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Original article

Lower-Limb Lengths and Angles in Children Older than Six Years: Reliability and Reference Values by EOS® Stereoradiography

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ABSTRACT

Background: Lower-limb alignment in children is classically assessed clinically or based on conventional radiography, which is associated with projection bias. Low-dose biplanar radiography was described recently as an alternative to conventional imaging. The primary objective of this study was to assess the reliability of length and angle values inferred from 3D reconstructions in children seen in everyday practice. The secondary objective was to obtain reference values for goniometry parameters in children.

Hypothesis: 3D reconstructions can be used to assess the lower limbs in children.

Material and methods: The paediatric reliability study was done in 18 volunteers who were divided into three groups based on whether they were typically developing (TD) children, had skeletal development abnormalities, or had cerebral palsy. The reference data were obtained in 129 TD children. Each study participant underwent biplanar radiography with 3D reconstruction performed by experts and radiology technicians. Goniometry parameters were computed automatically. Reproducibility was assessed based on the intra-class coefficient (ICC) and the ISO 5725 standard (standard deviation of reproducibility, SD_R).

Results: For length parameters, the ICCs ranged from 0.94 to 1.00 and the SD_R from 2.1 to 3.5 mm. For angle parameters, the ICC and SD_R ranges were 0.60-0.95 and 0.9°-4.6°, respectively. No significant differences were found across experts or radiology technicians. Age-specific reference data are reported.

Discussion: These findings confirm the reliability of low-dose biplanar radiography for assessing lower-limb parameters in children seen in clinical practice. In addition, the study provides reference data for commonly measured parameters.

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Level of evidence: IV

Key Words: Lower limb. Low-dose biplanar X-ray imaging. Paediatrics.

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1. INTRODUCTION

Assessing lower-limb alignment is crucial in children to detect developmental abnormalities and to provide treatment guidance. However, few studies based on accurate measurement methods have provided data on normal paediatric values. Coronal lower-limb alignment in children is classically evaluated using semi-quantitative clinical [1] and radiological [2] methods. Radiography is associated with projection bias [2] but is nevertheless more accurate than clinical methods [3-6]. Salenius *et al.* [2] reported substantial uncertainty with tibio-femoral angle (TFA) values measured on conventional radiographs, particularly in children with combined axial abnormalities.

A reconstruction method based on low-dose biplanar calibrated images and a 3D model was validated recently as a tool for evaluating the radiological parameters of numerous anatomical structures [7-11]. This imaging and 3D reconstruction technique emerged as a promising alternative to the above-mentioned conventional procedures [12,13]. Gaumetou *et al.* established its reliability for evaluating segmental torsion of the lower limbs in children and adults [12].

Until now, studies of lower-limb parameters measured on low-dose biplanar radiographs focussed chiefly on differences between 2D and 3D values [14] or on comparing torsion measurements with those obtained by computed tomography [15]. Furthermore, most studies of reliability were conducted by research groups. Thus, whether low-dose biplanar radiography is reliable when performed in everyday practice by radiology technicians trained in conventional techniques has not been proven. Finally, according to a systematic literature review, available

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studies focussed chiefly on the technical usefulness of the method, and clinical studies need to be performed [16].

The primary objective of this study was to assess the reliability of length and angle values inferred from 3D reconstructions in children seen in everyday practice. The secondary objective was to obtain reference values for goniometry parameters in children. The working hypothesis was that 3D reconstructions can be used to assess the lower limbs in children.

2. PATIENTS AND METHODS

(2.1) Study participants

This study was approved by the appropriate ethics committees (CPP 06001 for Arts et Métiers ParisTech and 2013-A01568-37, N°76 09 2013 for the Nice paediatric hospitals CHU-Lenval). Informed consent was obtained from the patients and parents before study inclusion.

In all, 141 participants were included. Among them, 18 were volunteers aged 6 to 15 years who were recruited at the outpatient clinic for the reliability study. Of these 18 participants, 6 were typically developing (TD) children in whom radiographs were prescribed for non-orthopaedic medical reasons, 6 were non-TD (NTD) children with minor orthopaedic abnormalities that did not affect the study parameters, and 6 had cerebral palsy (CP). All 18 children were able to stand without help.

The collection of reference data was done in 129 TD children aged 6 to 15 years (including the 6 in the reliability study). Recruitment was during a paediatric orthopaedics visit, which allowed the exclusion of patients with axial, rotational, and/or length abnormalities. Both

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lower limbs of each participant were included, for a total of 258 lower limbs. The 129 participants were divided into four age groups as shown in Table 1 [12].

(2.2) Methods

Each participant underwent low-dose biplanar radiography using the EOS® system (EOS® Imaging, Paris, France), at one of two study sites (Arts et Métiers-ParisTech in Paris, n=82; and CHU-Lenval in Nice, n=59). The participant was standing in the shifted feet position [10]. Using biplanar images acquired within a calibrated environment and STEREOS software version 1.6.4.7977 [10, 12], the operator identified anatomical landmarks on the antero-posterior and lateral views, to obtain geometric parameters describing the lower limb. Based on these geometric parameters, the software automatically generated a pre-personalised 3D reconstruction, which was then back-projected onto the coronal and sagittal radiographs. The operator adjusted the contours of the 3D model to match the radiographic views. Based on the geometric parameters and specific points on the 3D model, the software automatically computed 3D angles and distances. For this study, the 3D angles were projected onto the coronal and sagittal planes to allow comparisons of 2D measurements with those reported previously. The following radiographic parameters were computed automatically: femoral mechanical angle (FMA), tibial mechanical angle (TMA), hip-knee-shaft angle (HKS), femoro-tibial angle (FTA), femoral head diameter (FHD), femoral neck length (FNL), and neck-shaft angle (NSA). The ratio of femoral over tibial length (F/T) was computed.

(2.3) Analysis method

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For the reliability study, reconstructions of each lower limb were obtained twice, in each of three independent paediatric orthopaedics centres. One reconstruction was done by an expert (orthopaedic surgeon with an in-depth understanding of the method) and by a radiology technician trained in the reconstruction technique and everyday use of the software. Thus, for each lower limb of each of the 18 participants, 6 reconstructions were obtained.

(2.4) Statistical analysis

The intra-class coefficient (ICC) and standard deviation of reproducibility (SD_R) were computed. For the SD_R, the ISO 5725 standard was used [17]. Reliability was then assessed based on a 95% confidence interval (95%CI) of $2 \cdot SD_R$. Finally, the values obtained by experts and technicians were compared.

The mean and standard deviation (SD) of each parameter were computed for the 129 participants in the reference data study and for the 6 NTD patients and 6 CP patients. Distribution normality was assessed using the Kolmogorov-Smirnov test. For each parameter, the mean and SD served to define normal channels (mean±1 SD), high and low subnormal channels (between mean±1 SD and mean±2SD), and high and low abnormal channels (> or < mean±2SD). Differences across age groups and between experts and technicians were evaluated using Student's t test (Statistica® software, Francisco Partners, San Francisco, CA, USA), with p values <0.05 considered significant.

3. RESULTS

Reliability (Table 2)

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For length parameters, the ICC values ranged from 0.94 to 1.00 and the SD_R values from 2.1 to 3.5 mm. The corresponding values for angle parameters were 0.60-0.95 and 0.9°-4.6°. No significant differences were found between experts and technicians for these parameters (p>0.5).

Reference data for lower-limb 3D radiological parameters

The values of all parameters were normally distributed. Table 1 reports the means and SDs of each parameter in each age group and Figures 1 to 4 the changes according to age. F/T was the most stable parameter, with a mean of 1.1±0.03 in all age groups. FNL was the parameter showing the greatest age-related changes, with a range of 131°±5° to 136°±7° across age groups.

Tables 3 and 4 report the normal, high and low subnormal, and abnormal values for each parameter. Data from the NTD and CP groups are shown in Table 5 and Figures 1 to 4.

4. DISCUSSION

To our knowledge, this is the first study establishing the reliability of lower-limb 3D reconstruction in children seen in everyday clinical practice. In addition, except for a study focussed on rotational parameters [12], no other studies have provided reference values for lengths and angles determined in children using 3D images.

The main limitation of this study is that the design was cross-sectional and not longitudinal. Females predominated, particularly in the 6- and 7-year-olds (Table 1). However, in this youngest age group, overall morphology shows no marked differences between girls and boys. On the other hand, the sex ratio imbalance precluded a reliable comparison of parameter

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values between females and males. For this study, we elected to consider only chronological age, as no difference with bone age was to be expected in our population of healthy children. Obtaining radiographs for bone age determination in the absence of a clinical indication would have been ethically debatable. Finally, the lower age limit of 6 years reflects a limitation of the EOS® system: the patient must stand immobile for about 10 s, which is difficult for children younger than 6 years.

The primary objective of this study was to assess the reliability of angle and length parameter values derived from 3D reconstructions in children seen in everyday practice. To this end, we determined both the ICC and the SD_R values. The ICC provides an overall estimate of the correlation between measurements by different observers but does not quantitatively evaluate the degree of uncertainty. Bland and Altman pointed out that correlations linking data values were not the most relevant assessment because, in clinical practice, quantitative values and information about uncertainty are required to establish a diagnosis (relative to normal channels) and for monitoring a patient over time [19]. The ISO 5725-2 standard describes “the basic method for the determination of repeatability and reproducibility of a standard measurement method” [17]. Consequently, in addition to ICC values, we computed SD_R values. Inter-observer reproducibility and 95%CIs of length parameters, although slightly less favourable than in research studies [10,11,18], are sufficient for clinical purposes. Reproducibility for angle parameters is comparable to previous data [10, 11, 18] (Table 2). Finally, compared to manual or automated measurements on conventional radiographs, reproducibility is better in our study [20].

The secondary objective of this study was to obtain reference values for lower-limb radiological parameters in health children. The availability of reference values is crucial to the

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optimal management of lower-limb abnormalities. To the best of our knowledge, no reference data for lower-limb length parameters, the NSA, or the HKS angle in children have been reported. Thus, our study provides original data.

Length parameters

FHD and FNL increased, as expected, throughout growth, and their values in the oldest age group (13 to 15 years) were similar to those reported in adults [21]. F/T remained stable throughout growth, with very little variability (SD, ±0.03). The F/T value is closely similar to that reported by Than *et al.* [21] in adults (1.2). This finding is of special interest, since evaluating the ratio of femoral and tibial lengths, for instance when planning limb lengthening, is of the utmost importance. In addition, in constitutional bone disorders, metaphyseal and epiphyseal abnormalities negatively affect bone growth, and reference to a normal F/T ratio is useful for correcting the abnormalities.

Angle parameters

The FMA and TMA values in our study are slightly higher than those reported by Sabarwhal *et al.* (87°-88° and 88°-90°, respectively). This difference is probably ascribable to the use in our study of 3D measurements, which eliminates problems related to measurements on a 2D projection of a 3D object when standard radiographs are used [22]. The decrease in valgus angulation after 7 years of age is consistent with reported data [2,3,22,23].

Patients in the NTD and CP groups

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Although evaluating abnormal lower limbs was not our objective, our study shows that the parameters whose values remained unchanged across age groups in the TD children (FMA, TMA, FTA, NSA, and F/T) were also unchanged in our NTD and CP children able to walk unassisted.

In conclusion, to our knowledge this is the first study focussing the key issue of the objective evaluation in everyday practice of coronal lower-limb alignment based on 3D reconstructions from low-dose biplanar X-ray images. The results confirm that the EOS® system can be used in everyday practice to assess the lower limbs of children, including those with orthopaedic deformities or cerebral palsy. The absence of statistically significant differences between values obtained by experiences orthopaedic surgeons and radiology technicians established that properly trained radiology techniques can perform the reconstructions.

In addition, the reference data provided here are parts of a continual effort to assist physicians in assessing lower-limb alignment, with the goal of improving patient monitoring or planning treatment strategies.

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Disclosure of interest: None of the authors has any conflicts of interest to disclose.

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Table 1. Main characteristics of the 129 study participants, by age group

	Group I 6 - 7 years	Group II 8 - 9 years	Group III 10 - 12 years	Group IV 13 - 15 years
Number of participants	18	21	56	34
Females/Males	16/2	13/8	43/13	20/14
Angles (°), mean±SD				
FMA	93 ± 2	93 ± 2	93 ± 2	93 ± 2
TMA	89 ± 2	88 ± 2	89 ± 2	87 ± 2
FTA	178 ± 2	179 ± 3	174 ± 4	177 ± 5
NSA	137 ± 8	131 ± 6	134 ± 5	132 ± 7
HKS	2 ± 1	3 ± 2	5 ± 1	5 ± 2
Longueurs (mm), mean±SD				
FHD	30 ± 2	34 ± 3	37 ± 3	42 ± 3
FNL	33 ± 5	40 ± 5	44 ± 5	52 ± 6

FMA, femoral mechanical angle; TMA, tibial mechanical angle; FTA, femoro-tibial angle; NSA, neck-shaft angle; HKS, hip-knee-shaft angle; FHD, femoral head diameter; FNL, femoral neck length

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Table 2. Intra-class coefficient (ICC) and standard deviation of reproducibility (SD_R) of the radiological parameters studied and comparison with previously reported data

Parameter	SD repeatability	SD reproducibility	95%CI	ICC	Chaibi et al. [10]	Chaibi et al. [10]	Quijano et al. [11]	Assi et al. [18]	Assi et al. [18]
					Fast 3D	Full 3D		TD	PC
					95%CI	95%CI	95%CI	95%CI	95%CI
Lengths (mm)									
FHD	1.0 mm	0.9 mm	2.1 mm	0.96	1.6	1.4	1.6		
FNL	1.7 mm	1.5 mm	3.4 mm	0.95					
FL	1.2 mm	1.1 mm	2.4 mm	1.0	2.4	1.8	1.9		
TL	1.6 mm	1.6 mm	3.3 mm	0.99	2.3	2.3	2.2		
Angles (°)									
FMA	1.2 °	1.2 °	2.5 °	0.81	2.7	1.3	2.3	0.7	0.7
TMA	2.1 °	2.0°	4.2 °	0.61	3.6	2.6	1.3	1.5	2.0
HKS	0.5 °	0.4 °	0.9 °	0.90	1.1	0.8	0.7	0.5	0.4
NSA	2.3 °	2.1 °	4.6 °	0.87	3.7	3.0	2.9	1.5	2.2
FTA	0.8 °	0.7 °	1.6 °	0.95			1.0		

FHD, femoral head diameter; FNL, femoral neck length; FL, femoral length; TL, tibial length; FMA, femoral mechanical angle; TMA, tibial mechanical angle; HKS, hip-knee-shaft angle; NSA, neck-shaft angle; FTA, femoro-tibial angle

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Table 3. Mean, subnormal, and abnormal values of parameters that did not change with age

<table>
<tr><th></th><th></th><th>Abnormal low
<-2 SD</th><th>Subnormal low
-1 to -2 SD</th><th>Normal
±1 SD</th><th>Subnormal high
1 to 2 SD</th><th>Abnormal high
>2 SD</th></tr>
<tr><td>FMA (°)</td><td>I-IV[a]</td><td><89</td><td>89 - 91</td><td>91 - 95</td><td>95 - 98</td><td>> 98</td></tr>
<tr><td>F/T ratio</td><td>I-IV[a]</td><td colspan="2"><1.1</td><td>1.1 – 1.2</td><td colspan="2">> 1.2</td></tr>
</table>

FMA, femoral mechanical angle; F/T ratio, ratio of femoral over tibial length

[a]The Roman numerals refer to the age groups described in Table 1.

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Table 4. Mean, subnormal, and abnormal values of parameters that did changed with age

		Abnormal low <-2 SD	Subnormal low -1 to -2 SD	Normal ±1 SD	Subnormal high 1 to 2 SD	Abnormal high >2 SD
ATM (°)	I-II-III[a]	<84	84 to 87	87 to 91	91 to 93	>93
	IV[a]	<82	82 to 85	85 to 90	90 to 92	>92
AFT (°)	I[a]	<174	174 to 176	176 to 180	180 to 182	>182
	II[a]	<173	173 to 176	176 to 182	182 to 185	>185
	III[a]	<166	166 to 170	170 to 178	178 to 182	>182
	IV[a]	<168	168 to 172	172 to 182	182 to 187	>187
HKS (°)	I[a]	<-1	-1 to 1	1 to 4	4 to 6	>6
	II[a]	<-3	-3 to 2	2 to 12	12 to 16	>16
	III-IV[a]	<2	2 to 4	4 to 6	6 to 8	>8
ACD (°)	I[a]	<121	121 to 129	129 to 145	145 to 152	>152
	II[a]	<119	119 to 125	125 to 137	137 to 143	>143
	III[a]	<123	123 to 129	129 to 140	140 to 145	>145
	IV[a]	<118	118 to 125	125 to 139	139 to 146	>146
DTF (mm)	I[a]	<25	25 to 27	27 to 32	32 to 35	>35
	II[a]	<28	28 to 31	31 to 37	37 to 40	>40
	III[a]	<31	31 to 34	34 to 40	40 to 43	>43
	IV[a]	<35	35 to 39	39 to 45	45 to 48	>48
LC (mm)	I[a]	<23	23 to 28	28 to 38	38 to 43	>43
	II[a]	<29	29 to 34	34 to 45	45 to 50	>50
	III[a]	<33	33 to 38	38 to 50	50 to 55	>55
	IV[a]	<41	41 to 47	47 to 58	58 to 64	>64

TMA, tibial mechanical angle; FTA, femoro-tibial angle; HKS, hip-knee-shaft angle; NSA, neck-shaft angle; FHD, femoral head diameter; FNL, femoral neck length

[a]The Roman numerals refer to the age groups described in Table 1.

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Table 5. Mean±SD of the lower-limb parameters in non-typically developing (NTD) children and children with cerebral palsy (CP)

	NTD N=12 limbs	CP N=12 limbs
FMA	94 ± 3	92 ± 2
TMA	88 ± 3	89 ± 2
FTA	178 ± 4	180 ± 2
NSA	134 ± 6	134 ± 6
HKS	3 ± 2	4 ± 1
FHD	35 ± 6	30 ± 3
FNL	38 ± 11	36 ± 4
F/T	1.1 ± 0.0	1.1 ± 0.0

FMA, femoral mechanical angle; TMA, tibial mechanical angle; FTA, femoro-tibial angle; NSA, neck-shaft angle; HKS, hip-knee-shaft angle; FHD, femoral head diameter; FNL, femoral neck length; F/T, ratio of femoral over tibial length

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FIGURE LEGENDS

Figure 1

Changes across age groups in mean values of the femoral mechanical angle (FMA), tibial mechanical angle (TMA), femoro-tibial angle (FTA), and neck-shaft angle (NSA) (all angles in degrees)

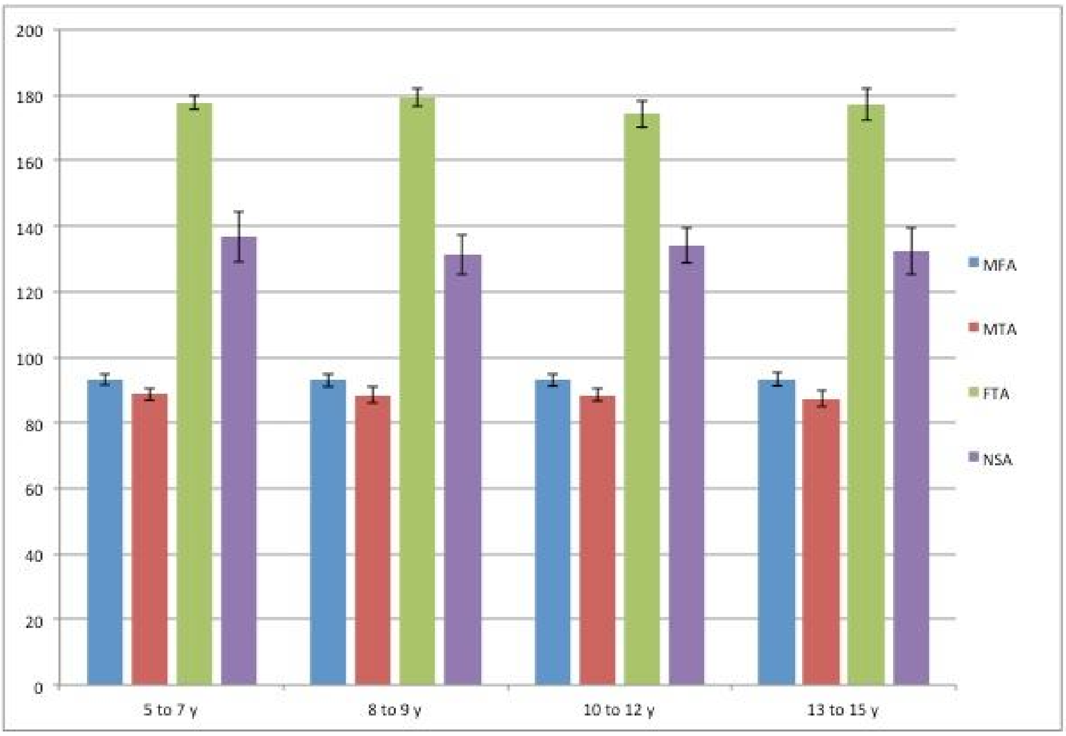

Figure 2

Changes across age groups in mean values of the ratio of femoral over tibial length ratio

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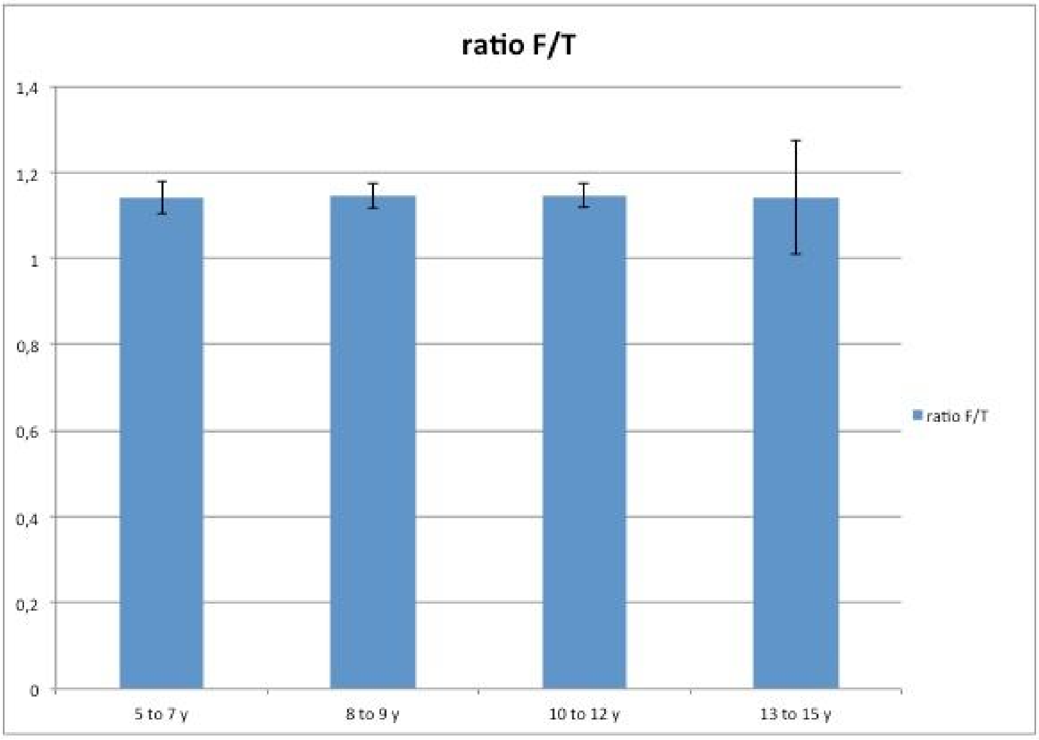

Figure 3

Changes across age groups in mean values of femoral head diameter (FHD, mm) and femoral neck length (FNL, mm)

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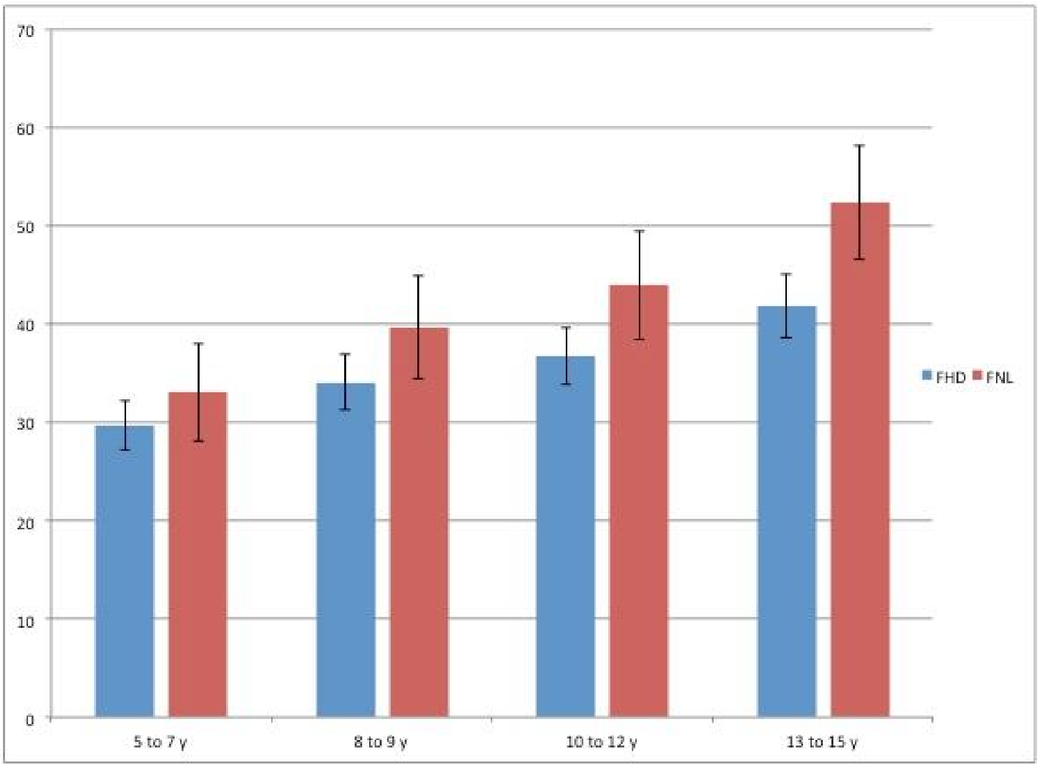

Figure 4

Changes across age groups in mean values of the hip-knee-shaft angle (HKS, in degrees))

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