ORIGINAL ARTICLE

Thoracic cage volume and dimension assessment by optoelectronic molding in normal children and adolescents during growth

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Abstract

Purpose The thoracic spine, the chondral and osseous ribs, and the sternum together make up the thoracic cage. These elements are strictly correlated, although their growth is not synchronous. The purpose of this study is to provide a comprehensive data set of thoracic dimensions and non-invasive volumetric assessment in a large cohort of males and females from early childhood to young adult age.

Methods In all, 622 healthy individuals (406 girls, 216 boys) aged 6–18 years were consecutively enrolled between 2006 and 2016. All had to be healthy with no history of spinal deformity, or any lung, cardiovascular, systemic or neuromuscular disease. The optical ORTEN system for trunk surface data acquisition was used to calculate thoracic cage volume (V) and perimeter (Pe), anterior–posterior depth (AP) and transverse diameter (TD), AP/TD ratio, sternal length (St), and T1–T12 distance (Tle) in all patients.

Results The overall average age was 11.1 ± 2.5 years (4–18) for girls and 11.0 ± 3.1 years (4–18) for boys. Average growth parameters were: standing height 146.2 ± 14.6 cm (103–172) for girls and 146.4 ± 20.0 cm (94–192) for boys, sitting height 75.4 ± 8.6 cm (61–91) for girls and 75.5 ± 10.3 cm (60–99) for boys, weight 37.6 ± 10.4 kg (16–65) for girls and 38.3 ± 14.3 kg (13.7–104) for boys, BMI 16.7 ± 3.7 (18.5–26) for girls and 17.0 ± 3.3 (18.7–34.3) for boys. At age 6–8 years: V was 52.5% of its final size in girls and 44.9% in boys; Pe was 80.2% its final length in girls and 76.8% in boys; St reached 68% of its final size in girls and 66.9% in boys; Tle reached 73.3% of its final length in girls and 71.2% in boys. At skeletal maturity, thoracic cage volume in boys was 19.4% greater than in girls ($p < 0.05$). AP/TD ratio remained < 1 in all age groups and did not differ between genders ($p > 0.05$).

Conclusion Growth of the thoracic cage is shown to be a gradual process that is more linear than previously reported. Only small increases in annual growth rates were observed during the pubertal growth spurt. The most important events characterizing thoracic cage development occurred during the first few years of postnatal growth. The circular cross-section of the very young child's thorax reached adult-like proportions together with its ovoid shape before age 6 years.

Keywords Thoracic cage · Dimensions · Volume · Perimeter · Diameter · Growth

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Introduction

Development of the spine and thoracic cage comprises a complex series of events involving multiple metabolic processes, genes and signaling pathways [1, 5, 6, 15, 16, 27, 34]. Even if several research works have been carried out, we still have a poor understanding of how the thoracic cage develops throughout life [2, 3, 8, 10, 11, 14, 17, 18, 33, 35, 36].

Thurlbeck hypothesized that the larger thoracic cage and lung volume of males could be attributed to a higher rate of alveolar multiplication in boys than in girls, and was established during the first years of life [1, 6, 7, 17, 27, 34].

Bellamare et al. reported sex differences in thoracic dimensions and configuration of normal individuals. In particular, they found that the thoracic cage was about 10% larger in males than in females [33]. They hypothesized that the smaller thoracic cage in females could be accounted for by a greater inclination of the ribs [4, 26, 33].

Weaver et al. reported a morphometric analysis of visible variation in ribs with age and sex, and observed an increase in the overall size of the rib cage that was most evident up to age 20 years. Thereafter, thoracic cage modification was minimal [20].

More recently, Dimeglio et al. estimated values of thoracic cage volume at different ages: at birth, the thoracic cage volume is about 6% of its final size and reaches 30% by age five and 50% by age 10. Between age 10 and skeletal maturity, the thoracic cage volume doubles, before it ultimately stops growing [6, 23]. Thoracic cage shape also varies with age [6, 15].

Shi et al. report that thoracic cage geometry varies with age, gender and stature, but is not related to BMI [32].

Only comprehensive knowledge of normal growth parameters can improve our understanding of both normal and abnormal spine and thoracic cage growth, and of the pathologic changes in a growing spine and chest resulting from a spinal deformity [2, 3, 14, 35].

The purpose of this study is to provide a comprehensive data set of thoracic dimensions and non-invasive volumetric assessment during growth, from early childhood to adulthood. This data is aimed to improve clinical evaluation, conservative and surgical treatment in patients with spinal deformities in comparison to a normal population of male and female children and adolescents.

Methods

Institutional review board approval (Comité Consultatif de Protection des Personnes se Prêtant a des Recherches Biomédicales—Montpellier St. Eloi, France; ref. CPPRB 060701) was obtained for this prospective study. Informed consent for participation in the study was obtained from participants or, where participants are children, a parent or guardian.

In all, 622 (406 female, 216 male) healthy children, adolescents and young adults (range 5–18 years) were consecutively enrolled between 2006 and 2016.

All patients had to be healthy with no history of structural spinal deformity or any lung, cardiovascular, systemic or neuromuscular disease. In addition, all pre-adolescents, adolescents and young adult subjects had to be nonsmokers.

Acquisition of thoracic cage volume and dimensions

Optical molding of the trunk and the thoracic cage has been performed in a standardized way over the last 10 years (2006–2016) with the ORTEN system (Lyon, France).

The principle of the ORTEN system is based on light band projections and analysis of band deformations on the body [10, 24]. The patients wore skintight white disposable stockinet, which made the optical reflection uniform.

Standardized anatomical landmarks were drawn on the stockinet with a black marker pen: anterior superior iliac spines, jugular notch, xiphoid process, inferior border of the 10th rib in the anterior axillary line, and the spinous processes of T1 and T12 (Fig. 1).

Patients stood at the center of the cabin with their hands raised behind their head. They were asked to stop breathing while being scanned.

Each of the four columns of the cabin was equipped with two electro-optical light band projectors, one for the upper part and one for the lower part of the trunk, and a charge-coupled device camera, placed symmetrically between light band projectors.

During the optical molding process, two consecutive projections and recordings were made in 1.6 s. This enabled us to minimize motion artifacts and allowed millimeter-range precision.

Recorded video images were then converted into a digitized three-dimensional image using the COMFORTAD software version 1.0 (ORTEN, Lyon, France).

In particular, during data acquisition, the four columns generated on the patient a structured network of fringes; the imprint was then used to reconstruct the external
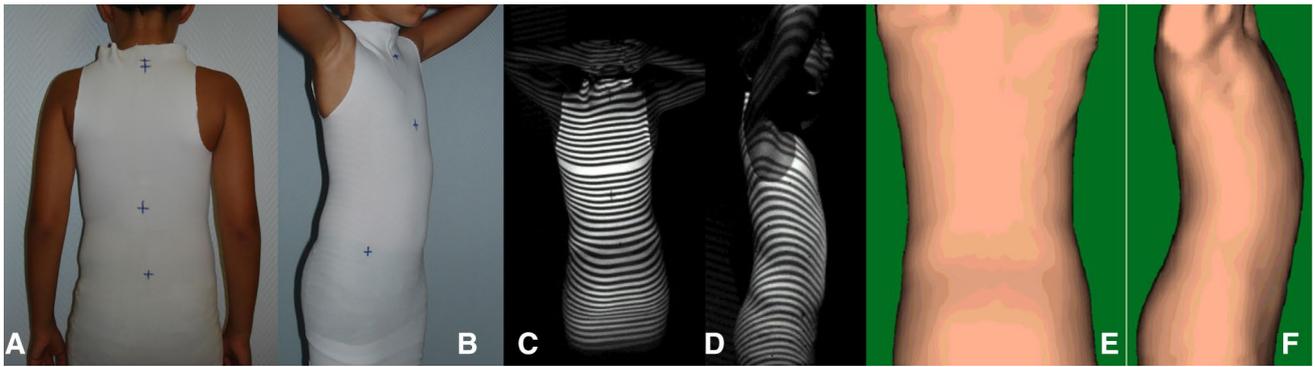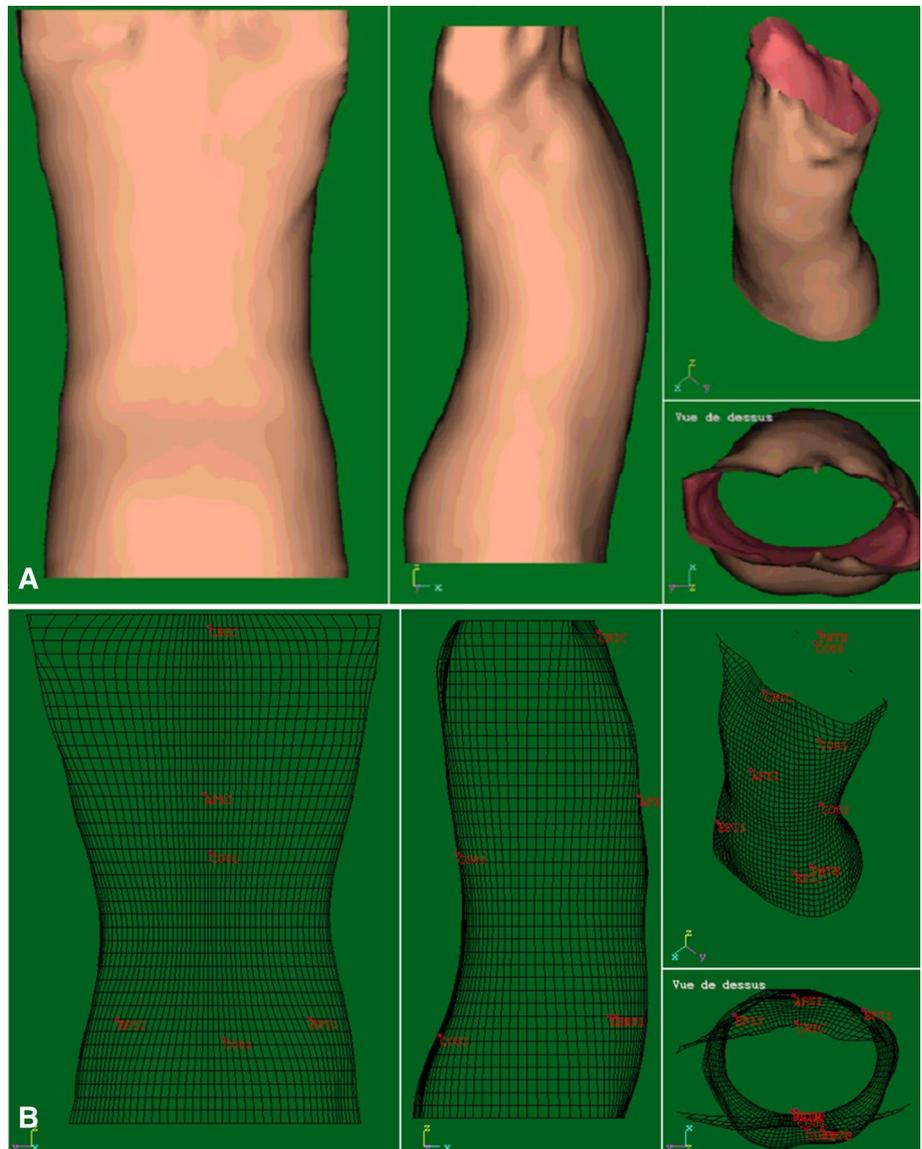
Fig. 1 Posterior (**a**) and antero-lateral view (**b**) of a patient prior to data acquisition (**c, d**). Anatomical landmarks are drawn on the stockinet (**a, b**). Three-dimensional reconstruction following data acquisition (**e, f**)

Fig. 2 Volumetric thoracic cage reconstruction following data acquisition used for measurements (**a, b**)

surface of the trunk thanks to the analysis of the relief by triangulation. This image was then refined by implementing the previously defined anatomical landmarks and by superimposition of a theoretical spine and thorax model. The volume corresponding to the breast in adolescent girls, the proximal portion of both arms as well as the surplus volume engendered by the *Dorsalis Major* during the rise of arms (both genders) were subtracted manually, at this stage, to avoid a bias of the volume of the rib cage (Fig. 2).

The following parameters were measured: thoracic cage volume (in dm^3), anterior–posterior (AP) and transversal diameters (TD) of the thoracic cage at the level of the xiphoid process (in cm), the AP/TD ratio, the thoracic perimeter at xiphoid level, and sternal and T1–T12 segment lengths (in cm). In particular, the thoracic volume was calculated from the cross-sectional plane tangent to the jugular notch, proximally, to the cross-sectional plane tangent to the inferior border of the 10th rib, distally. Standing and sitting height (in cm), weight (in kg) and body mass index (BMI) were also measured in all the patients.

Statistical analysis

Statistical analysis was performed using Stata software (version 13, StataCorp, College Station, US). Continuous data were presented as mean ± standard deviation and as median [interquartile range] according to statistical distribution (assumption of normality assessed by Shapiro–Wilk test) and as the number of patients and associated percentages for categorical parameters. Comparisons between groups (for age classes and gender) were performed using analysis of variance (ANOVA) or Kruskal–Wallis (KW) test when anova assumptions were not met [(1) normality studied as described previously and (2) Bartlett test for analysis of homoscedasticity]. When appropriate, a post hoc test was applied to take into account multiple comparisons: Tukey–Kramer after ANOVA and Dunn test post-KW. The tests were two-sided, with a Type I error set at $\alpha = 0.05$.

Results

This study comprised 622 healthy children, adolescents and young adults (406 girls, 216 boys) aged between 5 and 18 years. All the patients underwent an optical trunk surface data acquisition during the study period.

Table 1 gives the demographics of the female and male patients.

The overall average age was 11.1 ± 2.5 years (4–18) for girls and 11.0 ± 3.1 years (4–18) for boys. Average growth parameters were: standing height 146.2 ± 14.6 cm (103–172) for girls and 146.4 ± 20.0 cm (94–192) for boys, sitting

Table 1 Subject characteristics

	Females ($n = 406$)	Males ($n = 216$)	p value
Age (years)	11.1 ± 2.5	11 ± 3.1	0.47
Sitting height (cm)	75.4 ± 8.6	75.5 ± 10.3	0.94
Standing height (cm)	146.2 ± 14.6	146.4 ± 20	0.87
Weight (kg)	37.6 ± 10.4	38.3 ± 14.3	0.49
Body mass index (kg/m^2)	16.7 ± 3.7	17 ± 3.3	0.26

Results are expressed as mean ± standard deviation

cm centimeter, *m* meter, *kg* kilogram

height 75.4 ± 8.6 cm (61–91) for girls and 75.5 ± 10.3 cm (60–99) for boys, weight 37.6 ± 10.4 kg (16–65) for girls and 38.3 ± 14.3 kg (13.7–104) for boys, BMI 16.7 ± 3.7 (18.5–26) for girls and 17.0 ± 3.3 (18.7–34.3) for boys.

Thoracic cage volume

Between age 5 and skeletal maturity thoracic cage volume increased by 5.39 dm^3 (+116.4%) in girls and by 8.05 dm^3 (+183.8%) in boys. At skeletal maturity, thoracic cage volume was 24.1% greater in boys than in girls ($p < 0.001$).

Table 2 summarizes the changes in thoracic cage volume during growth for girls and boys.

Thoracic cage perimeter

On average, the thoracic perimeter was 58.05 ± 3.24 cm in girls and 56.34 ± 2.52 cm in boys at age 5 years. It attained a mean value of 74.47 ± 4.39 cm in girls (+28.3%) and 79.15 ± 6.26 cm in boys (+40.5%) at skeletal maturity (Fig. 3). At skeletal maturity, thoracic perimeter volume was 6.3% greater in boys than in girls ($p = 0.01$).

Table 2 outlines the changes in thoracic cage perimeter during growth for girls and boys.

Anterior–posterior diameter, transverse diameter and AP/TD ratio

At age 5, the difference between AP and TD was 5.86 ± 1.10 cm in girls and 4.42 ± 2.72 cm in boys. At skeletal maturity, the difference was 7.62 ± 2.13 in girls (+30%) and 8.4 ± 2.02 cm in boys (+90%). Thus the overall thoracic cage shape evolved from ovoid at birth to elliptical at skeletal maturity.

At the end of growth, the thoracic cage had an average AP of 19.11 ± 2.14 cm in girls and 20.32 ± 2.12 cm in boys, and an average TD of 26.73 ± 1.52 cm in girls and 28.72 ± 2.24 cm in boys. The AP/TD ratio did not change significantly during growth in either the girls or the boys (range 0.7–0.89 in both) (Fig. 3).

Table 2 Thoracic cage volume (dm^3), perimeter (cm), anterior–posterior diameter (AP), transverse diameter (TD), AP/TD ratio, and sternal and T1–T12 lengths

Age (years)	Thoracic cage volume (dm^3)	Thoracic cage perimeter (cm)	AP diameter (cm)	TD diameter (cm)	AP/TD ratio (%)	Sternal length (cm)	T1–T12 length (cm)
Females ($n=406$)							
5 ($n=11$), mean ± sd	4.63 ± 0.77	58.05 ± 3.24	14.91 ± 1.41	20.77 ± 1.17	71.76 ± 5.09	11.23 ± 1.34	17.59 ± 1.43
Median [IQR]	4.4 [4.2; 5.2]	58.5 [55.5; 61.5]	15.0 [14.0; 16.5]	20.5 [20.0; 22.0]	73.2 [71.4; 75.0]	11.0 [10.0; 12.0]	18.0 [17.0; 18.0]
6–7 ($n=44$), mean ± sd	5.26 ± 0.69	59.72 ± 3.56	15.57 ± 1.11	21.17 ± 1.33	73.65 ± 5.13	12.82 ± 1.35	18.68 ± 1.51
Median [IQR]	5.3 [4.8; 5.8]	59.0 [57.3; 62.5]	15.3 [15.0; 16.5]	21.0 [20.5; 22.0]	73.7 [69.4; 76.5]	12.8 [12.0; 13.5]	18.5 [18.0; 20.0]
8–10 ($n=120$), mean ± sd	6.77 ± 1.43	65.45 ± 5.58	16.82 ± 1.69	23.39 ± 2.05	72.05 ± 5.48	14.59 ± 1.47	21.07 ± 2.1
Median [IQR]	6.4 [5.7; 7.5]	64.5 [61.2; 68.5]	16.5 [15.5; 18.0]	23.0 [22.0; 24.8]	72.6 [68.1; 75.0]	14.5 [13.5; 15.5]	20.5 [19.8; 22.0]
11 ($n=73$), mean ± sd	8.09 ± 1.68	68.82 ± 9.55	17.68 ± 3.08	24.78 ± 2.14	71.53 ± 11.27	16.07 ± 1.75	23.10 ± 2.43
Median [IQR]	7.6 [6.8; 9.4]	6.09 [64.5; 73.0]	18.0 [16.0; 19.0]	24.0 [23.5; 26.0]	72.7 [67.9; 76.6]	16.0 [15.0; 17.0]	23.0 [21.0; 25.0]
12 ($n=62$), mean ± sd	8.68 ± 1.37	70.91 ± 4.19	18.32 ± 1.57	25.31 ± 1.49	72.39 ± 4.65	17.1 ± 1.48	24.11 ± 1.91
Median [IQR]	8.7 [7.4; 9.7]	71.0 [67.0; 73.5]	18.0 [17.0; 19.5]	25.5 [24.0; 26.5]	72.0 [69.4; 75.9]	17.0 [16.0; 18.0]	24.0 [23.0; 25.5]
13–14 ($n=79$), mean ± sd	9.37 ± 1.31	72.74 ± 4.36	18.7 ± 1.61	25.85 ± 1.56	72.43 ± 5.94	18.13 ± 1.75	24.72 ± 2.24
Median [IQR]	9.4 [8.7; 10.2]	72.5 [70.0; 75.5]	18.5 [17.5; 20.0]	26.0 [25.0; 27.0]	72.5 [68.6; 75.9]	18.5 [17.0; 19.0]	24.5 [23.0; 25.5]
15–18 ($n=17$), mean ± sd	10.02 ± 1.26	74.47 ± 4.39	19.11 ± 2.14	26.73 ± 1.52	71.57 ± 0.7.45	18.85 ± 1.51	25.47 ± 1.96
Median [IQR]	10.1 [9.5; 10.6]	74.0 [70.5; 76.0]	19.0 [18.0; 20.5]	26.5 [25.5; 27.5]	74.0 [66.7; 76.5]	19.0 [17.5; 20.0]	24.0 [24.0; 27.0]
p value (evolution)	<0.001	<0.001	<0.001	<0.001	0.60	<0.001	<0.001
Males ($n=216$)							
5 ($n=13$), mean ± sd	4.38 ± 0.58	56.34 ± 2.52	15.00 ± 1.79	19.42 ± 1.63	77.95 ± 13.21	10.61 ± 1.15	17.42 ± 1.68
Median [IQR]	4.5 [4.1; 4.7]	57.0 [54.5; 58.5]	15.0 [14.0; 15.0]	20.0 [18.5; 20.0]	75.0 [70.0; 80.0]	11.0 [9.5; 11.0]	17.0 [16.5; 18.0]
6–7 ($n=28$), mean ± sd	5.58 ± 0.69	60.82 ± 5.4	16.36 ± 1.19	21.11 ± 3.70	89.17 ± 7.88	12.86 ± 1.25	19.39 ± 1.59
Median [IQR]	5.5 [5.1; 6.1]	61.3 [59.0; 64.0]	16.0 [15.5; 17.5]	21.8 [21.0; 22.8]	74.4 [71.4; 77.3]	12.5 [12.5; 13.0]	19.0 [18.0; 21.0]
8–10 ($n=66$), mean ± sd	7.13 ± 1.39	66.57 ± 4.72	17.51 ± 1.56	23.62 ± 1.78	74.26 ± 5.78	14.23 ± 1.3	21.36 ± 2.05
Median [IQR]	7.1 [6.3; 7.6]	66.0 [63.0; 69.5]	17.5 [16.5; 18.5]	23.8 [22.5; 24.5]	74.5 [70.8; 78.3]	14.0 [13.5; 15.0]	21.0 [20.0; 23.0]
11–12 ($n=42$), Mean ± sd	8.99 ± 2.21	72.14 ± 6.7	18.81 ± 2.06	25.61 ± 2.41	73.62 ± 6.58	16.53 ± 1.95	23.75 ± 2.02
Median [IQR]	8.6 [7.6; 10.0]	71.3 [67.5; 74.0]	18.5 [17.5; 20.5]	25.3 [24.0; 27.0]	72.7 [70.4; 78.2]	16.0 [15.0; 17.5]	24.0 [22.0; 25.0]
13 ($n=25$), mean ± sd	10.17 ± 1.59	70.59 ± 14.1	18.98 ± 1.65	26.2 ± 2.20	72.81 ± 7.43	17.94 ± 1.79	25.1 ± 2.29
Median [IQR]	10.4 [9.6; 11.3]	73.7 [71.0; 76.0]	19.0 [18.0; 19.5]	26.5 [25.0; 27.0]	73.1 [69.2; 78.7]	18.5 [17.0; 19.0]	24.5 [24.0; 26.5]

Table 2 (continued)

Age (years)	Thoracic cage volume (dm³)	Thoracic cage perimeter (cm)	AP diameter (cm)	TD diameter (cm)	AP/TD ratio (%)	Sternal length (cm)	T1–T12 length (cm)
14 (n=22), mean±sd	11.72±2.87	78.25±8.11	19.98±2.74	28.22±2.60	70.80±6.82	18.47±1.21	25.73±2.55
Median [IQR]	11.4 [9.9; 13.1]	77.0 [73.0; 81.0]	20.0 [18.5; 21.0]	28.0 [26.5; 30.0]	69.6 [67.8; 75.0]	18.5 [18.0; 19.5]	25.0 [24.0; 27.5]
15–18 (n=20), mean±sd	12.43±2.41	79.15±6.26	20.32±2.12	28.72±2.24	70.86±6.19	19.22±1.75	27.25±2.83
Median [IQR]	12.4 [10.6; 13.7]	78.3 [74.0; 83.0]	20.3 [18.8; 21.5]	28.5 [27.0; 30.0]	73.1 [65.5; 76.2]	18.8 [18.0; 20.3]	27.0 [26.0; 29.5]
p value (evolution)	<0.001	<0.001	<0.001	<0.001	0.38	<0.001	<0.001

Results are expressed as mean±standard deviation

IQR interquartile range, *cm* centimeter, *dm* decimeter

Table 2 outline the changes in AP, TD and AP/TD ratio for boys and girls (Table 2).

Sternal length

On average, the sternal length was 11.23 ± 1.34 cm in girls and 10.61 ± 1.15 cm in boys at age 5 years. It attained a mean value of 18.85 ± 1.51 cm in girls (+67.9%) and 19.22 ± 1.75 cm in boys (+81.1%) at skeletal maturity (Fig. 4). At skeletal maturity, sternal length was 2% greater in boys than in girls ($p = 0.49$).

Table 2 summarizes the changes in sternal length during growth for girls and boys (Table 2).

T1–T12 length

On average, the T1–T12 length was 17.59 ± 1.43 cm in girls and 17.42 ± 1.68 cm in boys at age 5 years. It attained a mean value of 25.47 ± 1.96 cm in girls and 27.25 ± 2.83 cm in boys at skeletal maturity. Between age 5 and skeletal maturity, T1–T12 length increased by 7.88 cm (+44.8%) in girls and by 9.83 cm (+56.4%) in boys (Fig. 4). At skeletal maturity, T1–T12 length was 8% longer in boys than in girls ($p = 0.03$).

Table 2 summarizes the changes in T1–T12 length during growth for girls and boys (Table 2).

Discussion

This study gives normative values for the different components of the "rib–vertebral–sternal complex" during growth, i.e., thoracic cage volume, AP, TD, AP/TD ratio, sternal length and T1–T12 length.

Data were obtained via optical molding of the trunk [10, 24]. These represent the first normal data published for this technique in children, adolescents and young adults of both genders. Three-dimensional models of the normal thoracic cage are mainly based on spinal and thoracic radiographs and/or computed tomography scans, and assess a relatively small number of subjects [21, 22, 28]. Several torso surface reconstruction techniques in subjects with and without scoliosis to analyze thoracic cage shape and dimensions have been described [10, 19, 25, 29, 30].

Growth is an essential part of the natural history of any orthopedic disorder in the growing child.

The spine surgeon needs to know how the "rib–vertebral–sternal complex" develops, and the changing proportions of its various components. The concept of "rib–vertebral–sternal complex" emphasizes that there is a normal interaction between the organic components of the spine, the thoracic cage, and the heart–lungs system [5, 7]. It encloses the three-dimensional thoracic cavity, and tends to constitute an elastic structural model similar to a cube in shape. However, in the presence of scoliosis, the thoracic cage can become rigid and flat, interfering with lung expansion [2, 3, 7, 8, 10, 14, 15, 32].

Although charts and diagrams are only models or templates, it is important to consider the normal values of the "rib–vertebral–sternal complex" components and to understand the significance of these values in order to evaluate the impact of a spinal deformity on a growing organism. Charts and diagrams define trends and outline the evolution of growth. Their use should help the surgeon avoid uncertain or unnecessary treatments and develop successful strategies.

Optical molding is increasingly used in clinical practice. Its non-invasiveness and absence of radiation exposure make it ideal for the assessment of thoracic cage dimensions [10, 19, 25, 29, 35]. Thoracic cage dimensions are measurable with the optical ORTEN system, which is normally used for brace confection [24]. This tool allows
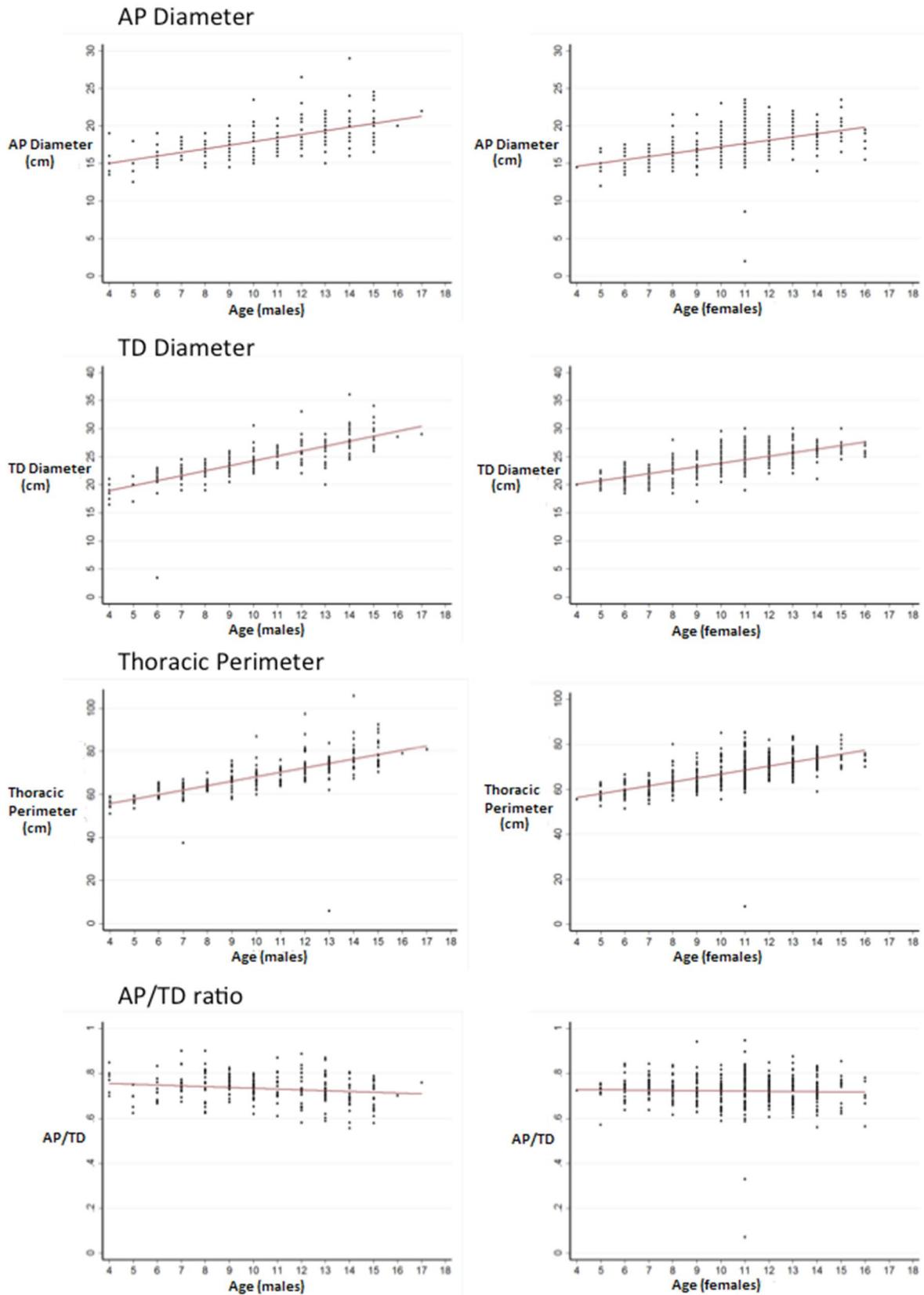
Fig. 3 Scattergrams for anterior–posterior depth of the thoracic cage (AP diameter), transversal (TD) diameter, thoracic perimeter and AP/TD ratio. Males are on the left column, females on the right
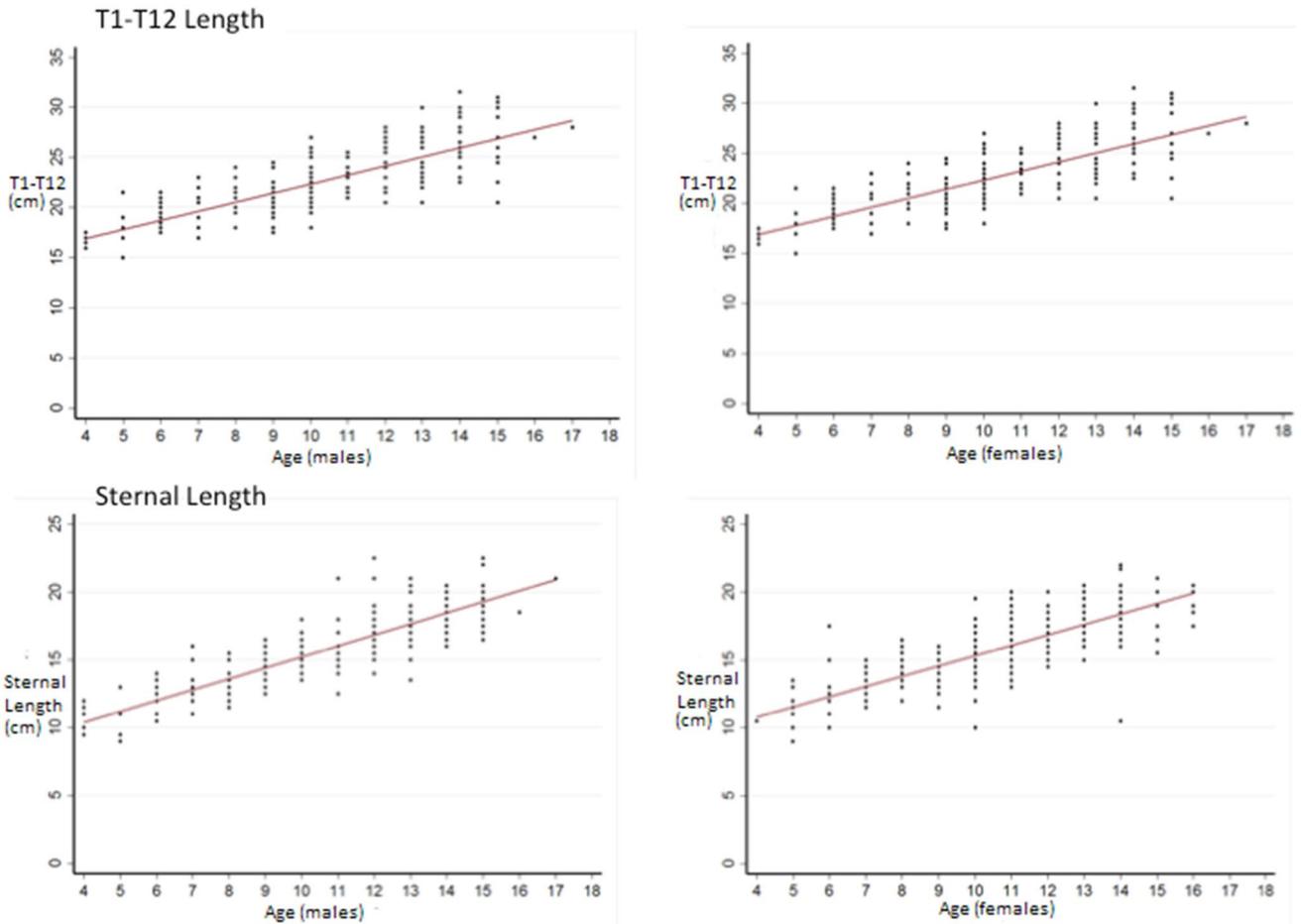
Fig. 4 Scattergrams for T1–T12 and sternal length. Males are on the left column, females on the right

measurement of width, depth, perimeter and volume of the thoracic cage as previously reported [9, 10, 12, 19, 23, 25, 29].

Growth of the "rib–vertebral–sternal complex" is shown to be more linear than previously reported, with only a small increase in annual growth rates during the pubertal growth spurt for both girls and boys (Figs. 3, 4). It is a gradual process: between the age of 5 and skeletal maturity, the thoracic cage volume doubles in girls and triples in boys. At skeletal maturity, thoracic cage volume in boys is 24.1% greater than in girls (Table 2). The differences between genders seem to be secondary to a higher annual growth rate of each component of the "rib–vertebral–sternal" complex in boys compared with girls. However, not all the components of the "rib–vertebral–sternal complex" progress exactly at the same speed. Between 6 and 8 years of age, the thoracic volume reached 52.5% and 44.9% of its final dimensions in girls and boys, respectively. On the other hand, sternal length reached 68% of its final size in girls and 66.9% in boys and T1–T12 length reached 73.3% of its final length in girls and 71.2% in boys. At the same time, thoracic perimeter
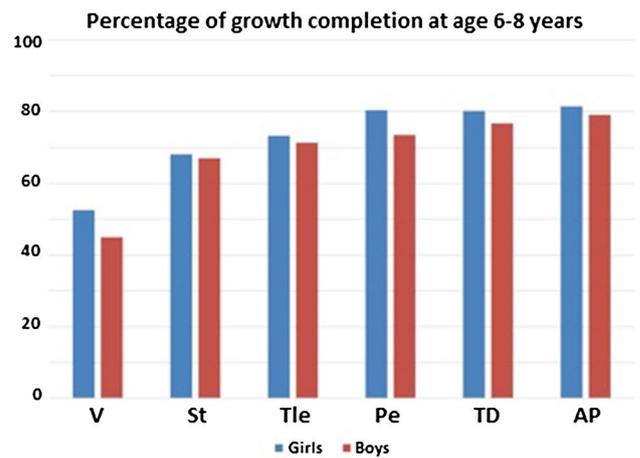

Fig. 5 Percentage of growth completion at age 6–8 years in females and males of volume (*V*), sternal length (St), T1–T12 length (Tle), thoracic perimeter (Pe), transversal diameter (TD) and anterior–posterior depth of thoracic cage

reached 80.2% and 76.8% of its final size in girls and boys, respectively (Fig. 5).

The circular cross section of the very young child's thorax reached adult-like proportions together with its ovoid shape before age 6 years. This age-related shape change can be quantified using the AP/TD ratio, also known as the Thoracic Index. A value close to 1 indicates a circular cross section, a value less than 1 an oval cross section [5, 7, 12–14, 23, 30]. In our cohort of healthy subjects, the AP/TD ratio remained below 1 in all age groups, indicating that changes most likely occurred before age 6 years (Table 2). Oppenshaw et al. evaluated chest radiographs from 38 individuals aged 1 month to 31 years and computed tomography scans from 28 individuals aged 3 months to 18 years. They reported marked changes in the thoracic cage shape during the first 3–4 years of life. However, they pooled boys and girls [24, 28]. Despite the study limitations, our data corroborate the hypothesis of Oppenshaw et al. This is further supported by the fact that about 30–50% of alveoli are present at birth and from the late fetal stage to 4 years of age, the number of alveoli grows by a factor of ten. It appears that the most important events that characterize the "rib–vertebral–sternal complex" development occur during the first few years of postnatal growth [1, 17, 27]. After this early period, as shown by Bastir et al., the upper thorax grows more relative to the lower portion, transforming the pyramidal infant thorax into the barrel-shaped one of adults [1].

Contrary to previous studies, our data come from patients measured in a standing position. Romei et al. report that variation in posture may affect shape and function of the thoracic cage [1, 31].

The most important limitation of our study is the lack of data acquired in children younger than age 5 years due to lack of compliance in infants aged 1–4 years.

The second limitation is that data analyzed here may not be transferable between populations or from one country to another. Looking beyond racial diversity, there are growth constants (i.e., stages through which every child must pass regardless of chronologic age) that are the same within ethnic groups. Additional differences between genders might be found in an analysis of a larger cohort of subjects.

Thirdly, data were obtained in a static position, as we did not investigate the biomechanical changes of the thoracic cage occurring during breathing. However, all patients were assessed in a static, standardized standing position.

In conclusion, this study assessed thoracic dimensions and volume by optoelectronic molding in a large cohort of males and females, from early childhood to skeletal maturity. It provides a set of normal values for thoracic cage volume, AP, TD, AP/TD, thoracic perimeter, sternal length and T1–T12 length. These data give the clinician reference values to appraise the impact of a spinal deformity on thoracic cage dimensions and volume and can be used for evaluating and comparing the thoracic cage shapes of patients with or without progressive spinal deformities.

Compliance with ethical standards

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