	0.14	1.13	0.15	1.03	0.14
	Pg	1.79	0.19	2.18	0.17	2.26	0.11	2.03	0.13	1.50	0.13

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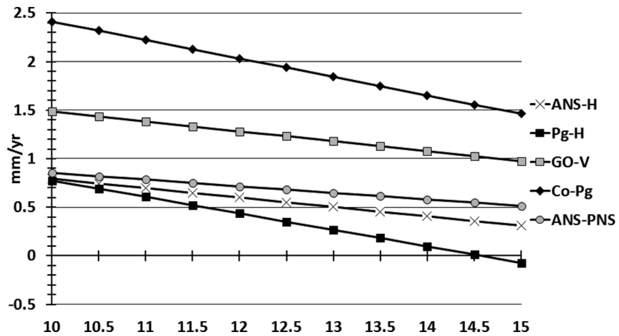

Figure 4 Rates of growth of measurements not exhibiting spurts in females 10–15 years of age.

1964; Hans and Enlow, 1995). Superimpositions on natural structures (Baumrind *et al*., 1992; Buschang and Gandini Jr, 2002) and implants (Baumrind *et al*., 1992b) have shown that there is approximately 1.0 mm of resorption at gonion for every 2.8 mm of superior condylar growth. Moreover, remodeling at gonion has been related to forward rotation and mandibular displacement, with the subjects exhibiting the greatest inferior displacements also showing the greatest superior drift of gonion (Buschang and Gandini Jr, 2002).

The posterior growth of gonion, which also exhibited a spurt, accounted for the adolescent spurt in the distance Go–Pg. Histological and implant studies have shown that little or no modeling takes place on the anterior surface of the chin (Enlow and Harris, 1964; Björk and Skieller, 1983; Baumrind *et al*., 1992b), which is why this region is used for superimposing mandibles (Björk and Skieller, 1983). Growth spurts for corpus length have been previously reported (Nanda, 1955; Tracy and Savara, 1966; Savara and Tracy, 1967; Ohtsuki *et al*., 1982; Lewis *et al*., 1985; Bhatia and Leighton, 1993; Franchi *et al*., 2000; Chvatal *et al*., 2005). Since maxillary length does not exhibit a spurt, it is unlikely that the spurt in corpus length represents an adaptation for the eruption of teeth (Nanda, 1955). The accelerated growth at gonion could be associated with posterior changes in the position of the glenoid fossa (Baumrind *et al*., 1983; Buschang and Santos-Pinto, 1998), which might be indirectly influenced by the spheno-occipital synchondrosis (Harkness and Trotter, 1980; Ohtsuki *et al*., 1982; Lewis *et al*., 1985). Acceleration of growth at gonion might also be related to the forward mandibular rotation and associated anterior displacement of gonion that occurs during adolescence (Björk, 1969; Björk and Skieller, 1983; Buschang and Gandini Jr, 2002). Horizontal modeling of the ramus is most closely related to horizontal mandibular displacements (Buschang and Gandini Jr, 2002); subjects with the greatest posterior modeling show more anterior mandibular displacements and greater forward rotation.

Peak adolescent growth velocities for the maxilla occurred more than 6 months before the peaks of the three mandibular measures. It has been previously shown that maxillary measures peak before peak height velocity (Krogman, 1968), whereas mandibular measures peak after peak height velocity (Thompson *et al*., 1976; Lewis *et al*., 1985). Differences in the timing of peak growth velocities among structures are not limited to the craniofacial complex. Peak adolescent velocity of leg length precedes peak velocity for sitting height, which in turn occurs close to the timing of peak velocity in upper arm length (Roche and Lewis, 1974; Smith and Buschang, 2005). Differences between jaws in the timing of peak velocity could be related to maturity differences (Buschang *et al*. 1983) and hold important clinical implications with respect to the timing of orthodontic treatment. For example, orthodontists seeking to take advantage of peak adolescent mandibular growth would want to start treatment later than those taking advantage of peak maxillary growth.

Perhaps the most interesting outcome of the present study relates to the fact that the chin does not exhibit an AP growth spurt. Instead of accelerating, the horizontal rates of movements for Pg steadily decrease throughout adolescence. The present study shows that the lack of spurt previously reported for SNB and SNPg (Bishara *et al*., 1981; Jamison *et al*., 1982; Baccetti *et al*., 2000; Reyes *et al*., 2006; Alexander *et al*., 2009) is not due to the anterior movements of nasion associated with frontal sinus enlargement or surface remodeling (Roche and Lewis, 1974; Ohtsuki *et al*., 1982). The lack of a horizontal spurt is probably related to the fact that the anterior repositioning of the chin during growth is primarily due to mandibular rotation, with the greatest chin projection often associated with condyles growing in a more anterior direction (Björk and Skieller, 1972). The lack of an adolescent spurt in horizontal chin position is fundamentally important for orthodontists attempting to take advantage of growth using functional/orthopedic appliances (Baccetti *et al*., 2000).

The horizontal changes of the anterior maxilla (ANS) and maxillary length (ANS–PNS) also did not exhibit growth spurts. It has been previously shown that there are no adolescent spurts for S–N–A, S–N–ANS or S–N–PNS (Jamison *et al*., 1982; Ohtsuki *et al*., 1982) but spurts for Co–A point (Alexander *et al*., 2009) and Ptm–A point (Jamison *et al*., 1982). Bhatia and Leighton (1993) also showed no clear adolescent spurt for ANS–PNS of girls. However, neither of these measure pure horizontal changes in the position of the maxilla; they include vertical components of growth, which clearly exhibit an adolescent spurt. Moreover, condylion is influenced by the posterior repositioning of the glenoid fossa (Buschang and Santos-Pinto, 1998). These data indicate that there is no adolescent spurt in AP dimension or position of the maxilla; growth velocities decrease regularly over time. The velocity decreases were less for ANS than Pg, indicating that the mandible of French–Canadian females becomes more retrognathic over time. Increasing retrognathism with age among adolescent females has been previously reported (Buschang *et al*, 1988; Nanda and Ghosh, 1995; Bishara, 1998; Jacob and Buschang, 2011).

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Conclusions

Based on 111 female subjects and explaining 77–89.3% of the variation, multilevel models of the adolescent craniofacial growth curves showed:

1. No adolescent growth spurts for six measurements, including the horizontal changes of ANS, PNS, Pg, the vertical changes of Go, ANS–PNS and Co–Pg. All of the measures except the horizontal changes at PNS exhibited decreasing rates of change (quadratic polynomials) between 10 and 15 years of age.
2. Adolescent growth spurts for five measurements, including the vertical changes of ANS, PNS and Pg, the horizontal change of Go, and Go–Pg.
3. Peak growth velocities occurring 0.7–1.35 years earlier for the maxillary than mandibular measurements.

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