

Axial and appendicular body proportions for evaluation of limb and trunk asymmetry

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Submitted 2015-12-11. Accepted 2016-10-11

Non-standard abbreviations

ASIS – Anterior Superior Iliac Spinous Height
EA – Entire Arm Length
FA – Forearm Length
H – Hand Length
K – Knee Height
SiH – Sitting Height
StH – Standing Height
T – Tibial Length
UA – Upper Arm Length

Background and purpose — When children with irregular body proportions or asymmetric limbs present, it may be unclear where the pathology is located. An improved understanding of the clinical ratio between upper extremity, lower extremity, and spine length may help elucidate whether there is disproportion between the trunk and limbs, and whether there is a reduction deficit of the shorter limb rather than hypertrophy of the longer limb.

Patients and methods — We used the Brush Foundation study of child growth and development, which was a prospective, longitudinal study of healthy children between the 1930s and the 1950s, and we collected serial clinical measurements for 290 children at 3,326 visits. Children ranged from 2 to 20 years of age during the study period. Linear and quadratic regression were used to construct nomographs and 95% prediction intervals for anthropometric body proportions.

Results — The maximum anterior superior iliac spine height to sitting height ratio occurred at 12.4 years in females and at 14.17 years in males. Overall, the ratio of arm length to sitting height was 0.76 (SD 0.06), the ratio of arm length to anterior superior iliac spine height was 0.76 (SD 0.03), and the ratio of anterior superior iliac spine height to sitting height was 0.98 (SD 0.13). When comparing ratios between arm length, anterior superior iliac spine height, and sitting height, the smallest variance between appendicular proportions was found in the arm length to anterior superior iliac spine height ratio.

Interpretation — We recommend comparisons between total arm length and anterior superior iliac spine height to distinguish limb reduction deficits from hemi-hypertrophy, with sitting height being used only if combined upper and lower extremity discrepancy is noted.

Anthropometric body proportions afford the clinician diagnostic criteria during the assessment of irregular growth. During the work-up of tall or short stature, comparison of ratios of upper and lower segment heights can be used to aid in the diagnosis of Klinefelter's syndrome, Marfan syndrome, and other conditions (Eveleth and Tanner 1976). For individuals with deformity of the extremity, limb amputations, or those with muscle contractures, anthropometric ratios can be used to compare, predict, and extrapolate limb measurements—which are then used to guide certain treatments. (Herber and Milner 1987, Yun et al. 1995, Cheng et al. 1996, Fredriks et al. 2005) Similarly, when children present for the evaluation of asymmetric extremities, it can be unclear on visual inspection whether a limb reduction deficit or hemi-hypertrophy is present. Physical examination alone can be insufficient to be able to determine this (Ballock et al. 1997), so normative data can be helpful when making a diagnosis.

To our knowledge, there has been no large series of Caucasian body proportions relevant to the evaluation of skeletal disorders. The existing literature has shown important differences between sexes and racial groups for a number of body proportions; however, most of these data are not organized on parameters pertinent to orthopedic evaluation (Zorab et al. 1963, Piedade et al. 1977, Palomino et al. 1978, Engstrom et al. 1981, Johnston et al. 1982, Ohyama et al. 1987, Jacobs et al. 1988, Jarzem and Gledhill 1993, Leung et al. 1996). It would therefore be valuable to have representative human body proportions for a range of ages. Consequently, we analyzed the records of a large, prospectively collected growth inquiry containing the anthropometric dimensions of Caucasian children. This information provided a reference regarding normal body

proportions, which could be used in the diagnosis of disproportionate growth of the axial and appendicular skeleton.

Patients and methods

The Brush Foundation study of child growth and development

Data in this study were taken from 290 patients in the Brush Foundation Growth Inquiry who were enrolled from 1930 through 1942. The Brush Foundation study was a longitudinal growth inquiry that included a population of children from northeast Ohio. These children had been approved by family physicians and were selected for enrollment from local schools based on their exceptional health (Nelson et al. 2000). These individuals were declared free of any systemic disease, and were believed not to have any structural deformity. The children were examined at 3, 6, 9, and 12 months of age, then every 6 months until they were 5 years old—at which point they were examined on an annual basis. The majority of these children were above-average economically and educationally. Essentially all of them were Caucasian. The 290 participants used in this study were differentiated and selected from the other 999 Brush Foundation participants on the basis of having had either a large number of total visits or a large number of visits about the time of skeletal maturity.

Anthropometric dimensions

Measurements of limb and body proportions were made by Dr T. Wingate Todd and the study coordinators at the Laboratory of Anatomy, Case Western Reserve University, from 1930 through 1956. Measurements were taken on the left side, in normal dress clothes with shoes removed. The measurement techniques relevant to this study included: Standing Height (StH), measured free-standing from the vertex of the skull to the floor with an anthropometric rod; Sitting Height (SiH), measured with the subject sitting on a flat bench with spine and neck as erect as possible with head in the Frankfort plane. Measurement was made from the bench to the vertex of the skull; Anterior Iliac Spinous Height (ASIS), measured from the highest point on the curve of the anterior superior spine of the ilium to the floor. This measurement was used to represent the lower extremity height; Knee Height (K), from the superior border of the medial condyle of the tibia to the floor; Tibial Length (T), measured in the recumbent position, with knee flexed, and thigh abducted and laterally rotated. The measurement was made from the proximal margin of the medial condyle of the tibia to the distal border of the medial malleolus; Entire Arm Length (EA), measured from the inferior surface of the tip of the acromion to the tip of the middle finger; Upper Arm Length (UA), measured from the tip of the acromion to the proximal margin of the head of the radius; Forearm Length (FA), measured from the proximal margin of the head of the radius to the distal end of the radial styloid;

Hand Length (H), measured from the end of the radial styloid to the tip of the middle finger.

All values were recorded to the nearest millimeter. A complete description of the measurement techniques is available (Simmons and Greulich 1944).

There were 290 patients with 3,326 unique visits. The average number of visits per patient was 11.5, with 89 patients (31%) having a complete series of 23 measurements between the ages of 3 months and 16 years. There were 151 boys and 139 girls.

Statistics

Comparisons of the spine or comparisons relating to axial height (ASIS, SiH, StH) were correlated to age by plotting each data point, and subsequently generating a series of regression model candidates in order to determine if there was a linear or a non-linear relationship. All axial height data were initially considered to be linearly dependent on age, but simple linear regression failed to fit the data. A polynomial equation was therefore introduced, along with potential models for exponential, logarithmic fit. Each model was visually inspected for goodness-of-fit, analysis of residual plots, and R-squared values. After confirming earlier reports that quadratic regression was the most appropriate for comparisons involving age, 95% confidence intervals (CIs) were calculated and plotted based on the intercept coordinate (Fredriks et al. 2005).

The regression modeling was repeated for individual limb proportions. Comparisons of axial and appendicular proportions, independent of age, were best modeled with direct linear regression, as also shown earlier (Cheng et al. 1996).

For each regression model, the probability plots of the regression standardized residual were inspected for normality, scatter plots of the standardized residuals were inspected for homoscedasticity, and the lack of any undue influence from outliers was confirmed with a Cook's distance of < 1 . 95% prediction intervals of the constant (intercept) were calculated and plotted (Ratkowsky 1970, Harrell 2001, Roth 2009). Variability within and between subjects was separated by fitting conditional (mixed) models. Variables were assumed to be normally distributed after analysis of P-P and Q-Q plots. No reliability corrections were necessary for any comparison. Multicollinearity was assessed through inspection of individual coefficient tolerances and VIF values, all of which were below 10.

To determine the age ranges for which these ratios were most consistent, the 1-year changes in each ratio were plotted against age using the serial measurements for each individual child. The mean and standard deviation (SD) for different age ranges were plotted. All comparisons were done separately for each sex. SPSS version 22.0 was used for all data analyses. Significance was set at $p < 0.05$.

Ethics

This study was approved by the UHCMC institutional review board (approval number: 08-14-28).

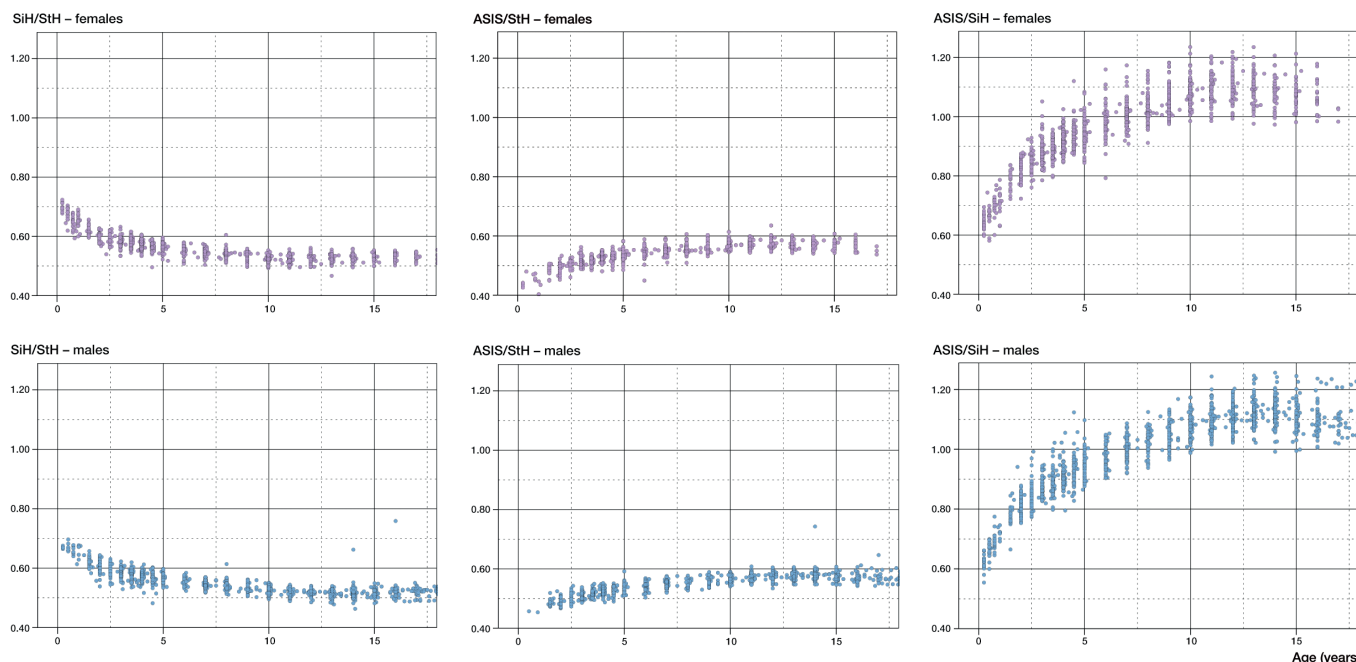


Figure 1. Sitting Height/Standing Height (SiH/StH), ASIS/Standing Height (ASIS/StH), and ASIS/Sitting Height (ASIS/SiH) plotted for females and males. Visual inspection and regression modeling confirms a non-linear relationship.

Results

Axial proportions with age

A quadratic regression analysis was performed to compare the ratios of SiH/StH, ASIS/StH, and ASIS/SiH with age (Tables 1 and 2, see Supplementary data). Raw data points were plotted for each sex (Figure 1), as well as 95% prediction intervals with superimposed quadratic regression lines (Figure 2).

Appendicular proportions

Linear regression was used to compare individual ratios independently of age (Tables 3 and 4, see Supplementary data). Raw data points were plotted for each sex (representative example, Figure 3), as well as 95% prediction intervals with superimposed linear regression lines (representative examples, Figure 4, see Supplementary data).

The mean and standard deviations of EA, SiH, and ASIS proportions were plotted in 2-year increments (Figure 5). The overall ratio of EA to SiH was 0.76 (SD 0.06), the ratio of EA to ASIS height was 0.76 (SD 0.03), and the ratio of ASIS to SiH was 0.98 (SD 0.13). The standard deviations for the overall population and each 2-year increment were smallest in the EA to ASIS comparison.

Change in proportions per year

The minimum rate of change ($-b/2a$) of ASIS/SiH occurred at a mean age of 12.4 years for females and 14.2 for males. The means and standard deviations for select ratios, along with the average 1-year change in ratios and their standard deviations,

were plotted along with the average change in ratio for each 1-year age interval (Table 5 and Figure 6, see Supplementary data). Comparisons between EA, ASIS, and SiH show that EA/ASIS becomes fairly consistent by 3 years of age with ratios changing less than 0.02 after that point, while EA/SiH and ASIS/SiH have fluctuations above 0.02 until 9 and 13 years, respectively.

Discussion

Our results provide normative information on human body proportions in growing Caucasian children. To our knowledge, this is the largest and most complete study of anthropometric proportions reported in the literature. The reference charts provided will be useful in evaluating numerous clinical situations.

This study and others showed that the relationships between body proportions and age are non-linear and best modeled quadratically—with slight but statistically significant differences between sexes. (Cheng et al. 1996, 1998, Bogin et al. 2002). The ratio of Sitting Height to Standing Height has been used to diagnose children with abnormally tall or short stature. Marfan syndrome, Klinefelter's syndrome, and gonadotropin deficiency are examples of diseases associated with tall stature. Conditions associated with short stature, such as hypochondroplasia, are characterized by disproportionately short legs. In both instances, these diseases present similar clinical and diagnostic challenges when the confirmatory genetic test-

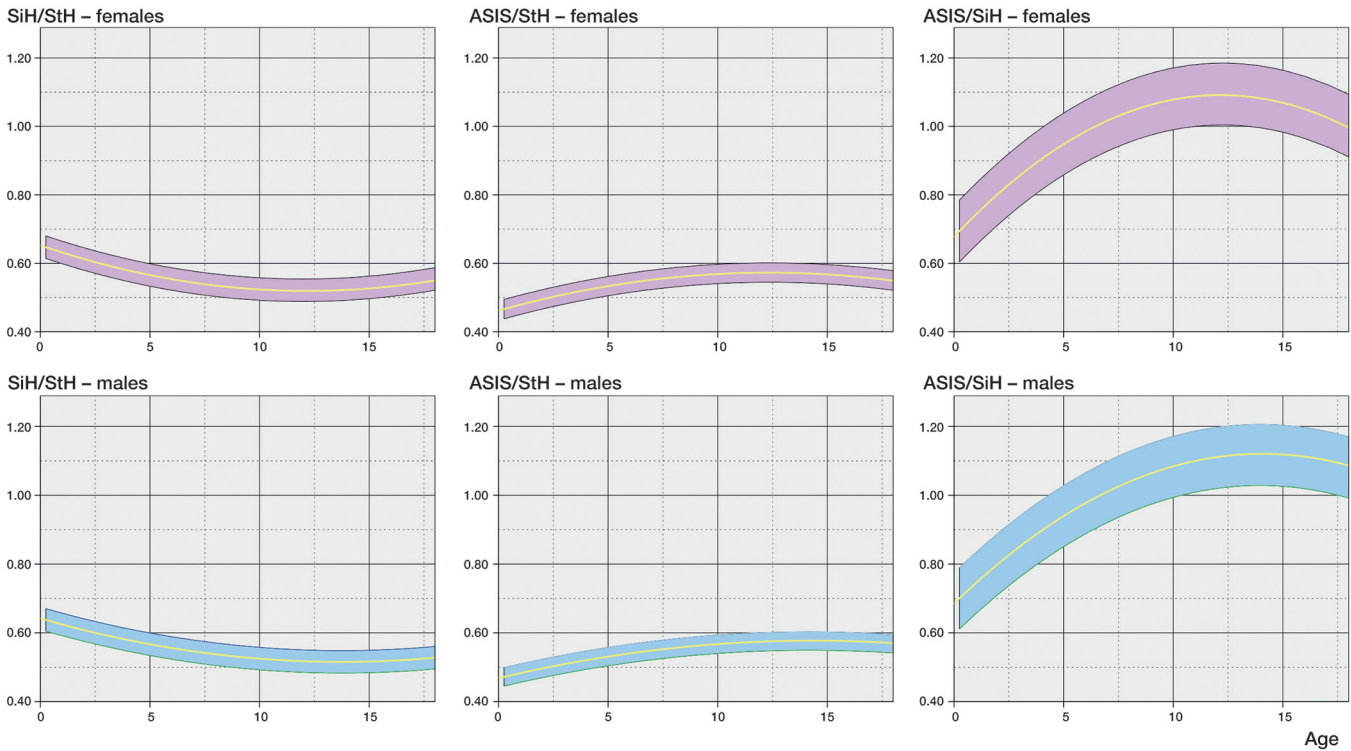


Figure 2. Sitting Height/Standing Height (SiH/StH), ASIS/Standing Height (ASIS/StH), and ASIS/Sitting Height (ASIS/SiH) ratios versus age are quadratically modeled. The exact regression lines (yellow) are taken from the coefficients in Tables 1 and 2. The pink area and blue area represent the 95% confidence intervals for girls and boys, respectively. For SiH/StH, the minimum x-coordinate for any quadratic equation can be calculated from $(-b/2a)$. In this example, the minimum SiH/StH occurred at 12.17 years in females and 14.17 years in males.

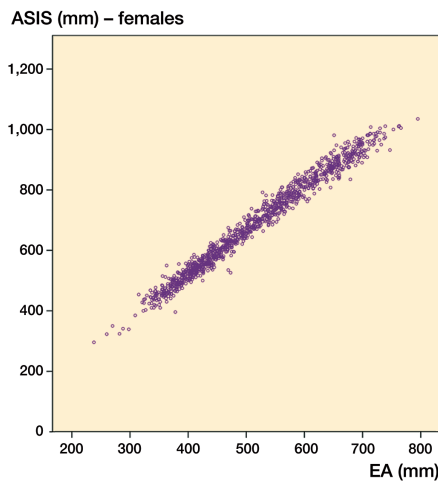


Figure 3. Entire Arm Length (EA) plotted against ASIS in females shows a strongly positive linear correlation. This example includes 1,392 data points. This was a representative example chosen from individual proportions in Tables 3 and 4.

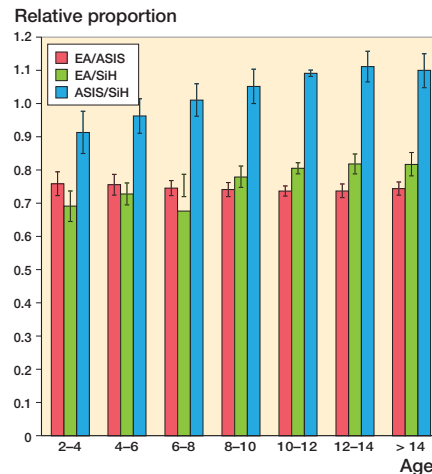


Figure 5. Entire Arm Length (EA)/ASIS, Entire Arm Length (EA)/Sitting Height (SiH), and ASIS/Sitting Height (SiH): mean and standard deviations plotted in 2-year intervals. The figure demonstrates that the ratio between Entire Arm Length and ASIS varied the least with age, and had a consistently smaller standard deviation at each age.

ing required is not available (Judge and Dietz 2005, Chang et al. 2015). Fredriks et al. (2005) showed that patients with Sitting Height/Standing Height ratios 2 standard deviations below the mean had a likelihood ratio 15-times higher for a positive genetic test result confirming a diagnosis of Marfans

in Dutch children. Similarly, these authors showed that when evaluating patients for suspected hypochondroplasia, 8 out of 10 had Sitting Height/Standing Height ratios 2 standard deviations above the mean (80% sensitivity). These authors presented their findings using an alternative statistical analysis,

making it impossible to directly compare our anthropometric model to theirs. However, the Sitting Height/Standing Height nomograms and ratios presented by Fredriks et al. directly reflect those reported in the present study.

In this study, the maximum value for ASIS/Sitting Height occurred at a mean age of 12.4 years for females and 14.2 for males. This can be explained by the relative increase in trunk growth that occurs after puberty. In accordance with this, pre-pubescent development is characterized by more rapid growth in limbs. These trends are identical to data presented elsewhere (Tanner et al. 1970, Steele and Mattox 1987). A study done in Chinese children (Cheng et al. 1996) showed similar body proportions for Sitting Height/Standing Height ratios, and similar trends for lower extremity comparisons even though the measuring techniques varied slightly.

We found a strong linear relationship between each of the anthropometric ratios. These proportions were chosen based on what we believe represents the most clinically meaningful information relevant to the work-up of an asymmetric limb. In general, comparisons of upper segment axial proportions to the lower segment height (ASIS) showed less variability than those to the spine. This is probably due to continued trunk (spine) growth into adolescence. Due to this, we recommend comparisons between the upper and lower extremities when trying to evaluate limb asymmetry, with comparisons to the spine only being used when both the upper and lower extremities are affected. Comparisons to upper extremities consistently showed less variability.

There were statistically significant differences in body proportions between sexes, with males having proportionally longer arms and females having proportionally longer legs. Similar trends have been reported by other authors, who have debated the etiology and consequences of these findings. Some explanations have focused on the energetics of locomotion, climate adaptations, and the biomechanical advantages relating to fitness in both sexes (Eveleth 1978, Himes 1979, Aiello and Wells 2002, Bogin et al. 2002).

The example clinical scenarios presented above give insight into some of our intended applications during the work-up of asymmetric extremities. However, the results of our study may have other implications outside of our primary purpose. For example, Tanner's fundamental work on growth and sexual development relied on anthropometric data (Tanner et al. 1956, Tanner 1962, Tanner et al. 1970). Paley et al. (2000) presented the "multiplier method" for calculating predicted limb discrepancy at skeletal maturity. There has also been interest in estimating height from appendicular length (Rongen-Westlaken et al. 1997, Silventoinen 2003). Other genetic conditions not discussed, such as Turner's syndrome, Prader-Willi syndrome, among others, rely on such anthropometric information (Hughes et al. 1986, Cassidy 1997, Festen et al. 2008).

Our study had some limitations. In constructing the regression models, all individuals and data points were combined. Therefore, the growth trend lines for specific individuals were

different in each case. However, averaging of all specimens together offers the reader the statistical advantage of maximizing power and effect size, and provides a correlation representative of the entire population (Sokal and Rohlf 1995, Tabachnick and Fidell 2001). Only Caucasians were included, so the applicability to other races is limited. All ratios that we obtained were from measurements collected during the 1930s to 1950s. It is possible that they may not be representative of modern individuals. Mul et al. (2001) have shown that a change in secular growth has occurred over the past 200 years, with lower segment length representing an increasing percentage of total height. Tanner et al. (1982) made similar observations in a Japanese population from 1957 through 1977. Given the large amount of resources involved in collecting data for this study, we suspect that it would be impractical to replicate it in the present day.

Similarly, given the long period of data collection involved, not all measurements were performed by the same individual. Roche and Sun (2005) acknowledged that there was considerable inter-experimenter variability for Sitting Height and Standing Height, which differed by an average of 0.3 cm and 0.5 cm, respectively, in the Fels longitudinal study. Dimeglio et al. (2001) suggested that the difficulties of collecting anthropometric measurements in young children are largely to blame for variations in body proportions in this age range. However, Tanner et al. (1976) and Wales et al. (1992) reported less inter-observer variability and suggested that variations are more likely to be due to external influences rather than experimenter error. To our knowledge, there is no inter-experimenter reliability information available. However, the meticulous measurement techniques employed by Todd and his colleagues have been described in earlier literature (Cobb 1959), and the R-squared values obtained in this study equaled or exceeded those in comparable reports. Finally, it has been suggested that the age of puberty has been changing over the past 50 years, which would contribute most to changes in axial proportions. (Marshall and Tanner 1970, Palmert and Dunkel 2012).

In summary, these normative data serve as a reference for axial and appendicular body proportions in Caucasians. Tables 1–4 can be used to derive practical values from the regression models presented. Where possible, we recommend that comparisons be made from the upper segment (EA) and lower segment (ASIS) proportions, as these values fluctuated less with age. Moreover, distinguishing of hemi-hypertrophy from a limb reduction deficit can be best achieved by examining the linear relationship between ASIS and total arm length, with the use of Sitting Height being reserved for combined upper and lower extremity deformity.

Clinical examples

Clinical application example 1

A girl of 4 years and 3 months of age is evaluated for short stature. There is a family history of hypochondroplasia. Using measuring techniques described above, the physician mea-

sures a Sitting Height (SiH) of 600 mm and a Standing Height (StH) of 900 mm.

(1) Determine the average value for the SiH/StH ratio (Table 1):
 $(\text{SiH}/\text{StH}) = 0.00086 (\text{age})^2 - 0.02190 (\text{age}) + 0.6525$

$(\text{SiH}/\text{StH}) = 0.00086 (4.25)^2 - 0.02190 (4.25) + 0.6525 = 0.58$

Alternatively, the reader can simply refer to Figure 4a to confirm this visually. The 95% CI is from approximately 0.54 to 0.62.

(2) The SiH/StH ratio for this child is 600 mm/900 mm = 0.67

Conclusion: The ratio in this example (0.67) is well above the 95% confidence interval for that age range, indicating that the child has relatively more trunk length than lower extremity length.

Clinical application example 2

A six-year-old Caucasian boy presents for evaluation of asymmetric upper extremities. Using measurement techniques described above, the physician measures an ASIS height (ASIS) of 650 mm, a right arm length (EA) of 525 mm, and a left arm length of 495 mm.

(1) Determine the average value for EA as a function of ASIS (Table 4):

$(\text{EA}) = 0.569 (\text{ASIS}) + 168.082$

$(\text{EA}) = 0.569 (650) + 168.082 = 537.93 \text{ mm.}$

(2) Determine the upper and lower bounds of the 95% PI for EA as a function of ASIS:

Upper 95% CI (EA) = $0.569 (650) + 220.351 = 590.201 \text{ mm}$

Lower 95% CI (EA) = $0.569 (650) + 122.260 = 492.11 \text{ mm}$

Conclusion: The right arm (EA) falls within the 95% PI for the respective ASIS height, but the left arm (EA) does not, suggesting a hypoplastic left arm. Figure 6b could have been used to extrapolate this information from the inverse plot. Note that the age of the patient is not included in this calculation.

Clinical application example 3

A 13-year-old boy with achondroplasia presents at a specialized limb deformity center. After extensive personal research into the subject and lengthy discussions with several physicians and among the family, the child would like to pursue lengthening surgery of both humeri, and both femora and tibiae. His Sitting Height is 700 mm, the Entire Arm Length is 425 mm, and ASIS height is 545 mm. What amount of lengthening would help him take on average body proportions?

(1) Determine the average value and lower limit of the 95% PI for EA as a function of SiH (Table 4):

$(\text{EA}) = 1.043 (\text{SiH}) - 189.452$

$(\text{EA}) = 1.043 (700) - 189.452 = 540.64 \text{ mm}$

(lower end of 95% CI is 448.379 mm)

(2) Determine the average value and lower limit of the 95% CI for ASIS as a function of SiH (Table 4):

$(\text{ASIS}) = 1.570 (\text{SiH}) - 418.800$

$(\text{ASIS}) = 1.570 (700) - 418.800 = 680.2 \text{ mm}$

(lower end of 95% PI is 540.243 mm)

Conclusion: His Entire Arm Length discrepancy is 448.379 mm – 425 mm = 23.379 mm from the lower end of 95% CI, and 115 mm from average proportions. His lower extremity length discrepancy is 540.243 mm – 535 mm = 5.0243 mm from the lower end of 95% CI, and 135.2 mm from average proportions.

An online body proportions calculator is available:
www.pedslimbdeformity.com

Supplementary data

Figures 4 and 6 and Tables 1–5 are available as supplementary data in the online version of this article <http://dx.doi.org/10.1080/17453674.2016.1265876>.

DW helped design the study, collected data, conducted data analysis, performed statistical computations, drafted the manuscript, and approved the final version as submitted. RL organized the research group, helped design the study, reviewed and interpreted data, critically reviewed and edited the manuscript, and approved the final version as submitted. SL helped design the study, collected data, reviewed and edited the manuscript, and approved the final version as submitted. JS conceptualized the study, designed the study, created and organized a large database, interpreted the data, critically reviewed and edited the manuscript, and approved the final version as submitted. DC conceptualized the study, designed it, interpreted the data, critically reviewed and edited the manuscript, and approved the final version as submitted.

There were no internal or external sources of funding.

No competing interests declared.

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