ACTA ODONTOLOGICA SCANDINAVICA
2023, VOL. 81, NO. 6, 464–472
https://doi.org/10.1080/00016357.2023.2176920

Taylor & Francis
Taylor & Francis Group

ORIGINAL ARTICLE

Check for updates

Association between dental and skeletal maturation in Scandinavian children born between 2005 and 2010

Astrid Rathcke Poulsen and Liselotte Sonnesen

Department of Odontology, Section of Orthodontics, Faculty of Health and Medical Sciences, University of Copenhagen, Copenhagen, Denmark

ABSTRACT

Objective: The aim of this cross-sectional study was to analyse the association between dental and skeletal maturation in children born between 2005 and 2010.

Materials and methods: Dental and skeletal maturation of 117 ethnic Scandinavian children born between 2005 and 2010 (70 girls, 47 boys, mean age 11.48 years) was analysed. Dental maturation (DM) was assessed on orthopantomographs (OPs) by using Demirjian's and Haavikko's methods while skeletal maturation was assessed on hand-wrist radiographs by use of Helm's method. The correlation between skeletal and DM was analysed using Spearman's rho (*R*s). Additionally, the most frequent DM stage in relation to the skeletal maturation stage was analysed by logistic regression adjusted for age and sex.

Results: The correlation between dental and skeletal maturation was significant for all teeth ($Rs = 0.071–0.562$; $p < .000–p = .035$) except for the first incisor and the first molar. Logistic regression analysis showed that when the mandibular and maxillary canines are ¾ mineralized, this is significantly associated with the beginning of the adolescent period before peak height velocity (PHV) (PP2= $p < .005–< .05$). Likewise, when the mandibular second premolars are ¾ mineralized, this is significantly associated with the maturation stage PP2= or S (PP2= $p < .05$, S: $p < .005–< .05$), both of which are before PHV at the beginning of the adolescent period.

Limitations: Limited sample size and the X-rays were taken before orthodontic treatment, which may have introduced a selection bias.

Conclusions: When the root of the canines or second premolars is ¾ mineralized, it may indicate the beginning of the adolescent period with increased skeletal growth intensity.

ARTICLE HISTORY
Received 10 May 2022
Revised 30 January 2023
Accepted 31 January 2023

KEYWORDS
Dental maturation; skeletal maturation; Haavikko's method; Demirjian's method; Helm's method

Introduction

The speed with which children physically mature has increased substantially in the past century, which has likely, among other things, been caused by vast improvements in living standards and nutritional intake [1–6]. Not only has the growth within the peak height velocity (PHV) increased, but children now reach the PHV at an earlier age than in previous generations [1]. Furthermore, studies have confirmed that the velocity of dental maturation (DM) has increased during the past decades [2,3,7]. Consensus is yet to be reached regarding whether dental development is mostly driven by genetics [8], or by external factors, such as nutritional intake and living standards [3,9,10]. Both internal and external factors do, however, appear to affect dental development as high energy intake may be correlated with advanced DM [2,7], while agenesis, syndromes, growth deficiencies, and endocrine disorders may be correlated with delayed DM [2,11,12]. As both genetics, geography and living conditions may affect the velocity of maturation, the association between DM and SM in Scandinavia may differ from other parts of the world [13].

Some previous studies found no association between DM and SM [11,14,15], while one previous study did suggest a correlation between SM and DM [16]. However, several recent studies have found a relationship between SM and DM [6,17–28]. There is, however, a lack of consensus regarding the strength of the association and consequently not consensus on whether DM should be used as a diagnostic tool for estimating the timing of pubertal growth. Some studies have investigated this aspect and concluded that tooth development is not a reliable indicator of SM as the association between DM and SM is too weak [17,27–30], while other studies have found that DM can be used as an indicator of SM [6,18–22,24–26]. Although the question has been a topic of research interest in the past years, evidence from recent Scandinavian settings have so far remained limited.

Thus, this study utilizes a recent dataset consisting of hand-wrist radiographs and orthopantomographs (OPs) of present-day ethnic Scandinavian children. The children were born in the period 2005–2010, and the radiographs were obtained in 2013–2020. The aim of the study was to estimate

CONTACT Liselotte Sonnesen alson@sund.ku.dk Department of Odontology, Section of Orthodontics, Faculty of Health and Medical Sciences, University of Copenhagen, Copenhagen, Denmark

the correlation between DM and SM in a recent Scandinavian setting based on hand-wrist radiographs, which to the best of our knowledge is a novel contribution. Furthermore, the study aimed to investigate whether specific teeth can inform practitioners of the SM stage. As both DM and SM are influenced by age and sex [1,31,32], the analysis was adjusted for the effects of age and sex. To our knowledge this study is the first to take sex and age effects into account in the assessment of the association between DM and SM.

Materials and methods

The data consisted of hand-wrist radiographs and OPs from 117 Danish children, consisting of 70 girls (mean age 11.28 years, range 8.0–13.85 years at OP and hand-wrist) and 47 boys (mean age 11.98 years, range 9.66–14.75 years at OP and hand-wrist). The subjects were systematically collected from a group of 468 children born in the period between 2005 and 2010 (cf. Figure 1) prior to orthodontic treatment at the Postgraduate Education of Orthodontics, Department of Odontology, University of Copenhagen, Denmark (UC-ODON). The data was obtained between 2013 and 2020 and included all children that satisfied the inclusion and exclusion criteria outlined in Figure 1. The inclusion criteria were: healthy; ethnic Scandinavian in the age between 7 and 15 years [5,32]. The exclusion criteria were: growth anomalies; dentition abnormalities; crowding; children in current or previous hormone treatment; yet to reach SM stage PP2= were in the SM stages PP3u and MP3u; insufficient radiograph quality [31,33] (Figure 1). The applied inclusion and exclusion criteria followed previous specified criteria for use of the methods in this study [31,33,34]. The additional exclusion criteria with regards to SM stages were applied to ensure clinical relevance.

The study followed the ethical standards of the 1964 Helsinki declaration and its subsequent revisions. All X-rays were taken before orthodontic treatment as part of the diagnostics and treatment plan prior to orthodontic treatment in line with guidelines from the Danish Ministry of Health. Informed consent was obtained the day the X-ray was taken. The protocol was approved by The Danish Data Protection Agency (J.No: 514-0548/20-3000).

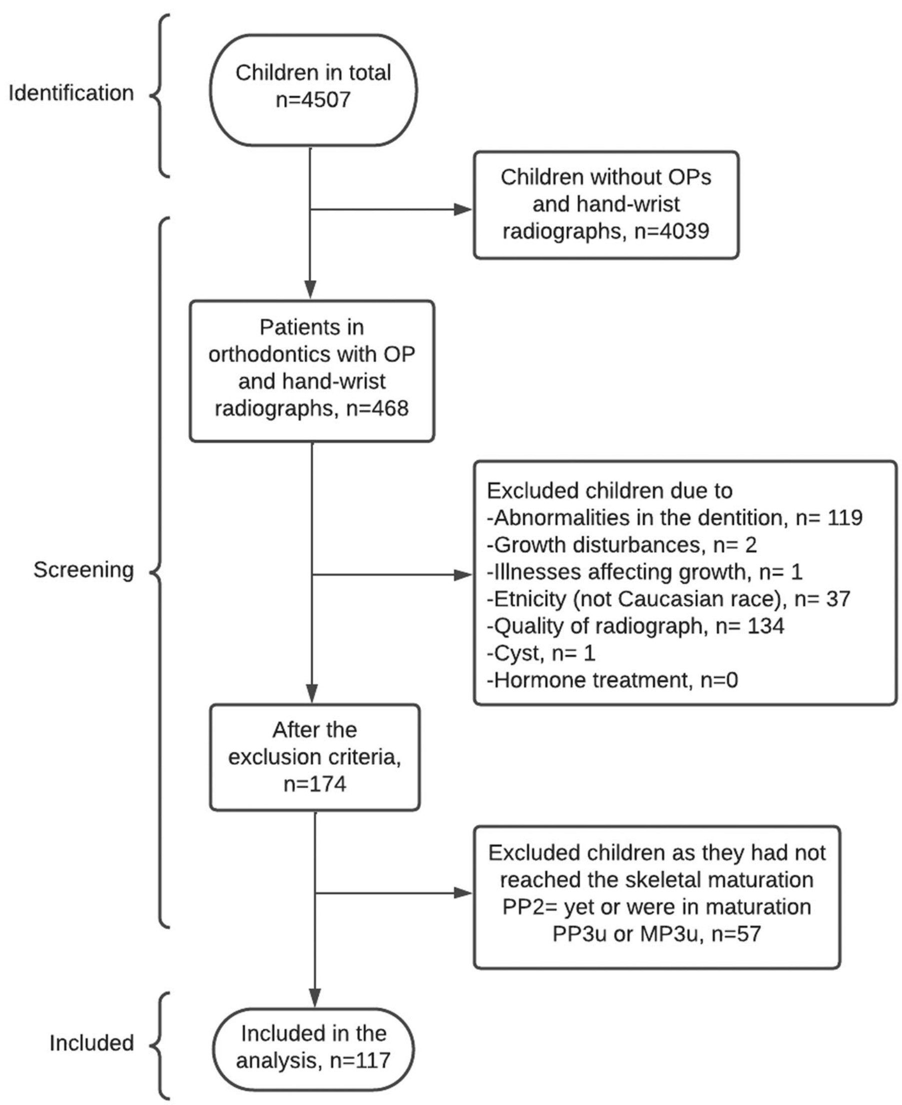

Figure 1. Flowchart of the included children born 2005–2010.

Table 1. Description of the dental maturation stages according to Demirjian and Haavikko [33,34].

Maturation	Description
Demirjian maturation stages	
A	Calcified dots in the upper part
B	Calcified dots have merged and form cusps
C	The enamel formation of the occlusal surface is complete and dentin formation has begun
D	Crown formation till enamel-cement formation is complete and root formation has begun
E	Further root formation, but the root is still shorter than the crown
F	The root is the same length or longer than the crown
G	The root formation is complete, but the apex is not closed
H	Apex is closed
Haavikko maturation stages	
O	Crypt is formed, and no calcification is visible
C_i	Calcified dots in the upper part
C_{CO}	Calcified dots have merged and form cusps
$Cr_{1/2}$	Crown half formed
$Cr_{3/4}$	Crown 3/4 formed
Cr_C	Crown formation complete
R_i	Root formation has begun
$R_{1/4}$	Root 1/4 formed
$R_{1/2}$	Root 1/2 formed
$R_{3/4}$	Root 3/4 formed
R_c	Root formation complete
A_c	Apex closed

Table 2. Description of the skeletal maturation stages according to Helm et al. [31].

Helm et al. maturation stages	
Maturation	Description
PP2=	The width of the epiphysis is equal to its diaphysis on the proximal phalanx of the second finger.
MP3=	The width of the epiphysis is equal to its diaphysis of the middle phalanx of the third finger.
S	The ulnar sesamoid by the metacarpophalangeal joint on the first finger is visible.
$MP3_{CAP}$	The epiphysis disc on the middle phalanx of the third finger sharpens at the ends and curves upwards.
DP3u	Complete fusion of epiphysis and diaphysis on the distal phalanx of the third finger.
PP3u	Complete fusion of the epiphysis and diaphysis on the proximal phalanx of the third finger
MP3u	Complete fusion of epiphysis and diaphysis on the middle phalanx of the third finger.

Method

The analyses were performed by an examiner who was trained and calibrated by an experienced examiner before the assessment of the DM and SM.

Dental maturation

DM was determined from OP by both Demirjian's and Haavikko's methods to examine maturity *via* various methods [33,34]. OPs were taken with a Planmeca ProMax 3D Max system prior to orthodontic treatment. The radiographs were digitized (ArionG4, Pro Curis AB, Lund, Sweden) and analysed on a digital display. The examiner was blinded with regard to information about age and sex.

Demirjian's method was implemented by assessing the degree of mineralization for each permanent tooth in the left side of the mandible except for the third molar [34]. The maturation stage was set on a scale of 8 stages (A–H) (Table 1). For Haavikko's method, the permanent dentition of both the mandible and maxilla were assessed based on 12 maturation stages (O–A_C), 6 of which described the crown formation while the other 6 described the root formation [33] (Table 1). Each tooth was then given a maturation stage, which was represented in a numerical value ranging from 1 to 12 (O–A_C) [33].

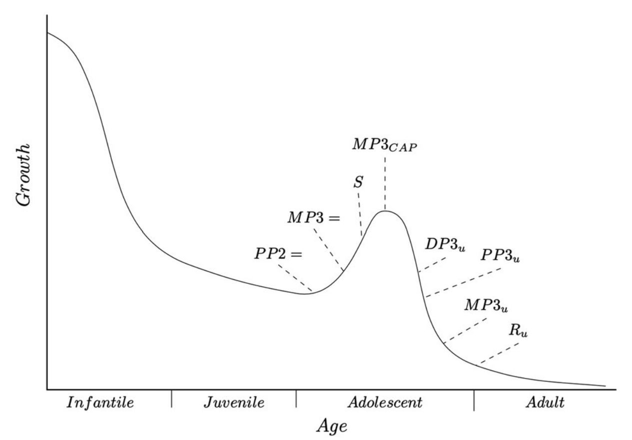

Figure 2. Illustration of the maturation stages of the hand on the growth curve in relation to age [31].

Skeletal maturation

SM was assessed on hand-wrist radiographs by Helm's method [31]. Hand-wrist radiographs of the right hand were taken in a cephalostat (Planmeca ProMax® cephalostat) with a focus-film distance of 170 cm on a non-screen film, no grid: 60–62 kV according to Greulich and Pyle [35]. The radiographs were digitized (ArionG4, Pro Curis AB, Lund, Sweden) and visually assessed on a digital display. The examiner was blinded for information of sex and age. The hand-wrist radiographs were classified into seven stages of hand ossification, representing the SM stage of the child (Table 2, Figure 2). Only the SM stages PP2=, MP3=, S, $MP3_{CAP}$ and DP3u were included in the analysis as these maturation stages are of clinical interest in the planning of orthodontic treatments.

Statistical analyses

SPSS version 28.0 (IBM, Inc, Chicago, IL) was used for the statistical analysis. The significance level was set to 5% ($p < .05$). Quantile–Quantile plots (Q–Q-plots) indicated that data were normally distributed. The correlation between DM and SM was analysed by Spearman's rho (R_S). The frequencies of DM stages in relation to each of the SM stages were noted for each tooth. Furthermore, the most frequent DM stage in relation to the SM stages was analysed by logistic regression adjusted for age and sex except from Demirjian stage H and Haavikko stage Ac. The SM stage was entered as the dependent variable while the DM stage of the tooth of interest was entered along with age and sex as an explanatory variable. DM stages corresponding to a closed apex were not included in the logistic regression analysis, as the exact timing of this event was unknown.

Reliability

The intra-reliability of SM and DM stages were assessed by re-analysing 25 OPs and hand-wrist radiographs after a week. The intra-reliability assessed by Cohen's Kappa [36] was 0.96 and 0.94, which corresponds to a high degree of intra-reliability [36]. Moreover, there was no instance of discrepancy greater than one maturation stage between the two evaluations. In instances where the assessments were not identical, the OPs or hand-wrist radiographs were assessed by both authors and discussed until coming to an agreement.

Results

Overall, the DM stages of all teeth were significantly and positively correlated with the SM stage ($Rs = 0.071–0.562$;

Table 3. Dental maturation of teeth as assessed according to Demirjian in relation to the different skeletal maturation stages.

T	SM			DM *n* (%)				CC	
		D	E	F	G	H	Total	R_S	*p*
I1								–	–
	PP2=	–	–	–	–	18 (100.0)	18 (100.0)		
	MP3=	–	–	–	–	31 (100.0)	31 (100.0)		
	S	–	–	–	–	37 (100.0)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	25 (100.0)	25 (100.0)		
	DP3u	–	–	–	–	6 (100.0)	6 (100.0)		
I2		–	–	–				0.225	**.014**
	PP2=	–	–	–	2 (11.1)	16 (88.9)	18 (100.0)		
	MP3=	–	–	–	3 (9.7)	28 (90.3)	31 (100.0)		
	S	–	–	–	–	37 (100.0)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	25 (100.0)	25 (100.0)		
	DP3u	–	–	–	–	6 (100.0)	6 (100.0)		
C								0.562	**.000**
	PP2=	–	–	13 (72.2)	3 (16.7)	2 (11.1)	18 (100.0)		
	MP3=	–	–	14 (45.2)	9 (29.0)	8 (25.8)	31 (100.0)		
	S	–	–	11 (29.7)	8 (21.6)	18 (48.6)	37 (100.0)		
	$MP3_{CAP}$	–	–	2 (8.0)	2 (8.0)	21 (84.0)	25 (100.0)		
	DP3u	–	–	–	–	6 (100.0)	6 (100.0)		
P1								0.466	**.000**
	PP2=	–	1 (5.6)	15 (83.3)	2 (11.1)	–	18 (100.0)		
	MP3=	–	1 (3.2)	15 (48.4)	9 (29.0)	6 (19.4)	31 (100.0)		
	S	–	–	19 (51.4)	10 (27.0)	8 (21.6)	37 (100.0)		
	$MP3_{CAP}$	–	–	6 (24.0)	5 (20.0)	14 (56.0)	25 (100.0)		
	DP3u	–	–	–	3 (50.0)	3 (50.0)	6 (100.0)		
P2		–						0.425	**.000**
	PP2=	–	1 (5.6)	***17 (94.4)****	–	–	18 (100.0)		
	MP3=	–	4 (12.9)	***19 (61.3)***	5 (16.1)	3 (9.7)	31 (100.0)		
	S	–	1 (2.7)	***26 (70.3)****	8 (21.6)	2 (5.4)	37 (100.0)		
	$MP3_{CAP}$	–	–	11 (44.0)	7 (28.0)	7 (28.0)	25 (100.0)		
	DP3u	–	–	2 (33.3)	2 (33.3)	2 (33.3)	6 (100.0)		
M1		–	–					0.210	**.023**
	PP2=	–	–	–	3 (16.7)	15 (83.3)	18 (100.0)		
	MP3=	–	–	–	6 (19.4)	25 (80.6)	31 (100.0)		
	S	–	–	–	2 (5.5)	35 (94.6)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	1 (4.0)	24 (96.0)	25 (100.0)		
	DP3u	–	–	–	–	6 (100.0)	6 (100.0)		
M2		–	–					0.419	**.000**
	PP2=	–	7 (38.9)	9 (50.0)	2 (11.1)	–	18 (100.0)		
	MP3=	–	7 (22.6)	12 (38.7)	12 (38.7)	–	31 (100.0)		
	S	1 (2.7)	3 (8.1)	18 (48.6)	15 (40.5)	–	37 (100.0)		
	$MP3_{CAP}$	–	2 (8.0)	6 (24.0)	***13 (52.0)***	4 (16.0)	25 (100.0)		
	DP3u	–	1 (16.7)	–	3 (50.0)	2 (33.3)	6 (100.0)		

T: tooth; SM: skeletal maturation; DM: dental maturation; CC: correlation coefficient; *n*: number of children in each dental stage and in total; R_S: correlation between dental and skeletal maturation as analysed by Spearman's rho; *p*: probability

*$p < .05$ by logistic regression adjusted for age and sex.

Bold and italic values indicate DM and SM stages tested by logistic regression analysis. Bold values indicate significant association between DM and SM tested by spearman's rho.

Table 4. Dental maturation of the maxillary teeth as assessed according to Haavikko in relation to the different skeletal maturation stages.

T	SM	DM Ri	*n* (%) R1/4	R1/2	R3/4	RC	AC	Total	CC *Rs*	*p*
I1									0.165	.075
	PP2=	–	–	–	1 (5.6)	–	17 (94.4)	18 (100.0)		
	MP3=	–	–	–	–	–	31 (100.0)	31 (100).0		
	S	–	–	–	–	–	37 (100.0)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	–	25 (100.0)	25 (100.0)		
	DP3u	–	–	–	–	–	6 (100.0)	6 (100.0)		
I2		–	–	–					0.275	**.003**
	PP2=	–	–	–	1 (5.6)	3 (16.7)	14 (77.8)	18 (100.0)		
	MP3=	–	–	–	1 (3.2)	4 (12.9)	26 (83.9)	31 (100.0)		
	S	–	–	–	–	2 (5.4)	35 (94.6)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	–	25 (100.0)	25 (100.0)		
	DP3u	–	–	–	–	–	6 (100.0)	6 (100.0)		
C									0.512	**.000**
	PP2=	–	–	2 (11.1)	***14 (77.8)******	2 (11.1)	–	18 (100.0)		
	MP3=	–	–	3 (9.7)	***15 (48.4)***	5 (16.1)	8 (25.8)	31 (100.0)		
	S	–	–	–	***15 (40.5)***	10 (27.0)	12 (32.4)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	4 (16.0)	8 (32.0)	13 (52.0)	25 (100.0)		
	DP3u	–	–	–	–	1 (16.7)	5 (83.3)	6 (100.0)		
P1									0.419	**.000**
	PP2=	–	3 (16.7)	5 (27.8)	3 (16.7)	4 (22.2)	3 (16.7)	18 (100.0)		
	MP3=	–	2 (6.5)	5 (16.1)	5 (16.1)	4 (12.9)	15 (48.4)	31 (100.0)		
	S	–	–	4 (10.8)	9 (24.3)	6 (16.2)	18 (48.6)	37 (100.0)		
	$MP3_{CAP}$	–	1 (4.0)	–	2 (8.0)	4 (16.0)	18 (72.0)	25 (100.0)		
	DP3u	–	–	–	–	–	6 (100.0)	6 (100.0)		
P2									0.421	**.000**
	PP2=	1 (5.6)	6 (33.3)	5 (27.8)	3 (16.7)	2 (11.1)	1 (5.6)	18 (100.0)		
	MP3=	–	6 (19.4)	4 (12.9)	5 (16.1)	5 (16.1)	11 (35.5)	31 (100.0)		
	S	–	5 (13.5)	7 (18.9)	7 (18.9)	6 (16.2)	12 (32.4)	37 (100.0)		
	$MP3_{CAP}$	1 (4.0)	1 (4.0)	2 (8.0)	2 (8.0)	6 (24.0)	13 (52.0)	25 (100.0)		
	DP3u	–	–	–	1 (16.7)	1 (16.7)	4 (66.7)	6 (100.0)		
M1		–	–	–					0.071	.447
	PP2=	–	–	–	–	–	18 (100.0)	18 (100.0)		
	MP3=	–	–	–	–	1 (3.2)	30 (96.8)	31 (100.0)		
	S	–	–	–	–	–	37 (100.0)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	–	25 (100.0)	25 (100.0)		
	DP3u	–	–	–	–	–	6 (100.0)	6 (100.0)		
M2									0.447	**.000**
	PP2=	–	9 (50.0)	4 (22.2)	3 (16.7)	2 (11.1)	–	18 (100.0)		
	MP3=	3 (9.7)	11 (35.5)	5 (16.1)	1 (3.2)	5 (16.1)	6 (19.4)	31 (100.0)		
	S	–	9 (24.3)	6 (16.2)	5 (13.5)	4 (10.8)	13 (35.1)	37 (100.0)		
	$MP3_{CAP}$	–	3 (12.0)	3 (12.0)	–	6 (24.0)	13 (52.0)	25 (100.0)		
	DP3u	–	1 (16.7)	–	–	1 (16.7)	4 (66.7)	6 (100.0)		

T: tooth; SM: skeletal maturation; DM: dental maturation; CC: correlation coefficient; *n*: number of children in each dental stage and in total; R_S: correlation between dental and skeletal maturation as analysed by Spearman's rho; *p*: probability.
$^{***}p < .001$ by logistic regression adjusted for age and sex.
Bold and italic values indicate DM and SM stages tested by logistic regression analysis. Bold values indicate significant association between DM and SM tested by spearman's rho.

Table 5. Dental maturation of the maxillary third molar as assessed in accordance with Haavikko in relation to the different skeletal maturation stages.

T	SM	C_{CO}	$Cr_{1/2}$	$Cr_{3/4}$	Cr_C	DM Ri	*n* (%) $R_{1/4}$	$R_{1/2}$	Total	CC R_S	*p*
M3										0.307	**.003**
	PP2=	5 (35.7)	4 (28.6)	–	4 (28.6)	1 (7.1)	–	–	14 (100.0)		
	MP3=	3 (14.3)	4 (19.0)	2 (9.5)	–	10 (47.6)	2 (9.5)	–	21 (100.0)		
	S	5 (16.7)	3 (10.0)	3 (10.0)	10 (33.3)	7 (23.3)	2 (6.7)	–	30 (100.0)		
	$MP3_{CAP}$	2 (9.5)	2 (9.5)	1 (4.8)	–	***14 (66.7)***	2 (9.5)	–	21 (100.0)		
	DP3u	3 (60.0)	–	1 (20.0)	–	–	–	1 (20.0)	5 (100.0)		

T: tooth; SM: skeletal maturation; DM: dental maturation; CC: correlation coefficient; *n*: number of children in each dental stage and in total; R_S: correlation between dental and skeletal maturation as analysed by Spearman's rho; *p*: probability.
Bold and italic values indicate DM and SM stages tested by logistic regression analysis. Bold values indicate significant association between DM and SM tested by spearman's rho.

$p < .000$–$p = .035$), except for the first incisor and the first molar (Tables 3–7). The strongest correlations were found for the canines (R_S = 0.500–0.562; $p < .001$) and the second premolars (R_S = 0.419–0.466; $p < .001$). An association was not possible to calculate on the first incisors, as they were all rooted.

Based on Demirjian's method, the mandibular second premolar in the DM stage F was significantly positively associated with the SM stage PP2= or S when adjusted for age and sex ($p < .05$, highlighted in Table 3). This indicates that when the roots of the mandibular second premolars are 3/4 formed or have similar length as the crown (DM stage F),

Table 6. Dental maturation of mandibular teeth as assessed in accordance with Haavikko in relation to the different skeletal maturation stages.

T	SM	DM	n (%)						CC	
		Ri	$R_{1/4}$	$R_{1/2}$	$R_{3/4}$	R_C	A_C	Total	R_S	*p*
I1									–	–
	PP2=	–	–	–	–	–	18 (100.0)	18 (100.0)		
	MP3=	–	–	–	–	–	31 (100.0)	31 (100.0)		
	S	–	–	–	–	–	37 (100.0)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	–	25 (100.0)	25 (100.0)		
	DP3u	–	–	–	–	–	6 (100.0)	6 (100.0)		
I2									0.196	**.035**
	PP2=	–	–	–	–	2 (11.1)	16 (88.9)	18 (100.0)		
	MP3=	–	–	–	–	3 (9.7)	28 (90.3)	31 (100.0)		
	S	–	–	–	–	1 (2.7)	36 (97.3)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	–	25 (100.0)	25 (100.0)		
	DP3u	–	–	–	–	–	6 (100.0)	6 (100.0)		
C									0.500	**.000**
	PP2=	–	–	–	***15 (83.3)******	3 (16.7)	–	18 (100.0)		
	MP3=	–	–	–	15 (48.4)	5 (16.1)	11 (35.5)	31 (100.0)		
	S	–	–	–	12 (32.4)	9 (24.3)	16 (43.2)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	2 (8.0)	6 (24.0)	17 (68.0)	25 (100.0)		
	DP3u	–	–	–	–	2 (33.3)	4 (66.7)	6 (100.0)		
P1									0.446	**.000**
	PP2=	–	1 (5.6)	3 (16.7)	11 (61.1)	2 (11.1)	1 (5.6)	18 (100.0)		
	MP3=	–	1 (3.2)	4 (12.9)	8 (25.8)	11 (35.5)	7 (22.6)	31 (100.0)		
	S	–	–	–	16 (43.2)	9 (24.3)	12 (32.4)	37 (100.0)		
	$MP3_{CAP}$	–	–	1 (4)	5 (20.0)	5 (20.0)	14 (56.0)	25 (100.0)		
	DP3u	–	–	–	–	2 (33.3)	4 (66.7)	6 (100.0)		
P2									0.463	**.000**
	PP2=	–	2 (11.1)	6 (33.3)	10 (55.6)	–	–	18 (100.0)		
	MP3=	–	3 (9.7)	5 (16.1)	***16 (51.6)***	4 (12.9)	3 (9.7)	31 (100.0)		
	S	–	1 (2.7)	2 (5.4)	***24 (64.9)******	8 (21.6)	2 (5.4)	37 (100.0)		
	$MP3_{CAP}$	–	–	2 (8.0)	9 (36.0)	6 (24.0)	8 (32.0)	25 (100.0)		
	DP3u	–	–	–	2 (33.3)	2 (33.3)	2 (33.3)	6 (100.0)		
M1									0.336	**.000**
	PP2=	–	–	–	–	6 (33.3)	12 (66.7)	18 (100.0)		
	MP3=	–	–	–	–	6 (19.4)	25 (80.6)	31 (100.0)		
	S	–	–	–	–	2 (5.4)	35 (94.6)	37 (100.0)		
	$MP3_{CAP}$	–	–	–	–	1 (4.0)	24 (96.0)	25 (100.0)		
	DP3u	–	–	–	–	–	6 (100.0)	6 (100.0)		
M2									0.356	**.000**
	PP2=	–	6 (33.3)	3 (16.7)	9 (50.0)	–	–	18 (100.0)		
	MP3=	3 (9.7)	3 (9.7)	6 (19.4)	7 (22.6)	10 (32.3)	2 (6.5)	31 (100.0)		
	S	–	6 (16.2)	7 (18.9)	12 (32.4)	12 (32.4)	–	37 (100.0)		
	$MP3_{CAP}$	–	2 (8.0)	2 (8.0)	4 (16.0)	14 (56.0)	3 (12.0)	25 (100.0)		
	DP3u	–	–	1 (16.7)	1 (16.7)	3 (50.0)	1 (16.7)	6 (100.0)		

T: tooth; SM: skeletal maturation; DM: dental maturation; CC: correlation coefficient; *n*: number of children in each dental stage and in total; R_S: correlation between dental and skeletal maturation as analysed by Spearman's rho; *p*: probability.
*$p < .05$ by logistic regression adjusted for age and sex.
***$p < .001$ by logistic regression adjusted for age and sex.
Bold and italic values indicate DM and SM stages tested by logistic regression analysis. Bold values indicate significant association between DM and SM tested by spearman's rho.

Table 7. Dental maturation of the third mandibular molar as assessed according to Haavikko in relation to the different skeletal maturation stages.

T	SM							DM	n (%)			CC	
		O	Ci	C_{CO}	$Cr_{1/2}$	$Cr_{3/4}$	Cr_C	Ri	$R_{1/4}$	$R_{1/2}$	Total	R_S	*p*
M3												0.298	**.003**
	PP2=	2 (12.5)	1 (6.3)	5 (31.3)	3 (18.8)	3 (18.8)	–	2 (12.5)	–	–	16 (100.0)		
	MP3=	1 (4.2)	2 (8.3)	3 (12.5)	5 (20.8)	3 (12.5)	–	7 (29.2)	3 (12.5)	–	24 (100.0)		
	S	1 (3.2)	–	8 (25.8)	2 (6.5)	10 (32.3)	1 (3.2)	9 (29.0)	–	–	31 (100.0)		
	$MP3_{CAP}$	1 (4.2)	–	5 (20.8)	2 (8.3)	1 (4.2)	–	***14 (58.3)***	1 (4.2)	–	24 (100.0)		
	DP3u	–	–	–	1 (25.0)	1 (25.0)	–	1 (25.0)	–	1 (25.0)	4 (100.0)		

T: tooth; SM: skeletal maturation; DM: dental maturation; CC: correlation coefficient; *n*: number of children in each dental stage and in total; R_S: correlation between dental and skeletal maturation as measured in Spearman's rho; *p*: probability.
Bold and italic values indicate DM and SM stages tested by logistic regression analysis. Bold values indicate significant association between DM and SM tested by spearman's rho.

this is either significantly associated with the beginning of the adolescent period (SM stage PP2=) or with the period shortly before PHV (SM stage S, approx. 1 year according to [1], Figure 2).

The DM stages in the maxilla based on Haavikko's method in relation to the SM stages are presented in Tables 4 and 5. The maxillary canine in the DM stage $R_{3/4}$ was significantly positively associated with the SM stage PP2= when adjusted for age and sex ($p < .001$, highlighted in Table 4). This indicates that when the roots of the maxillary canines are $^3/_4$ formed (DM stage $R_{3/4}$), this is significantly associated with the beginning of the adolescent period (SM stage PP2=, Figure 2).

The DM stages in the mandible based on Haavikko's method in relation to the SM stages are presented in Tables 6 and 7. The mandibular canine and the mandibular second premolar in the DM stage $R_{3/4}$ were significantly positively associated with the SM stage PP2= or SM stage S when adjusted for age and sex ($p < .05$ and $p < .001$, respectively, highlighted in Table 6). These results indicate that when the roots of the mandibular canines and the mandibular second premolars are ¾ formed (DM stage $R_{3/4}$), this is significantly associated with either the beginning of the adolescent period (SM stage PP2=) or shortly before PHV (SM stage S, approx. 1 year according to [1], Figure 2).

Discussion

The majority of the previous literature have been based on Asian or South American populations [18–22,27,28,37], which may not be comparable with other countries since the velocity of growth may differ across countries [32,38,39]. This study expanded the literature by investigating the association between DM and SM within a group of Scandinavian children based on hand-wrist radiographs and OP's obtained in 2013–2020, which to the best of our knowledge has not been reported before.

In general, previous classical articles have found limited evidence of any association between SM and DM [9,14,15], whereas more recent contributions have estimated a correlation between DM and SM with differing observations on the correlation [19–28,37]. The difference in results between the previous classical studies and the more recent studies may be due to a secular trend in maturation [1], but may also be multifactorial as the teeth and skeletal areas are affected by various factors [2,11,38–40].

In this study, the strongest association between SM and DM was found on the maxillary and mandibular canines evaluated by using both Demirjian's and Haavikko's methods. This is in agreement with recent studies from other countries that have found a strong association between SM and DM on the mandibular canines [18,21,23,27,28,41]. A systematic review from 2018 [18], based on studies from Asia, North America and South America, found that the strongest correlation was between the mandibular canines and the SM based on hand-wrist radiographs. In addition, it was found that the strongest correlations between SM and DM were in both the second premolars and canines in the mandible in Polish children [42], whereas a study from India found the strongest correlation on the maxillary canines [37]. A majority of the studies were solely based on Demirjian's method that focus on the mandible [17–26,41,43], and therefore only relatively few studies include the maxilla [18,20,29,37] as in this study.

In general, the results of this study showed that the majority of the mandibular canine and second premolar were in DM stage F (roots are ¾ formed) for children in SM stage PP2= (beginning of the adolescent period), which in general is consistent with the literature in other countries. In Turkish children, Demirjian's maturity F on the second premolar might indicate the beginning of the adolescent growth spurt [20]. In children from India [21], the US [43], and Thailand [17], the mandibular canines were mostly in Demirjian's maturity F by the beginning of the growth spurt, while in Italian children Demirjian's maturity E on the first premolar might indicate the beginning of the adolescent growth spurt [44]. Although some of the DM stages of the canine were associated with pre-pubertal SM stages, the diagnostic accuracy may not be sufficient [18].

This study further elaborated on the association between DM and SM by adjusting the association between DM and SM for age and sex as both DM and SM are influenced by age and sex [1,31,32]. It was found that ¾ root formation ($R_{3/4}$) in the canines indicated SM stage PP2=, which is in the beginning of the adolescent period with increased skeletal growth velocity. Additionally, ¾ root formation ($R_{3/4}$) or roots with similar length as the crown (F) in the second premolars indicated SM stage S, which is shortly before PHV [1]. To the best of our knowledge, this is a novel contribution and therefore this result will not be discussed further with regards to previous literature, but the association between DM and SM may be considered to be strengthened due to the age and sex adjustment.

Although the existing evidence on European populations is limited, there does not seem to be a systematic difference in the association between skeletal and DMs [20,28] across the European countries. Thus, the results of this study regarding association between DM and SM can serve as a consolidation of existing results and support the external validity of previous results, and the results of this study may as well be valid for various other countries.

This study did have limitations. The children included in the study were all orthodontic patients prior to orthodontic treatment, which might introduce a bias. Accordingly, the sample might not be representative of the general Danish or Scandinavian population. The sample was selected based on clear inclusion and exclusion criteria, following various previous studies [20–22], with the purpose of reducing possible selection bias and improving the chances of representability of the general Danish or Scandinavian population. Still, well-defined selection criteria do not necessarily limit selection bias or make the sample more representative. The inclusion and exclusion criteria did, however, limit the sample size, which is a drawback. Due to limited data availability, there were no 14-year-old girls nor any 8-year-old boys in this study, which limited the age range. These gaps may have occurred because girls and boys begin their orthodontic treatment at different ages due to differences in the maturation processes between the sexes [1,45].

The methods used in this study were well-validated, standard methods with a small variability [5,9]. The intra-reliability of the measurements was high compared to previous studies with a similar research design [19,20,37]. The examiner was blinded for assessment in regard to age and sex in order to reduce the presence of observation bias in the results. Furthermore, the analysis of the X-rays was performed by one examiner which potentially could introduce a measurement bias [46]. Therefore, the examiner was continuously calibrated with an experienced examiner. Thus, the internal validity of this study may be considered as sufficient due to the methods used, the results of the intra-reliability test, and the various attempt to reduce bias.

Conclusion

The strongest association between DM and SM in a recent Scandinavian population was found on the canines and the second premolars evaluated through both Demirjian's and Haavikkós methods, which is in agreement with previous studies in other countries. Furthermore, when the association between DM and SM was adjusted for age and sex, it was found that when the root of the canines or second premolars were $^3/_4$ mineralized, it was associated with the beginning of the adolescent period with increased skeletal growth intensity before PHV. These new results may prove valuable for screening of children and timing of orthodontic treatment.

Acknowledgements

Ib Jarle Christensen, Senior researcher, Department of Gastroenterology, Hvidovre Hospital, Denmark, is acknowledged for statistical assistance. Arman Teymouri Niknam, Academic Officer, Department of Odontology, Postgraduate Program in Orthodontics, University of Copenhagen, Denmark, is acknowledged for linguistic support.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors thank the Danish Dental Association [21318418] for financially supporting this study.

ORCID

Liselotte Sonnesen http://orcid.org/0000-0003-0320-8096

Data availability statement

The data underlying this article will be shared upon reasonable request to the corresponding author.

References

[1] Caspersen LM, Sonnesen L. Secular trend in the skeletal maturation in relation to peak height velocity – a comparison between two groups of children born 1969-1973 and 1996–2000. Eur J Orthod. 2020;42:cjz098.
[2] Jääsaari P, Tolvanen M, Niinikoski H, et al. Advanced dental maturity of Finnish 6- to 12-yr-old children is associated with high energy intake. Eur J Oral Sci. 2016;124(5):465–471.
[3] Holtgrave EA, Kretschmer R, Müller R. Acceleration in dental development; fact or fiction. Eur J Orthod. 1997;19(6):703–710.
[4] Eckert-Lind C, Busch AS, Petersen JH, et al. Worldwide secular trends in age at pubertal onset assessed by breast development among girls: a systematic review and meta-analysis. JAMA Pediatr. 2020;174(4):e195881.
[5] Svanholt M, Kjaer I. Developmental stages of permanent canines, premolars, and 2nd molars in 244 Danish children. Acta Odontol Scand. 2008;66(6):342–350.
[6] Macha M, Lamba B, Avula JSS, et al. Estimation of correlation between chronological age, skeletal age and dental age in children: a cross-sectional study. J Clin Diagn Res. 2017;11(9):ZC01–ZC04.
[7] Mack KB, Phillips C, Jain N, et al. Relationship between body mass index percentile and skeletal maturation and dental development in orthodontic patients. Am J Orthod Dentofacial Orthop. 2013;143(2):228–234.
[8] Chertkow S. Tooth mineralization as an indicator of the pubertal growth spurt. Am J Orthod. 1980;77(1):79–91.
[9] Demirjian A, Buschang PH, Tanguay R, et al. Interrelationships among measures of somatic, skeletal, dental, and sexual maturity. Am J Orthod. 1985;88(5):433–438.
[10] de Muinich Keizer SM, Mul D. Trends in pubertal development in Europe. Hum Reprod Update. 2001;7(3):287–291.
[11] Gelbrich B, Hirsch A, Dannhauer K-H, et al. Agenesis of second premolars and delayed dental development. J Orofac Orthop. 2015;76(4):338–350.
[12] Klein OD, Oberoi S, Huysseune A, et al. Developmental disorders of the dentition: an update. Am J Med Genet C Semin Med Genet. 2013;163C(4):318–332.
[13] Malina RM. Research on secular trends in auxology. Anthropol Anz. 1990;48(3):209–227.
[14] Bjørk A, Helm S. Prediction of the age of maximum pubertal growth in body height. Angle Orthod. 1967;37(2):134–143.
[15] Anderson DL, Thompson GW, Popovich F. Interrelationships of dental maturity, skeletal maturity, height and weight from age 4 to 14 years. Growth. 1975;39(4):453–462.
[16] Lewis AB, Garn SM. The relationship between tooth formation and other maturational factors. Angle Orthod. 1969;30(1):70–77.
[17] Krailassiri S, Anuwongnukroh N, Dechkunakorn S. Relationships between dental calcification stages and skeletal maturity indicators in Thai individuals. Angle Orthod. 2002;72(2):155–166.
[18] Bittencourt MA, Cericato GO, Franco A, et al. Accuracy of dental development for estimating the pubertal growth spurt in comparison to skeletal development: a systematic review and meta-analysis. Dentomaxillofac Radiol. 2017;47(4):20170362.
[19] Mollabashi V, Yousefi F, Gharebabaei L, et al. The relation between dental age and cervical vertebral maturation in orthodontic patients aged 8 to 16 years: a cross-sectional study. Int Orthod. 2019;17(4):710–718.
[20] Yilmaz SG, Harorli A, Kilic M, et al. Evaluation of the relationship between the Demirjian and nolla methods and the pubertal growth spurt stage predicted by skeletal maturation indicators in Turkish children aged 10-15: investigation study. Acta Odontol Scand. 2019;77(2):107–113.
[21] Ojha A, Prasanth MA, Singh V, et al. Assessment of correlation between dental calcification stages and skeletal maturity indicators. J Forensic Dent Sci. 2018;10(3):132–136.
[22] Motghare WW, Bedia AS, Degwekar SS, et al. Correlation of calcification of permanent mandibular canine, mandibular premolars, and permanent mandibular first and second molars with skeletal maturity in Indian population. J Forensic Dent Sci. 2016;8(2):67–73.
[23] Celik S, Zeren C, Çelikel A, et al. Applicability of the Demirjian method for dental assessment of Southern Turkish children. J Forensic Leg Med. 2014;25:1–5.
[24] Srkoc T, Mestrovic S, Anic-Milosevic S, et al. Association between dental and skeletal maturation stages in Croatian subjects. Acta Clin Croat. 2015;54(4):445–452.
[25] Oyonarte R, Sánchez-Ugarte F, Montt J, et al. Diagnostic assessment of tooth maturation of the mandibular second molars as a skeletal maturation indicator: a retrospective longitudinal study. Am J Orthod Dentofacial Orthop. 2020;158(3):383–390.

[26] Guillén LEA, Carmelo UP, Bancalari MP. Concordancia entre estadíos de calcificación dentaria y maduración esquelética en niños y adolescentes de una localidad peruana. Rev Estomatol Herediana. 2011;21:131–136.
[27] Barreto BCT, Marañón-Vásquez GA, Barreto LSDC, et al. Is there a correlation between dental and cervical vertebrae maturation stages in growing subjects? A systematic review and meta-analysis. Clin Oral Invest. 2022;26(5):3823–3842.
[28] Perinetti G, Westphalen GH, Biasotto M, et al. The diagnostic performance of dental maturity for identification of the circumpubertal growth phases: a meta-analysis. Prog Orthod. 2013;14:8.
[29] Sahin Sağlam AM, Gazilerli U. The relationship between dental and skeletal maturity. J Orofac Orthop. 2002;63(6):454–462.
[30] Gupta B, Anegundi R, Sudha P. Comparison of dental age of Hubli Dharwad children by Moore's method with the skeletal age and chronological age. Int J Dent Sci. 2007;6(1):1–7.
[31] Helm S, Siersbaek-Nielsen S, Skieller V. Skeletal maturation of the hand in relation to maximum pubertal growth in body height. Tandlægebladet. 1971;75:1223–1234.
[32] Chaillet N, Nyström M, Demirjian A. Comparison of dental maturity of children of different ethnic origins: international maturity curves for clinicians. J Forensic Sci. 2005;50(5):1164–1174.
[33] Haavikko K. The formation and the alveolar and clinical eruption of the permanent teeth: an orthopantomographic study. Helsinki: tr.: *forssan kirjapaino*. Suom Hammaslaak Toim. 1970;66:103–170.
[34] Demirjian A, Goldstein H, Tanner JM. A new system of dental age assessment. Hum Biol. 1973;45(2):211–227.
[35] Greulich WW, Pyle SI. Radiographic atlas of skeletal development of the hand and wrist. 2nd ed. Stanford (CA): Stanford University Press; 1959.
[36] Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics. 1977;33(1):159–174.
[37] Kumar S, Roy AS, Garg A, et al. Correlation between maxillary canine calcification and skeletal maturation. J Clin Diagn Res. 2017;11(5):ZC13–ZC16.
[38] Jayaraman J, Roberts GJ. Comparison of maturation in Hong Kong Chinese and United Kingdom caucasian populations. Forensic Sci Int. 2018;292:61–70.
[39] Suri L, Gagari E, Vastardis H. Delayed tooth eruption: pathogenesis, diagnosis, and treatment. A literature review. Am J Orthod Dentofacial Orthop. 2004;126(4):432–445.
[40] 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;101(2):145–151.
[41] Sasso A, Špalj S, Mady Maričić B, et al. Secular trend in dental development of permanent teeth in a population of Istria and the Littoral region of Croatia. J Forensic Sci. 2013;58(3):673–677. 77.
[42] Różyło-Kalinowska I, Kolasa A, Kalinowski P. Relationship between dental age according to Demirjian and cervical vertebrae maturity in polish children. Eur J Orthod. 2011;33(1):75–83.
[43] Coutinho S, Buschang PH, Miranda F. Relationships between mandibular canine calcification stages and skeletal maturity. Am J Orthod Dentofacial Orthop. 1993;104(3):262–268.
[44] Perinetti G, Contardo L, Gabrieli P, et al. Diagnostic performance of dental maturity for identification of skeletal maturation phase. Eur J Orthod. 2012;34(4):487–492.
[45] Björk A, Skieller V. Facial development and tooth eruption. Mondo Ortod. 1977;19(6):29–63.
[46] Jain S, Debbarma S, Jain D. Bias in dental research/dentistry. Ann Int Med Dent Res. 2016;2(5):5–9.