

# Use of Skeletal Maturation Based on Hand-Wrist Radiographic Analysis as a Predictor of Facial Growth: A Systematic Review

Carlos Flores-Mir, DDS, MSc, Cert Orth, PhD<sup>a</sup>; Brian Nebbe, BDS, Mdent, FFD(SA)Ortho, PhD<sup>b</sup>;  
Paul W. Major, DDS, MSc, MRCD(c)<sup>c</sup>

**Abstract:** The purpose of this systematic review was to evaluate the predictive value of hand-wrist radiographic assessment of skeletal maturity in estimating facial growth timing and velocity. A search of PubMed, Medline, Cochrane Database of Systematic Reviews, Embase, Web of Sciences, and Lilacs identified 16 articles that met the following inclusion criteria: use of hand-wrist radiographs for skeletal maturation determination, facial growth evaluated through cephalometric radiographs, and cross-sectional or longitudinal studies. Five articles were rejected because of major methodological issues. Most of the remaining articles had small sample size, and there was no report of randomization or method error. Skeletal maturity determined by hand-wrist radiographic analysis was well related to overall facial growth velocity. Maxillary and mandibular growth velocities were related to skeletal maturity, but their relationship was less robust than that for overall facial growth. The available articles have not adequately defined a relationship between cranial base growth velocity and skeletal maturity. Hand-wrist radiographic assessment of skeletal maturity for use in facial growth prediction should include bone staging as well as ossification events. The role of skeletal maturity assessment in clinical and research applications is discussed and recommendations are provided. (*Angle Orthod* 2004;74:118–124.)

**Key Words:** Hand-wrist radiographs; Skeletal maturation; Facial growth; Prediction

## INTRODUCTION

In orthodontic treatment planning, knowledge of facial growth velocity and percentage of facial growth remaining is very important for effective growth modification interventions. Furthermore, an understanding of percentage growth remaining after completion of orthodontic intervention may be important in predicting posttreatment rebound. Simultaneously, evidence-based orthodontic practice requires research into treatment outcome of various modalities. To facilitate this, the influence of normal growth during a study period should be isolated from the data to distill the effect of treatment intervention. Samples considered should be matched for craniofacial growth velocity and percentage of growth remaining.

Staging of human skeletal development has been assessed using physiological parameters including peak growth velocity in standing height, pubertal markers (such as voice changes in males, menarche in females, breast development, appearance of pubic hair, and appearance of axillary hair), radiographic assessment of bone maturation, chronological age, and staging of dental development.<sup>1,2</sup>

Peak growth velocity in standing height is the most valid representation of rate of overall skeletal growth. It forms a useful historic longitudinal measure of an individual's growth pattern but has little predictive value for future growth rate or percentage of total growth remaining. For this reason, an indication of the maturation level of an individual is necessary to predict future growth. Longitudinal measurements used to calculate peak standing height growth velocity do provide the "gold standard" to assess the validity of growth predictors.

Dental development indicators are not reliable predictors of an individual's stage of skeletal development.<sup>3–14</sup> Because there is wide variation among individuals in the timing of the pubertal growth spurt, chronologic age cannot also be used in the evaluation of adolescent growth.<sup>2,15–20</sup> Hägg and Taranger<sup>21</sup> reported a two-year sex difference for the beginning, peak, and end of the pubertal growth spurt in standing height for males and females. In addition, these authors reported an individual variation of approximately six years

<sup>a</sup> Postdoctoral Fellow, Division of Orthodontics, Department of Dentistry, University of Alberta, Edmonton, Alberta, Canada.

<sup>b</sup> Clinical Assistant Professor, Division of Orthodontics, Department of Dentistry, University of Alberta, Edmonton, Alberta, Canada.

<sup>c</sup> Professor, Director of Graduate Orthodontics, Department of Dentistry, University of Alberta, Edmonton, Alberta, Canada.

Corresponding author: Paul W. Major, DDS, MSc, MRCD(c), Faculty of Medicine and Dentistry, Room 4051b, Dentistry/Pharmacy Centre, University of Alberta, Edmonton, Alberta, Canada T6G 2N8 (e-mail: major@ualberta.ca).

Accepted: March 2003. Submitted: February 2003.

© 2004 by The EH Angle Education and Research Foundation, Inc.

in each growth event in both sexes. Furthermore, environmental factors may influence timing and rate of skeletal development.<sup>7</sup>

Skeletal maturation staging from radiographic analysis is a widely used approach to predict timing of pubertal growth, to estimate growth velocity, and to estimate the proportion of growth remaining. Although use of the cervical spine<sup>22,23</sup> and frontal sinus<sup>24</sup> has been reported, skeletal maturation is generally determined by using stages in the ossification of bones of the hand and wrist, because of the quantity of different types of bones available in the area,<sup>16,17,25-34</sup> or by evaluating the ossification onset of the ulnar sesamoid.<sup>3,28,30,31,35-38</sup>

Skeletal maturity is influenced in each individual by a combination of genetic and environmental factors. The ossification sequence and timing of the skeletal maturity within the hand-wrist area show polymorphism and sexual dimorphism, which can limit their clinical predictive use.<sup>16,19,39,40</sup> An important consideration is that the same pattern of skeletal growth can be found in almost every individual, but the initiation, duration, and amount of growth varies considerably during the pubertal growth spurt.<sup>41,42</sup> Some individuals are early maturers with a relatively short pubertal growth spurt, whereas others are late maturers with a larger pubertal growth spurt.<sup>17,18,25,29,43,44</sup>

There are two general approaches to assessment of the hand-wrist radiograph. The first method consists of the comparison methods of Greulich and Pyle<sup>27</sup> and Tanner et al.<sup>25</sup> Greulich and Pyle<sup>27</sup> use an atlas as a standard of comparison. The atlas is composed of plates of "typical" hand-wrist radiographs at six-month intervals of chronological age. Each bone of the subject's hand-wrist is compared with the corresponding bones in the atlas and is assigned an age in months. All ages are averaged yielding the "mean age" of the individual. In clinical use, this approach is often shortened to a gross assessment to find the best match of the individual with one of the plates.<sup>1</sup> The Tanner et al.<sup>25</sup> method also compares an individual with radiographic standards of skeletal maturity of "normal" children of similar age and sex. Individual bones are rated using a biological weighted scoring system to assign a "skeletal age."

The second general method of assessment of the hand-wrist radiograph uses specific indicators to relate skeletal maturation to the pubertal growth curve. This approach focuses on the maturation evaluation of the individual rather than on mean values. A number of indicators have been described in the literature including onset of calcification of the sesamoid, state of calcification of the hook of the hamate, and staging of the middle phalanges of the third finger.<sup>3,4,16,17,25-38</sup>

Bowden<sup>16</sup> described a graphical approach to determine an individual's placement on the male and female pubertal growth curve using criteria based on the ulnar, radius, carpal, metacarpals, phalanges, and the sesamoid bone. The relative growth velocity and percentage growth remaining

can be estimated. More recently, Fishman<sup>18,42,45</sup> developed a system for assessment of skeletal maturation on the basis of 11 discrete "skeletal maturity indicators (SMI)" covering the entire period of adolescent development. The indicators provide identification of progressive maturation events and are located on six anatomic sites on the thumb, third finger, fifth finger, and radius. He provided graphs and tables to estimate an individual's relative growth rate and percentage of total adolescent growth completed. These values are independent of chronological age.

A significant association between skeletal maturity and facial growth has been demonstrated.<sup>29,43,44,46,47</sup> Many studies<sup>2,35,36,44,48-51</sup> have shown an association between peak velocity of facial growth and peak velocity of statural growth during puberty. Individuals who demonstrated delayed or accelerated maturational schedules exhibited comparable delays or accelerations in skeletal maturation and facial growth.<sup>15,17,43,44,52</sup> Conversely, some studies<sup>19,24,47</sup> have shown little association between SMI and specific components of craniofacial growth. Some studies<sup>31,35,36,53-55</sup> suggest that facial growth and peak velocity of statural growth occur almost in parallel during puberty, whereas other studies<sup>18,43,44,56,57</sup> suggest that facial growth occurs later.

Because there is apparent controversy regarding the prediction capabilities of the hand-wrist analysis of skeletal maturation in determining the relative rate of facial growth and amount of unattained facial growth, a systematic review of available evidence is indicated. The purpose of this systematic review was to evaluate the prediction of facial growth from the skeletal maturity obtained from hand-wrist radiographs.

## MATERIALS AND METHODS

The following inclusion criteria were used to consider studies for this review:

- Use of hand-wrist radiographs for skeletal maturation determination.
- Facial growth evaluated through cephalometric radiographs.
- Cross-sectional and longitudinal studies.

To find the articles appropriate for this systematic review, a search was conducted in the following databases: Medline (from 1966 to week 5 of October 2002); PubMed (from 1966 to week 4 of November 2002); Cochrane Database of Systematic Reviews (to fourth Quarter 2002); Embase (from 1980 to Week 47, 2002); Web of Science (from 1975 to week 4 of November 2002); and Lilacs (from 1982 to November 2002).

Eligibility of the selected studies was determined by reading the abstracts of articles identified by the search. All the articles that seem to meet the inclusion criteria of the systematic review topic were selected and the actual articles collected. The reference lists of the retrieved articles were

**TABLE 1.** PubMed Search Strategy

No.	PubMed Search History	Results
1	Hand	165,427
2	Wrist	15,712
3	#1 and #2	5184
4	Bone development	23,597
5	Growth	810,278
6	#4 and #5	10,542
7	#3 and #6	133

also hand searched for any applicable studies that may have been missed in the database searches.

## RESULTS

Medline identified 58, PubMed 133, Cochrane Database for Systematic Reviews 0, Embase 3, Web of Science 1, and Lilacs 9 references. Almost all the references from the Medline, Embase, and Web of Science search were already found in the PubMed search (Table 1). None of the Lilacs references was in the PubMed search.

Sixteen articles, which fulfilled the selection criteria, were identified. From these, five were rejected because of methodological issues as stated in Table 2. A summary of the sample size and origin, study design and method of skeletal maturity analysis used from each of the 11 selected studies is presented (Table 3).

Bambha and van Natta<sup>29</sup> evaluated S-Gn length as a measure of overall facial growth. They reported that overall facial growth was consistently related to skeletal age and concluded that individuals who tend to mature early with advanced skeletal maturity have an early adolescent facial growth spurt, whereas children with retarded skeletal maturity tend to mature later.

Hunter<sup>35</sup> described that the maximum overall vertical facial growth (N-M) was coincident with maximum standing height growth velocity. In 88.3% of males a small amount of vertical facial growth occurred after skeletal maturation. A modest correlation ( $r = 0.76$ ) was found between mandibular growth rate (Ar-Po) and standing height growth velocity during the pubertal growth spurt in males and females. The absolute rate of growth of the mandible was greater in males, and mandibular growth continued after the end of the pubertal growth spurt in males. There was no difference in the rate of growth or in the absolute facial growth in the pubertal growth period among early, normal, and late developers.

Tofani<sup>15</sup> evaluated the annual growth changes in mandibular length, ramus height, and corpus length related to standing height growth velocity and skeletal maturity. There was a significant but modest correlation of onset of distal phalanges fusion with peak overall growth velocity in mandible length ( $r = 0.53$ ), ramus height ( $r = 0.60$ ), and body length ( $r = 0.71$ ).

Bergersen<sup>36</sup> evaluated change in facial growth velocity in

**TABLE 2.** Studies That Fulfilled Selection Criteria But Were Rejected

Authors	Reason to Reject
Rose <sup>46</sup>	Hand-wrist radiograph skeletal maturity analysis not described
Johnston et al <sup>2</sup>	Two-year interval between some subjects' records
Brown et al <sup>53</sup>	Methodology and sample similar to the study published by Grave <sup>31</sup>
Lewis and Roche <sup>49</sup>	11 subjects had missing radiographs
Arat et al <sup>62</sup>	Helm et al <sup>50</sup> criteria for skeletal maturity in males was used for a combined male-female sample

males during the two-year period of maximum standing height growth velocity (pubertal growth spurt). He considered the increases in maxillary length (S-ANS), upper anterior face height (N-ANS), lower anterior face height (ANS-Me), and cranial base (S-N) growth increments too small ( $<0.75$  mm/year) to be distinguished as a growth spurt. Total anterior face height (N-Me) and overall facial length (S-Go) did demonstrate growth spurts correlated with the pubertal growth spurt.

Pileski et al<sup>37</sup> evaluated mandibular growth (Co-symphysis point) from 45° oblique lateral skull radiographs. Peak mandibular growth velocity was preceded by the appearance of the sesamoid by 0.72 years in males and 1.09 years in females. Although statistically significant, the correlations were weak for males ( $r = 0.43$ ) and females ( $r = 0.36$ ).

Grave<sup>31</sup> reported that the peak overall vertical facial growth velocity (N-Gn) had moderately high correlations in males ( $r = 0.83$ ) and females ( $r = 0.84$ ) with peak standing height growth velocity. There were significant correlations (male,  $r = 0.87$ ; female,  $r = 0.76$ ) between peak growth velocities of the anterior cranial base (S-N) and peak growth velocities in standing height. The timing of ossification of the sesamoid was moderately weakly correlated to peak growth velocity of the anterior cranial base in males ( $r = .056$ ) and modestly correlated in females ( $r = 0.71$ ). Growth velocity in mandibular length (Ar-Pg) was significantly related to peak growth in standing height with moderately high correlations (males,  $r = 0.78$ ; females,  $r = 0.79$ ). In males, the only ossification event significantly related to mandibular growth velocity was the sesamoid with a moderately weak correlation ( $r = 0.52$ ). In females, ossification of the pisiform, hamate-1, hamate-2, and sesamoid were all significantly related to mandibular growth velocity with modestly weakly correlations ( $r = 0.51$ – $0.60$ ). Maxillary horizontal growth velocity was significantly correlated with peak standing height growth velocity in females ( $r = 0.76$ ) but not in males. There was a significant but moderate correlation between maxillary horizontal growth velocity and ossification of hamate-1, hamate-2, and sesamoid in females. There was a significant

**TABLE 3.** Studies Included for Review That Fulfill Selection Criteria

Authors	Sample	Sample Randomization Reported	Method Error Reported	Sample Origin	Skeletal Age Analysis
Bambha and van Natta <sup>29</sup>	22 female and 28 male; 9.9–18.9 years	No	No	Caucasians, Denver sample	Greulich and Pyle
Hunter <sup>35</sup>	34 female and 25 male; 7–18 years	Entire available population	Yes	Caucasians, Denver sample	Greulich and Pyle
Tofani <sup>15</sup>	20 female; 9–18 years	No	No	Caucasians, Case Western sample	Greulich and Pyle
Bergersen <sup>36</sup>	23 male; 0.1–24.4 years	No	No	Caucasians, Denver sample	Greulich and Pyle
Pilecki et al <sup>37</sup>	91 female and 108 male	No	No	Caucasians, Burlington sample	Custom method (sesamoid bone)
Grave <sup>31</sup>	36 female and 52 male; 8–18 years	No	No	Australian aboriginals, Yuendumu sample	Custom method (calcification events)
Fishman <sup>17</sup>	68 female and 60 male; 7.5–15 years	No	No	Not specified	Greulich and Pyle, Tanner and Whitehouse 2
Fishman <sup>18</sup>	756 female and 746 male; 0–25 years	No	No	Own practice, Denver, Rochester and Connecticut samples	Custom method (SMI stages)
Moore et al <sup>41</sup>	47 female and 39 male; 10–16 years	No	Yes	Case Western sample	Tanner and Whitehouse 2
Silveira et al <sup>58</sup>	34 female and 36 male; 11–22 years	No	No	Own practice and Rochester sample	Fishman method (SMI stages)
Sato et al <sup>59</sup>	22 female; 8–17 years	No	Yes	Japanese, origin not specified	Tanner and Whitehouse 2 and CSMAS

but moderate correlation between maxillary horizontal growth velocity and ossification of pisiform and hamate-1 in males. This infers some gender difference in timing of peak maxillary horizontal growth velocity.

Fishman<sup>17,18</sup> presented 11 SMI from hand-wrist radiographs and noted that the growth curves for standing height and facial growth related to skeletal maturity were not bell shaped. There was more rapid growth velocity increase leading up to peak growth velocity and more gradual decline after peak growth velocity. The asymmetry of the growth curve was more pronounced in females. There was close correlation between both maxillary (S-A) and overall mandibular growth rate (Ar-Gn) with skeletal maturation. There was an acceleration of maxillary and mandibular growth between SMI stages 6 and 7. There was a deceleration of maxillary and mandibular growth between SMI stages 7 and 9, where growth velocity leveled off. Males and females completed similar percentages of total growth at comparable SMI stages. At level SMI 6, approximately 50% of total adolescent maxillary and mandibular growth was completed.

Moore et al<sup>41</sup> evaluated growth measures against levels of skeletal age. The correlations between increase in standing height and stage of skeletal maturity were significantly but modestly correlated. There was a significant deceleration of overall anterior face height (N-Me) and mandibular body length (Go-Gn) in females between TW2 RUS skeletal ages 11- to 12-year and 13- to 14-year intervals. There was a significant acceleration of anterior face height, posterior face height (S-Go), and mandibular body length in

males between 11 to 12-year and 13- to 14-year intervals, and there was a significant deceleration between 13- to 14- and 15- to 16-year intervals. These correlations, however, were weak ( $r = 0.29$ – $0.49$ ). The velocity of posterior face height (S-Go) was not significantly different between TW2 RUS skeletal age groups in females. A significant correlation between anterior cranial base growth rate (S-N) and skeletal maturity for males or females was not identified.

Silveira et al<sup>58</sup> reported that the overall facial growth (S-Gn, S-A), horizontal maxillary growth increments (Ar-A), overall mandibular growth increments (Ar-Gn), and mandibular body length (Go-Po) were significantly larger in late maturers compared with average and early maturers. These differences were consistent throughout the different stages of Fishman's SMI (SMI 8–11, 9–11, and 10–11). Vertical growth rate of the ramus (Ar-Go) did not differ between early and late maturers. Finally, he reported that during the late stages of the pubertal growth spurt in average and late maturers, mandibular growth increments were significantly larger than maxillary growth increments. The maxilla showed a greater percentage of growth completion than the mandible until the final stage when mandibular growth tended to catch up.

Sato et al<sup>59</sup> compared several methods for the prediction of the mandibular (total length) growth potential: an ossification events method (based on third middle phalanx and radius), a growth potential method (based on TW2 and CSMAS bone age), a growth percentage method (based on TW2 and CSMAS bone age), a multiple regression method (based on chronological age, present length, and

bone age), and a growth chart method (based on average final mandible length for the sample multiplied by the SD of the present length calculated according to bone age). The average error between predicted final mandible length and actual length varied from 1.15 to 4.22 mm. From all these methods, the growth potential and the growth percentage had the best predictive values.

## DISCUSSION

Chronological age is not a valid predictor of skeletal growth velocity or skeletal maturity.<sup>2,15-17,19,20,60</sup> Sexual dimorphism is well documented,<sup>4,28</sup> and there is a wide range of individual variability in timing of periods of increased growth velocity.<sup>45</sup> The validity of skeletal maturity assessment using the hand-wrist radiograph in relation to overall skeletal growth velocity (standing height) has been well established and has been validated for several racial groups.<sup>20,21,32,38,40,44,50,60</sup> Correlation of skeletal age determined with the Greulich and Pyle<sup>27</sup> atlas and the Tanner et al.<sup>25</sup> analysis is good. However, interpretation of skeletal age requires the clinician or researcher to relate the published "norm" back to the population from which the case or sample in question is drawn, and that is not always available or possible. Secular trends are evident with successive generations becoming taller and reaching puberty at earlier stages.<sup>17</sup> Staging of skeletal maturity by describing relationships of specific features with the hand-wrist radiograph, such as initial ossification of the sesamoid and capping events of the phalanges, offer a useful alternative to skeletal aging.

Caution should be exercised in the application of the results presented in this review. Publications that presented methodological deficiencies, which would likely compromise the integrity of reported results, were excluded from this review. Unfortunately, most of the studies investigating the use of hand-wrist radiographic analysis of skeletal maturity were published before reporting of randomization, blinding, and method error were required. There are some further limitations in the interpretation of skeletal maturity from hand-wrist radiographs. Polymorphism in the sequence is common, and agenesis of some hand and wrist bones have been reported.<sup>40</sup> Estimation of the base growth line could be quite variable<sup>36</sup>; and even in databases with semiannual records, measurements of change in growth velocity are still gross estimations of onset of periods of growth acceleration, periods of growth deceleration, and peak growth velocity.<sup>19,34,41</sup> Most of the studies included in this review were based on annual records with relatively small sample sizes.<sup>15,29,31,36,37,41,49</sup> Only the Fishman<sup>17,18</sup> and Silveira et al.<sup>58</sup> articles used semiannual records, but these studies included treated orthodontic cases.

The validity of hand-wrist skeletal maturity in the evaluation of craniofacial growth has been questioned. Moore<sup>1</sup> pointed out that most of the bones of the body are pre-

formed in cartilage and develop by endochondral ossification. The bones of the face are formed by intramembranous ossification without cartilaginous precursors. Growth of the face may be regulated by factors other than those responsible for growth of the long bones. Furthermore, the craniofacial structures include several functional regions, which may have different growth responses to systemic and local environmental conditions. Overall facial growth has been assessed by chin position relative to the cranial base (S-Gn), which includes change in mandible length, and cranial base changes with relocation of the glenoid fossa. Vertical facial growth (N-M) with rotation of the mandible could also influence S-Gn length. Despite this limitation, all the articles included in this review reported that overall facial growth velocity was well related to standing height growth velocity and skeletal maturity. There was sexual dimorphism, and the overall facial growth curve was not bell shaped.<sup>1</sup> Fishman<sup>18</sup> reported that there was a rapid acceleration to peak growth velocity and a more progressive decline. This observation was more pronounced in females. The growth curves included in the Moore et al.<sup>41</sup> article show similar acceleration and deceleration, but the correlation between skeletal maturity and overall facial growth was not significant in females and only weakly correlated in males. It is possible that the Tanner et al. TW2 RUS analysis used by Moore was less sensitive than the SMI analysis developed by Fishman.

Fishman<sup>17,18</sup> reported close association between horizontal maxillary growth and skeletal maturity with no significant gender difference at specific stages of skeletal maturity. Grave<sup>31</sup> reported moderate but different correlations between specific hand-wrist ossification events and horizontal maxillary growth in males and females. He suggested that there might be some gender difference in timing of peak maxillary growth. The discrepancy between the findings of Fishman<sup>17,18</sup> and Grave<sup>31</sup> may be attributed to differences in the databases. The Fishman studies used semiannual records, whereas the study by Grave was based on annual records of a smaller sample.

The studies included in this review reported significant correlations (but variable correlation strength) between skeletal maturity and mandibular growth velocity. These findings are consistent with those of most other publications, which identify correlation of varying strengths between mandibular growth and standing height growth velocity.<sup>55,56,61</sup> Growth of mandibular body length was more closely correlated to skeletal maturity than to growth of ramus height.<sup>15,58</sup>

Data from the articles included in this review does not allow meaningful conclusions regarding the relationship of cranial base growth velocity and skeletal maturity. Growth increments in the anterior cranial base are small, and measurement error could explain the differences reported by Grave<sup>31</sup> and Moore et al.<sup>41</sup>

The relevance of the data presented in this systematic

review will depend on intended use of skeletal maturity assessment from hand-wrist radiographs. The primary clinical application of hand-wrist skeletal maturity assessment is to predict the timing of the pubertal growth spurt to take advantage of orthopedic treatment modalities. Although it is very clear that average growth curves based on chronological age are so variable that they are irrelevant, caution should be exercised in the application of hand-wrist skeletal maturity assessment. If advantage is to be taken of the growth spurt, it is necessary to be able to predict the onset several years in advance. The prediction improves as the age of the growth spurt is approached, which may necessitate repeated radiographic evaluation. The use of individual ossification events is of limited use in predicting the pubertal growth spurt,<sup>34</sup> and analyses that include bone stages as well as ossification events are recommended.

Hand-wrist radiographic assessment of skeletal maturity is a valuable tool in orthodontic research. Analysis approaches, such as the one described by Fishman,<sup>18,42,45</sup> which are based on relative growth velocity and percentage of growth remaining are more useful than analysis that yields a skeletal age. Avoidance of a skeletal age minimizes the influence of environment and racial composition of the sample. In most cases, use of relative growth rate and percentage growth remaining will resolve gender differences.

As recommended by Sato et al,<sup>59</sup> the accuracy of predicting growth may be improved if other parameters (morphologic, biological, or genetic indicators), in addition to hand-wrist radiographic evaluation are used.

In some research situations, it is not possible or feasible to use skeletal maturity as inclusion criteria. Obtaining hand-wrist radiographs to determine suitability for a particular study may create difficulties in recruitment and ethics approval. In some research endeavors, subject availability will limit sample size and rigorous application of skeletal maturity for inclusion may render the study impossible to complete. In some research conditions, the time interval between data collection is not consistent, and the total magnitude of growth will vary between subjects. Use of regression models with relative growth velocity and percentage growth remaining will allow the researcher to "factor out" the influence of growth in the overall dimensional change of interest.

## CONCLUSIONS

1. The overall horizontal and vertical facial growth velocity is related to SMI determined by analysis of hand-wrist radiographs.
2. Maxillary and mandibular growth velocities are related to skeletal maturity, but the correlations are less robust than those for overall facial growth velocity.
3. The available articles have not adequately defined a relationship between cranial base growth velocity and skeletal maturity.

4. Skeletal maturity analysis of hand-wrist radiographs for use in predicting facial growth velocity should include bone staging as well as ossification events.

## REFERENCES

1. Moore RN. Principles of dentofacial orthopedics. *Semin Orthod.* 1997;3:212–221.
2. Johnston FE, Hufham HP Jr, Moreschi AF, Terry GD. Skeletal maturation and cephalofacial development. *Angle Orthod.* 1965; 35:1–11.
3. Demirjian A, Buschang PH, Tanguay R, Patterson DK. Interrelationships among measures of somatic, skeletal, dental, and sexual maturity. *Am J Orthod.* 1985;88:433–438.
4. So LL. Skeletal maturation of the hand and wrist and its correlation with dental development. *Aust Orthod J.* 1997;15:1–9.
5. Marshall D. Radiographic correlation of hand, wrist, and tooth development. *Dent Radiogr Photogr.* 1976;49:51–72.
6. Coutinho S, Buschang PH, Miranda F. Relationships between mandibular canine calcification stages and skeletal maturity. *Am J Orthod Dentofacial Orthop.* 1993;104:262–268.
7. Mappes MS, Harris EF, Behrents RG. An example of regional variation in the tempos of tooth mineralization and hand-wrist ossification. *Am J Orthod Dentofacial Orthop.* 1992;10:145–151.
8. Chertkow S. Tooth mineralization as an indicator of the pubertal growth spurt. *Am J Orthod.* 1980;77:79–91.
9. Leinonen A, Wasz-Hockert B, Vuorinen P. Usefulness of the dental age obtained by orthopantomography as an indicator of the physical age. *Proc Finn Dent Soc.* 1972;68:235–242.
10. Bambha JK, van Natta MA. A longitudinal study of occlusion and tooth eruption in relation to skeletal maturation. *Am J Orthod.* 1959;847–855.
11. Sahin Saglam AM, Gazilerli U. The relationship between dental and skeletal maturity. *J Orofac Orthop.* 2002;63:454–462.
12. Liebgott B. Dental age: its relation to skeletal age and the time of peak circumpuberal growth in length of the mandible. *Dent J.* 1978;44:223–227.
13. Krailassiri S, Anuwongnukroh N, Dechkunakorn S. Relationships between dental calcification stages and skeletal maturity indicators in Thai individuals. *Angle Orthod.* 2002;72:155–166.
14. Mitani H. Occlusal and craniofacial growth changes during puberty. *Am J Orthod.* 1977;72:76–84.
15. Tofani MI. Mandibular growth at puberty. *Am J Orthod.* 1972; 62:176–195.
16. Bowden BD. Epiphysial changes in the hand/wrist area as indicators of adolescent stage. *Aust Orthod J.* 1976;4:87–104.
17. Fishman LS. Chronological versus skeletal age, an evaluation of craniofacial growth. *Angle Orthod.* 1979;49:181–189.
18. Fishman LS. Radiographic evaluation of skeletal maturation. A clinically oriented method based on hand-wrist films. *Angle Orthod.* 1982;52:88–112.
19. Houston WJ. Relationships between skeletal maturity estimated from hand-wrist radiographs and the timing of the adolescent growth spurt. *Eur J Orthod.* 1980;2:81–93.
20. Kimura K. Growth of the second metacarpal according to chronological age and skeletal maturation. *Anat Rec.* 1976;184:147–157.
21. Hägg U, Taranger J. Skeletal stages of the hand and wrist as indicators of the pubertal growth spurt. *Acta Odontol Scand.* 1980;38:187–200.
22. Garcia-Fernandez P, Torre H, Flores L, Rea J. The cervical vertebrae as maturational indicators. *J Clin Orthod.* 1998;32:221–225.
23. Mito T, Sato K, Mitani H. Cervical vertebral bone age in girls. *Am J Orthod Dentofacial Orthop.* 2002;122:380–385.

24. Ruf S, Pancherz H. Development of the frontal sinus in relation to somatic and skeletal maturity. A cephalometric roentgenographic study at puberty. *Eur J Orthod.* 1996;18:491–497.
25. Tanner JM, Whitehouse RH, Cameron N, Marshall WA, Healy MJR, Goldstein H. *Assessment of Skeletal Maturity and Prediction of Adult Height (TW2 Method)*. 2nd ed. London: Academic Press; 1983.
26. Falkner F, Tanner JM. *Human Growth*. New York, NY: Plenum Press; 1978:1–3.
27. Greulich WW, Pyle SI. *Radiographic Atlas of Skeletal Development of Hand and Wrist*. 2nd ed. Stanford, Calif: Stanford University Press; 1959.
28. Björk A, Helm S. Prediction of the age of maximum pubertal growth in body height. *Angle Orthod.* 1967;37:134–143.
29. Bambha JK, van Natta MA. Longitudinal study of facial growth in relation to skeletal maturation during adolescence. *Am J Orthod.* 1963;39:481–493.
30. Chapman SM. Ossification of the adductor sesamoid and the adolescent growth spurt. *Angle Orthod.* 1972;42:236–244.
31. Grave KC. Timing of facial growth: a study of relations with stature and ossification in the hand around puberty. *Aust Orthod J.* 1973;3:117–122.
32. Grave KC, Brown T. Skeletal ossification and the adolescent growth spurt. *Am J Orthod.* 1976;69:611–619.
33. So LL. Correlation of sexual maturation with skeletal age of southern Chinese girls. *Aust Orthod J.* 1997;14:215–217.
34. Houston WJ, Miller JC, Tanner JM. Prediction of the timing of the adolescent growth spurt from ossification events in hand-wrist films. *Br J Orthod.* 1979;6:145–152.
35. Hunter CJ. The correlation of facial growth with body height and skeletal maturation at adolescence. *Angle Orthod.* 1966;36:44–54.
36. Bergersen EO. The male adolescent facial growth spurt: its prediction and relation to skeletal maturation. *Angle Orthod.* 1972;42:319–338.
37. Pileski RC, Woodside DG, James GA. Relationship of the ulnar sesamoid bone and maximum mandibular growth velocity. *Angle Orthod.* 1973;43:162–170.
38. Bowden BD. Sesamoid bone appearance as an indicator of adolescence. *Aust Orthod J.* 1971;2:242–248.
39. Smith RJ. Misuse of hand-wrist radiographs. *Am J Orthod.* 1980;77:75–78.
40. Garn SM, Rohmann CG, Blumenthal T. Ossification sequence polymorphism and sexual dimorphism in skeletal development. *Am J Phys Anthropol.* 1966;24:101–115.
41. Moore RN, Moyer BA, DuBois LM. Skeletal maturation and craniofacial growth. *Am J Orthod Dentofacial Orthop.* 1990;98:33–40.
42. Fishman LS. Chapter 13. In: Subtelny JD. *Early Orthodontic Treatment*. Chicago, Ill: Quintessence Publishing Co; 2000: 265–285.
43. Bambha JK. Longitudinal cephalometric roentgenographic study of face and cranium in relation to body height. *J Am Dent Assoc.* 1961;63:776–799.
44. Nanda RS. The rates of growth of several facial components measured from serial cephalometric roentgenograms. *Am J Orthod.* 1955;41:658–673.
45. Fishman LS. Maturation patterns and prediction during adolescence. *Angle Orthod.* 1987;57:178–193.
46. Rose GJ. A cross-sectional study of the relationship of facial areas with several body dimensions. *Angle Orthod.* 1960;30:6–13.
47. Meredith HV. Childhood interrelations of anatomic growth rates. *Growth* 1962;26:23–39.
48. Singh IJ, Savara BS, Miller PA. Interrelations of selected measurements of the face and body in pre-adolescent and adolescent girls. *Growth* 1967;31:119–131.
49. Lewis AB, Roche AF. Elongation of the cranial base in girls during pubescence. *Angle Orthod.* 1972;42:358–367.
50. Helm S, Siersbaek-Nielsen S, Skieller V, Björk A. Skeletal maturation of the hand in relation to maximum pubertal growth in body height. *Tandlaegebladet* 1971;75:1223–1234.
51. Singer J. Physiologic timing of orthodontic treatment. *Angle Orthod.* 1980;50:322–333.
52. Burstone CJ. Process of maturation and growth prediction. *Am J Orthod.* 1963;49:907–919.
53. Brown T, Barrett MJ, Grave KC. Facial growth and skeletal maturation at adolescence. *Tandlaegebladet* 1971;75:1211–1222.
54. Lewis AB, Roche AF, Wagner B. Pubertal spurts in cranial base and mandible. Comparisons within individuals. *Angle Orthod.* 1985;55:17–30.
55. Bishara SE, Jamison JE, Peterson LC, DeKock WH. Longitudinal changes in standing height and mandibular parameters between the ages of 8 and 17 years. *Am J Orthod.* 1981;80:115–135.
56. Baughan B, Demirjian A, Levesque GY, Lapalme-Chaput L. The pattern of facial growth before and during puberty, as shown by French-Canadian girls. *Ann Hum Biol.* 1979;6:59–76.
57. Seide LJ. The relationship of dentofacial and skeletal maturation to malocclusion. *Am J Orthod.* 1959;45:801–816.
58. Silveira AM, Fishman LS, Subtelny JD, Kassebaum DK. Facial growth during adolescence in early, average and late maturers. *Angle Orthod.* 1992;62:185–190.
59. Sato K, Mito T, Mitani H. An accurate method of predicting mandibular growth potential based on bone maturity. *Am J Orthod Dentofacial Orthop.* 2001;120:286–293.
60. Hägg U, Taranger J. Maturation indicators and the pubertal growth spurt. *Am J Orthod.* 1982;82:299–309.
61. Thompson GW, Popovich F. Relationship of mandibular measurements to stature and weight in humans. *Growth* 1974;38:187–196.
62. Arat M, Koklu A, Ozdiler E, Rubenduz M, Erdogan B. Craniofacial growth and skeletal maturation: a mixed longitudinal study. *Eur J Orthod.* 2001;23:355–361.