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ORIGINAL ARTICLE

Evolution of the ischio-iliac lordosis during natural growth and its relation with the pelvic incidence

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Abstract

Purpose Human fully upright ambulation, with fully extended hips and knees, and the body's center of gravity directly above the hips, is unique in nature, and distinguishes humans from all other mammalians. This bipedalism is made possible by the development of a lordosis between the ischium and ilium; it allows to ambulate in this unique bipedal manner, without sacrificing forceful extension of the legs. This configuration in space introduces unique biomechanical forces with relevance for a number of spinal conditions. The aim of this study was to quantify the development of this lordosis between ischium and ilium in the normal growing and adult spine and to evaluate its correlation with the well-known clinical parameter, pelvic incidence.

Methods Consecutive series of three-dimensional computed tomography scans of the abdomen of 189 children and 310 adults without spino-pelvic pathologies were used. Scan indications were trauma screening or acute abdominal pathology. Using previously validated image processing techniques, femoral heads, center of the sacral endplate and the axes of the ischial bones were semi-automatically identified. A true sagittal view of the pelvis was automatically reconstructed, on which ischio-iliac angulation and pelvic incidence were calculated. The ischio-iliac angle was defined as the angle between the axes of the ischial bones and the line from the midpoint of the sacral endplate to the center of the femoral heads.

Results A wide natural variation of the ischio-iliac angle (3°–46°) and pelvic incidence (14°–77°) was observed. Pearson's analysis demonstrated a significant correlation between the ischio-iliac angle and pelvic incidence ($r = 0.558$, $P < 0.001$). Linear regression analysis revealed that ischio-iliac angle, as well as pelvic incidence,

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increases during childhood (+7° and +10°, respectively) and becomes constant after adolescence.
Conclusions The development of the ischio-iliac lordosis is unique in nature, is in harmonious continuity with the highly individual lumbar lordosis and defines the way the human spine is biomechanically loaded. The practical parameter that reflects this is the pelvic incidence; both values increase during growth and remain stable in adulthood.

Keywords Pelvic morphology · Spinal biomechanics · Ischio-iliac angle · Pelvic incidence · Pelvic lordosis

Introduction

In 1950, anthropologist Washburn pointed out the role of morphological changes of the pelvis as a crucial step forward towards pertinent bipedalism in human evolution [39]. Human bipedalism is unique, because it is characterized by an orthograde, double S-shaped spine, pendular limb motion and simultaneous extension of the hips and knees. This provided the evolutionary advantage that the hands could be used for non-locomotive tasks [1, 2, 30]. Already in early hominid specimens, it was found that lordotic angulation of the ilium relative to the ischium, combined with the shortening of the ilium, enabled the delicately balanced upright position of the human spine. The weight of the upper body was carried straight above the pelvis, while the potential for femoral extension was preserved by the unchanged orientation of the ischium [1, 2, 14, 30]. Even in human's closest relatives (chimpanzees and bonobos) there is almost no lordotic angulation between the ischium and ilium [2, 8, 26]. When a primate tries to stand upright, the trunk simply swings up on the femoral heads, to a point that the ischium points almost directly downward. The ischium, however, is the lever arm for the ischiofemoral muscles and plays an important role in the extension of the hips, and thus in forceful ambulation. In upright position with the ischium pointing straight down, the extensors of human primates will run out of power by the time the femoral shaft is vertical (Fig. 1). For occasional bipedal locomotion, primates need a typical 'bent-hip, bent-knee' posture that results in the trunk being anterior to the femoral heads, or an extreme lumbar lordosis in order to position the center of mass of the upper body straight above the supporting legs [8, 26, 38]. For an energy-efficient human bipedal locomotion, however, lordotic angulation of the ilium relative to the ischium was a prerequisite to be able to walk upright, while the potential of forceful femoral extension was preserved [14, 27, 38]. As a consequence of the lordotic ilio-ischial angulation and shortening of the ilium, the sacroiliac angulation had to increase as well in order to maintain the diameter of the bony birth canal [19, 39].

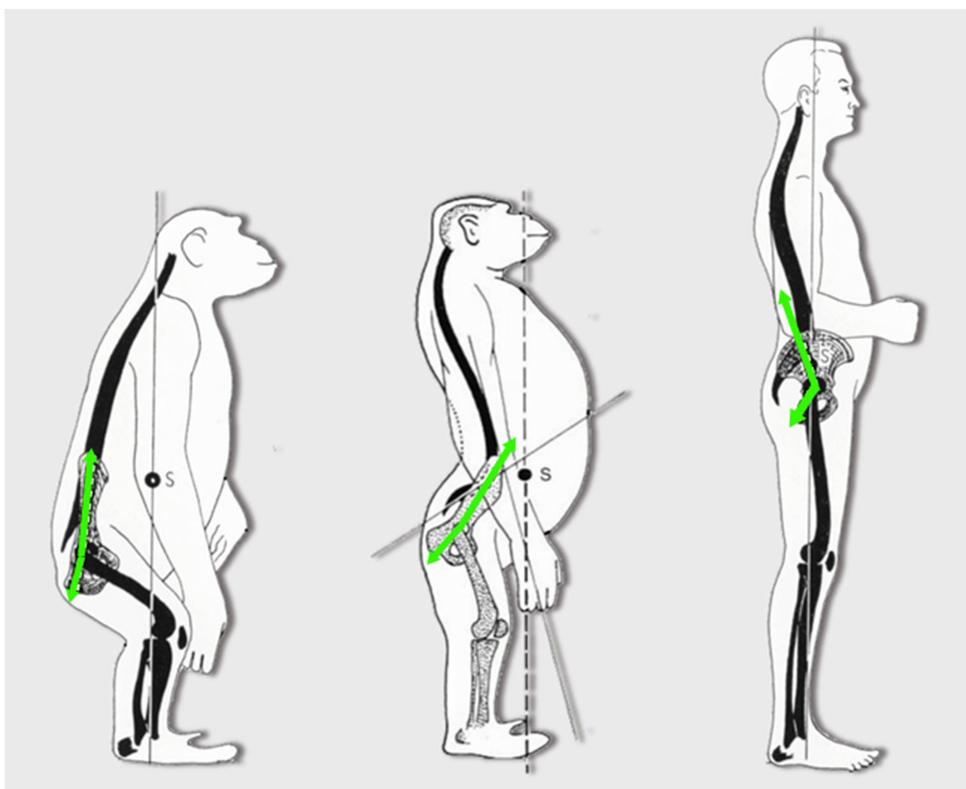


Fig. 1 Like all vertebrates, human primates typically display a 'bent-hip, bent-knee' posture during quadrupedal locomotion, but also during bipedal locomotion to preserve the potential of hip extension by the ischiofemoral muscles (*left*). Occasionally they could adopt a man-like fully erect posture with fully extended knees, but that would require an extreme lordosis of the lumbar spine (*middle*). Due to a lordotic angulation of the ischium and ilium, only humans are able to stand upright with only a relatively small lumbar lordosis in order to position the center of body mass (S) directly above the pelvis (*right*)

The fact that this unique human posture and ambulation simultaneously introduces unique biomechanical loading of the human spine, with unique consequences for spinal pathology, has received relatively little attention in the literature [6]. In the field of spinal pathology, there is increasing recognition of the importance of the morphology of the pelvis as a determinant of pelvic orientation and a regulator of global sagittal spinal alignment [5, 15, 16, 21, 22, 31, 33]. In clinical practice, pelvic morphology and orientation are usually assessed on lateral radiographs, using the pelvic incidence, pelvic tilt and sacral slope, respectively [5, 34]. More specifically, pelvic incidence describes the fixed position of the sacral endplate relative to the femoral heads, whereas pelvic tilt and sacral slope describe the variable position of the pelvis in space. Using the pelvic incidence, several investigators have shown that pelvic morphology, as well as global spinal parameters, changes during normal growth [7, 21, 22, 28]. Furthermore, sagittal spinal alignment has been demonstrated to play an important role in the initiation and progression of certain spinal deformities that are acquired during growth, such as idiopathic scoliosis, spondylolisthesis and Scheuermann's disease [6, 9, 18, 20, 23, 25]. The prerequisite for this uniquely human sagittal alignment, namely the lordotic angulation between the ischium and ilium, has so far received little attention and has never been quantified [32]. The aim of this study is therefore to quantify this lordotic angulation between the ischium and ilium in the normal growing and adult spine, and to evaluate its correlation with the pelvic incidence as a well-known parameter of sagittal balance.

Materials and methods

Population

After approval by our institutional ethics committee, our existing database of computed tomography (CT) images was searched to define two cohorts of patients, pediatrics (0–17 years of age) and adults (18 years of age or older). All patients had undergone CT examination for reasons unrelated to spinal pathology. Both cohorts consisted of all patients that had undergone CT examination of the abdomen for acute abdominal pathology or trauma screening at the emergency department of our institution (University Medical Center Utrecht, The Netherlands) between June 2005 and December 2012. Clinical and radiographic medical charts were reviewed by two orthopedic surgery residents to rule out preexistent spinal pathology. Patients with clinical or radiological evidence for trauma of the spine or pelvis, any pathology or previous surgery of the pelvis, spine or hips, or syndromes associated with disorders of growth were excluded. CT scans without complete visualization of the pelvis, including the most distal parts of both ischia, femoral heads and L5, or severe artifacts also led to exclusion. The scans were acquired with Philips Brilliance 16 and 64 scanners (Philips Medical Systems Nederland BV, Best, The Netherlands), and consisted of axially reconstructed images with 0.4–1.0 mm pixel size and 3.0–4.0 mm slice thickness. For each subject, age and gender were documented and used for subgroup analyses.

Measurement of pelvic parameters

Special in-house developed software was used to measure the pelvic incidence and ischio-iliac angle semi-automatically, in a systematic and reproducible way. The software was previously validated for pelvic incidence measurement on three-dimensional (3D) CT scans [37]. The computerized method (see supplementary material) was initiated by three click points that were manually indicated by one of the investigators, one within the corpus of L5 and one within each femoral head. From these points, the different

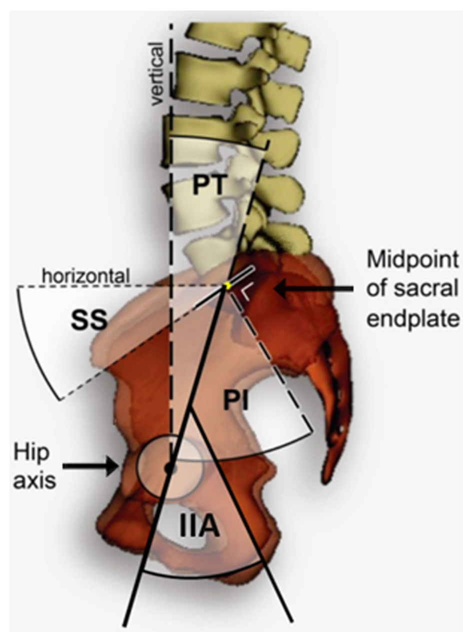


Fig. 2 Typically, pelvic morphology and orientation in the sagittal plane are described by three parameters: the sacral slope (SS), pelvic tilt (PT), and pelvic incidence (PI). The SS represents the angle between the sacral endplate and the *horizontal line*, the PT is defined as the angle between the vertical and the line connecting the midpoint of the sacral endplate to the hip axis, and the pelvic incidence is defined as the angle between the perpendicular of the sacral endplate and the line connecting the midpoint of the sacral endplate to the hip axis. Ischio-iliac angle (IIA) is represented by the angle between the ischium and ilium, and was defined as the mean angle between the axis of the left and right ischium, and the same line connecting the *midpoint* of the sacral endplate to the hip axis

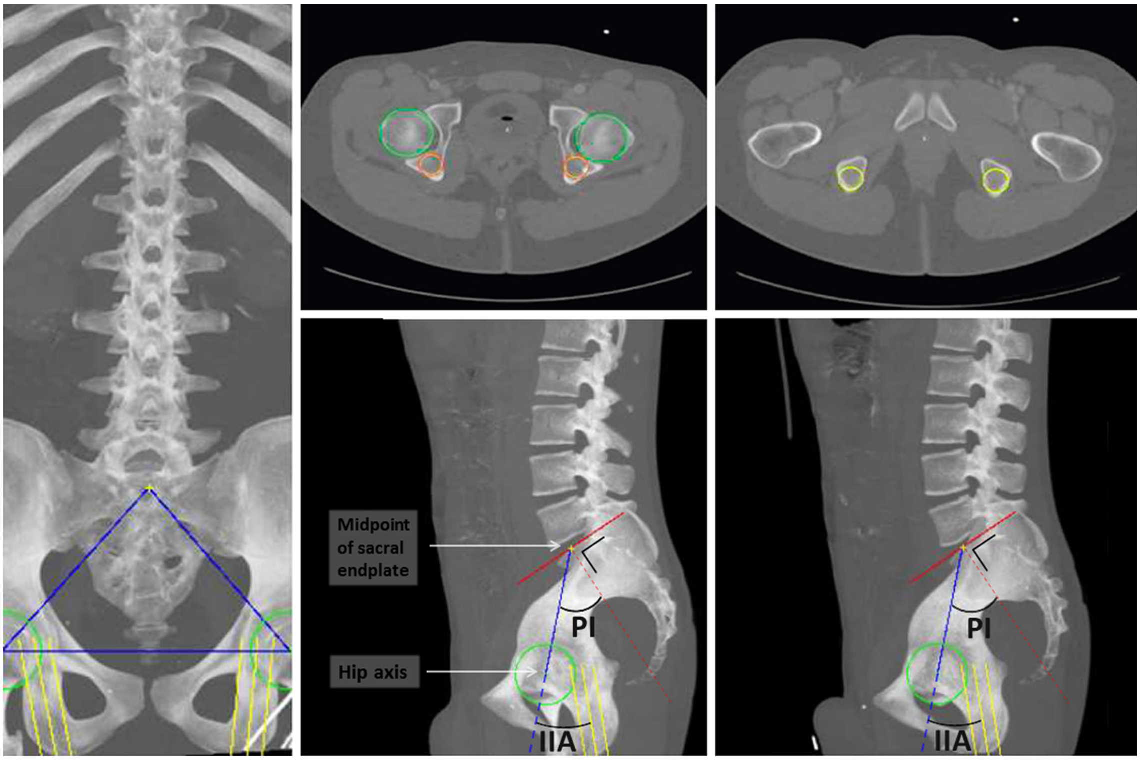


Fig. 3 Computerized measurement of the ischio-iliac angle (IIA) and pelvic incidence (PI) on a computed tomography scan of the abdomen in a 16-year-old male, using in-house developed software. Different projections are shown: *left* multiplanar reformatted image in the coronal plane, *top middle* transverse plane at the hip axis, *top right* transverse plane 5 cm caudal of the hip axis, *bottom middle and right* multiplanar reformatted images in the perfect sagittal view (exactly in line with the hip axis) showing the maximal intensity projection of the left and right half of the pelvis. The *green circles* indicate the spheres that best fit to the edges of the femoral heads in three dimensions (3D), with their centers representing the hip axis. The *yellow circles* and lines indicate the cylinders that best fit to the edges of the ischia in 3D, with their axis representing the axis of the ischium. The *blue triangle* connects the centers of the two femoral heads (hip axis) and the midpoint of the sacral endplate. The *red line* represents the inclination of the sacral endplate

anatomical structures of the pelvis were localized automatically in 3-D (Fig. 3): the midpoint of the sacral endplate was found by localizing the endplate below the L5 vertebral body and by the midpoint of the lines between the anterior and posterior edge, and between the left and right edge of the endplate. The centers of the femoral heads were localized by the exact centers of the spheres that best fit automatically between the 3-D edges of the femoral heads. The midpoint between the center of the left and right femoral head represented the midpoint of the hip axis. The centers of the femoral heads and sacral endplate served to determine the location of both ischia. The orientation of the axes of both ischia were automatically determined from a cylinder that best fit to the edges of each ischium, mimicking the orientation from ischial tuberosity, ischial body and inferior–posterior part of the acetabulum. Based on the orientation of the femoral heads, multiplanar 3-D image reformation was performed to obtain a 'true' sagittal view of the pelvis in which the centers of the femoral heads were exactly in line. On this oblique image, the ischio-iliac angle and pelvic incidence were calculated automatically. *Pelvic incidence* was defined as the angle between the line perpendicular to the sacral plate at its midpoint and the line connecting this point to the hip axis, as described by Legaye et al. [17]. We defined the *ischio-iliac angle* as the angle between the axes of the ischia as determined by computer calculation, and the line connecting the midpoint of the sacral endplate to the hip axis (Fig. 2).

Measurement validation

Measurement of pelvic incidence on 3-D CT images was validated in a previous study: high consistency between manual and computerized pelvic incidence measurements (intraclass correlation coefficient, ICC = 0.961) and high interobserver reliability (ICC = 0.994) was found [37]. Validation of the ischio-iliac angle measurement method was performed by three observers on a subgroup of 14 randomly selected CT scans of subjects with different ages and gender. Differences between manual and computerized measurements, as well as between different observers were evaluated. For the manual measurement, the observers

Table 1 Mean ischio-iliac angle and pelvic incidence with standard deviation (SD), range and level of statistical significance (*P*) for the pediatric and adult cohort, and for the complete study population

	Study population ($n = 499$)		Pediatrics ($n = 189$)		Adults ($n = 310$)		*P*
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	
Ischio-iliac angle (°)	23 (8)	3–46	19 (7)	3–40	26 (7)	9–46	<0.001
Pelvic incidence (°)	45 (11)	14–77	39 (10)	14–74	48 (11)	20–77	<0.001

determined (1) the inclination and midpoint of the sacral plate; (2) the centers of both femoral heads; and (3) both ischia on 3-D images. For the computerized measurement, the observers initiated the automatic calculation by manually placing three click points within each femoral head and the L5 vertebral body. In both the manual and automatic measurement method, the ischio-iliac angle was calculated on the image on which the femoral heads were in line with a 'true' sagittal view. The mean absolute difference (MAD) and ICC assessed the variability between the computerized and manual method, and between the observers.

Statistical analysis

Statistical analyses were performed using SPSS 20.0 (SPSS, Inc., Chicago, IL, USA). Descriptive statistics were computed, providing the mean, standard deviation (SD) and range. Before testing, normality of distribution was verified using *Q–Q* plots and Kolmogorov–Smirnov tests. Potential outliers were identified, original data checked and the effect of legitimate outliers on *t* tests was evaluated. Pearson's correlation analysis determined the correlation coefficient (r) between the pelvic incidence and ischio-iliac angle, ischio-iliac angle and age, and pelvic incidence and age in pediatrics and adults. Correlations <0.50 were defined as 'moderate', between 0.5 and 0.75 as 'good', and >0.75 as 'excellent'. Linear regression analysis was used to determine the changes of pelvic parameters with age. For comparison of continuous parameters between groups (pediatrics versus adults, and males versus females), Levene's test was used to test the equality of variances, and independent samples *t* test was used to test for statistical differences. The statistical significance level was set at 0.05.

Results

Out of 1,728 CT scans, 499 scans (189 pediatrics and 310 adults) were included in this study. The main reason for exclusion of pediatric patients was incompleteness of the scan, whereas for adults it was the suspicion of minor spinal trauma. The mean age of the pediatric cohort was 10.8 ± 5.6 years (range 0.0–17.9), 65 (34 %) were girls. *Q–Q* plots showed that relatively more adolescents (10–17 years) than infants and juveniles (0–9 years) could be included. However, when the pediatric age group was categorized into nine 2-year-age cohorts, at least 12 children could be enrolled in each cohort, and the number of included pediatric patients per cohort was evenly distributed. The mean age of the adult cohort was 44.5 ± 17.6 years (range 18.0–87.0) and 149 (48 %) were females. In the adult cohort, the subjects were evenly distributed among the 10-year-age cohorts.

A wide variation in the ischio-iliac angle and pelvic incidence was observed within the study population, both parameters were normally distributed in the pediatric and adult cohort, and no significant outliers were identified. The mean ischio-iliac angle was 23° ± 8° (range 3°–46°) and the mean pelvic incidence was 45° ± 11° (range 14°–77°). A statistically significant correlation and linear relation was observed between the ischio-iliac angle and pelvic incidence ($r = 0.56$, $P < 0.001$, ischio-iliac angle = 0.4 × pelvic incidence + 6.3). Both parameters differed significantly between the pediatric and adult cohort ($P < 0.001$) (Table 1). Correlation analysis revealed significant, but moderate correlation between the ischio-iliac angle and age in the pediatric cohort ($r = 0.29$, $P < 0.001$), and no statistically significant correlation in the adult cohort. Linear regression analysis showed that the ischio-iliac angle increased by 0.4° per year during childhood (ischio-iliac angle = 0.4° × age + 15), from 15° to 22°, and became constant during adulthood. The pelvic incidence correlated moderately with age in both pediatric ($r = 0.32$, $P < 0.001$) and adult ($r = 0.21$, $P < 0.001$) cohorts. More specifically, regression analysis showed that the pelvic incidence increased by 0.6° per year, from 33° to 44°, during growth (pelvic incidence = 0.6° × age + 33), and increased for 0.1° per year during adulthood (pelvic incidence = 0.1° × age + 42). Taking into account the effect of age, no statistical differences between both pelvic parameters were observed between the genders in the pediatric or adult cohort (Table 2).

Reliability and validity of the measurements

The comparison of manual and computerized measurements of the ischio-iliac angle revealed MAD of 3.6°

Table 2 Mean ischio-iliac angle and pelvic incidence with standard deviation (SD), range and level of statistical significance for boys and girls in the pediatric cohort, and for males and females in the adult cohort

	Boys ($n = 124$)		Girls ($n = 65$)		*P*
	Mean (SD)	Range	Mean (SD)	Range	
Ischio-iliac angle (°)	18 (7)	3–35	20 (7)	4–40	ns
Pelvic incidence (°)	38 (10)	14–71	40 (10)	17–74	ns
	Males ($n = 161$)		Females ($n = 149$)		*P*
	Mean (SD)	Range	Mean (SD)	Range	
Ischio-iliac angle (°)	25 (7)	9–42	26 (6)	12–46	ns
Pelvic incidence (°)	48 (10)	25–77	48 (11)	20–75	ns

ns not significant

(ICC = 0.857). In addition, interobserver reliability analysis for the manual and automatic ischio-iliac angle measurement methods showed high reliability (MAD = 1.0° and ICC = 0.993 for manual, and MAD = 0.2° and ICC = 0.999 for automatic method).

Discussion

A lordotic angulation between the ischial and iliac bone is a prerequisite for the unique way that humans ambulate, and for the subsequent unique biomechanical loading of the human spine [14, 39]. Although this angulation has been described before, this is the first study to quantify this angle in detail using computerized method in 499 humans of different ages [14, 39]. It demonstrated that:

1. Sagittal pelvic morphology parameters, ischio-iliac angle and pelvic incidence, increase significantly during pediatric growth and become relatively constant during adulthood;
2. A wide range of ischio-iliac angles as well as pelvic incidences was observed. Given the high reliability of the measurement method, the wide range of ischio-iliac angle (3°–46°) and pelvic incidence (14°–77°) in our population apparently represents the wide natural variation of pelvic morphology in the normal population, which is common for most spino-pelvic parameters [31, 35]
3. There is a positive linear relation between ischio-iliac angle and pelvic incidence:
4. Given the relationship between the ischio-iliac angulation and pelvic incidence, and the earlier established relationship between the pelvic incidence and lumbar lordosis, ischio-iliac lordosis can be considered to be in harmonious continuity with the lumbar lordosis [3, 22, 34].

In recent years, there has been an increasing recognition of the importance of the sagittal spino-pelvic alignment in relation to the functioning of the spine, and in the etio-pathogenesis of different spinal pathologies [5, 6, 15–17, 20–23, 31, 33]. The role of the pelvis as a determinant and regulator of spinal alignment, to keep the spine optimally balanced, has also become increasingly apparent [12, 17, 20].

The results of our study indicate that the sagittal alignment of the pelvis evolves during natural growth up to the end of the adolescent growth spurt. Previously, using two-dimensional radiographs, it was shown that the pelvic incidence increases slightly, thus altering sagittal spino-pelvic alignment during growth up to skeletal maturity [7, 21, 22, 28]. In more detail, Mangione et al. and Hanson et al. [11, 24] demonstrated in relatively small cohorts the difference between the pelvic incidence in fetuses, children and adults (with a mean pelvic incidence of 31° versus 39°–47° versus 55°–57°, respectively). Later, Mac-Thiong et al. confirmed these results in a cross-sectional population cohort of 341 children [21, 22]. Additionally, Mangione et al. and Mac-Thiong et al. reported a significant, but weak correlation of the pelvic incidence with age ($r = 0.36$ and 0.21, respectively), and showed that the pelvic incidence increased +0.5°–0.7° per year up to adulthood [21, 22, 24]. In the context of evolution, in 1998 Berge et al. reported the differences in length of the ilium in pelvises of 150 juvenile and adult primates, 60 human specimens and two early hominid pelvises. They showed that changes in pelvic proportions occur during growth and later life, and found that the two early hominid pelvises resemble pelvic morphology of human neonates. However, no sagittal pelvic parameters were quantified [4]. Recently, a study on the pelvic incidence in a historical collection of hominid pelvises, neonates and adults was published by Tardieu et al. [32]. Using a 3-D landmark scanner, they found a higher pelvic incidence in 51 adults (54.5° ± 12°) and seven early hominid pelvises (range 43°–54°), compared to 19 neonates (27.2° ± 12.8°). Therefore, they concluded that the infantile pelvis is "mechanically poorly adapted to balance the trunk on the lower limbs". The results of our study, for which 3-D image reformation was used, are very consistent with the results of other studies on pelvic morphology of children at different ages. These studies, however, only looked at pelvic incidence [7, 22, 35]. Our study looks at the underlying anatomical adaptations and adds a quantification of the ischio-iliac angle at different ages. The lordosis between the ischium and ilium is an evolutionary trait of *Homo sapiens* and is a prerequisite for our unique upright posture with a trunk that is delicately balanced straight above the pelvis [14, 39]. All other vertebrates, quadrupedal as well as bipedal, have their trunk in front of their hips, which leads to essentially different mechanical loading of the human spine, while the anatomy of the spine itself has remained essentially unchanged [14, 39].

Although positional parameters such as the sacral slope, pelvic tilt and lumbar lordosis are influenced by positioning of the patients, morphological pelvic parameters such as the ischio-iliac angle and pelvic incidence are not.

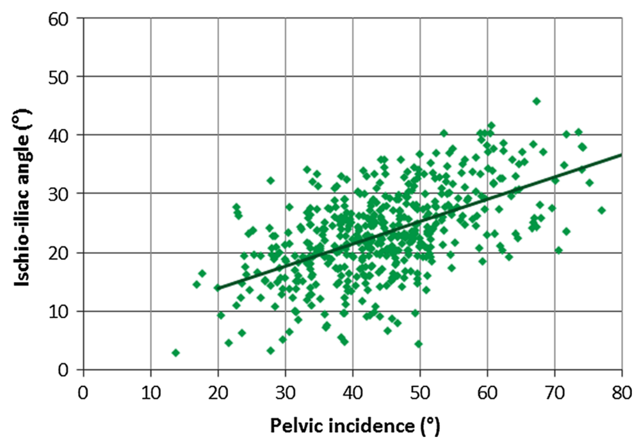
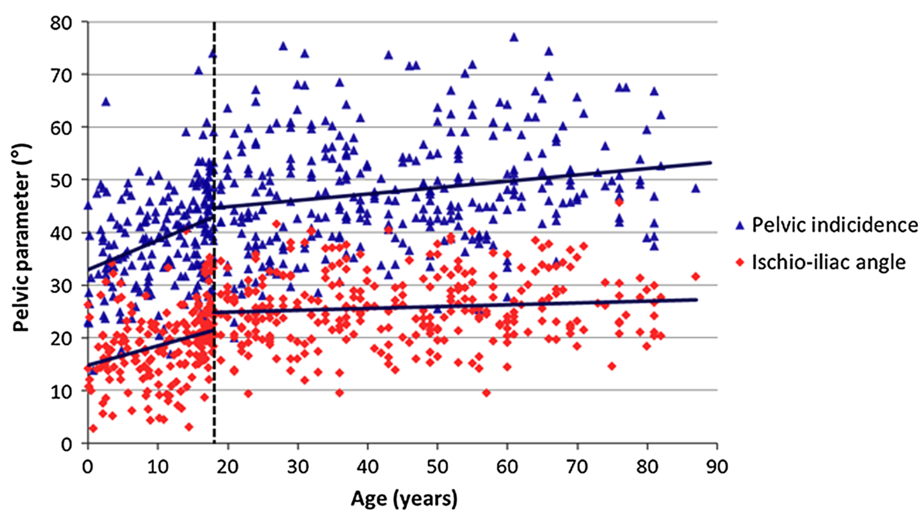


Fig. 4 Ischio-iliac angle versus pelvic incidence ($n = 499$). Pearson's correlation coefficient was $r = 0.558$ (level of statistical significance $P < 0.001$). Linear regression analysis revealed the formula ischio-iliac angle = 0.4 × pelvic incidence + 6.3

Therefore, due to the supine image acquisition of CT scans, these positional pelvic parameters could not be assessed. Neither could we evaluate the sagittal profile of the spinal curvature and its relation to pelvic incidence or ischio-iliac angulation. By using CT data and novel image processing techniques, we were able to quantify the ischio-iliac angle as well as the pelvic incidence on 3-D images with high accuracy and reproducibility in a large study population, as it was done for the pelvic incidence in a previous study [37]. Using this method, information bias and bias due to image acquisition was avoided. A strong positive correlation between the ischio-iliac angle and pelvic incidence was observed, which was also illustrated by the increasing ischio-iliac angle with the age of the subjects, synchronously with the increase of the pelvic incidence. Given the known correlation between the pelvic incidence and lumbar lordosis [3, 22, 34], the ischio-iliac lordosis apparently provides a harmonious continuity with a person's highly individual lumbar lordosis. The development of the ischio-iliac angle forms the anatomical basis for human upright spino-pelvic alignment. It aids our understanding of the differences in biomechanical loading of the human spine as compared to other vertebrates. It is not, however, a practical or clinically relevant parameter since it is impossible to measure it on plain radiographs [36].

There is a large variation in sagittal spino-pelvic parameters in the population. Variation of the ischio-iliac angle and pelvic incidence, and thus sagittal spinal alignment, results in differences in biomechanical loading and functioning of the human spine [31]. In human evolution,

Fig. 5 Ischio-iliac angle and pelvic incidence versus age in the pediatric ($n = 189$) and adult ($n = 310$) cohort. Ischio-iliac angle and pelvic incidence correlated significantly with age in pediatrics and in adults (r correlation coefficient; P level of significance)



	parameter	r	P	Regression formula
< 18 years	Ischio-iliac angle	0.29	<0.001	= 0.4 * age +14.7
	Pelvic incidence	0.32	<0.001	= 0.6 * age +33.0
≥ 18 years	Ischio-iliac angle	0.10	0.046	= 0.0 * age +24.2
	Pelvic incidence	0.21	<0.001	= 0.1 * age +42.5

the lordotic angulation of the pelvis in combination with the shortening of the ilium was a prerequisite for the unique human posture with the center of mass of the upper body straight over the pelvis. Simultaneously, the pelvic incidence increased to maintain the diameter of the bony birth canal [1, 3, 13, 32]. In this way, by keeping the ischium in a posterior orientation, the orientation and lever arm of the ischiofemoral and abductor muscles were preserved (Fig. 1) [10, 14]. Even in the oldest available pelvis of our hominid ancestors, the 3.2 million-year-old fossil of *Australopithecus afarensis*, popularly known as Lucy, an increased angulation between the ischium and ilium, and between the ischium and sacral bone (pelvic incidence) was found [29]. Human upright posture and bipedal ambulation, and therefore biomechanical loading of the human spine, thus differs considerably from other species, also other bipedal ones. In biomechanical experiments of Kouwenhoven et al. it was shown that the way the human spine is loaded implies a decrease in the rotational stiffness of (Figs. 4, 5) certain spinal segments, thus being a risk factor for the development of idiopathic scoliosis. Sagittal alignment has also been implicated in other pathologies as spondylolisthesis and osteoarthritis of the hip, and has been suggested to play a role in low back pain [23, 40].

In conclusion, an increasing ischio-iliac angle and pelvic incidence during normal growth was observed in this study. It displays a continuation of phylogenetic morphological changes of the human pelvis. It forms the basis for human upright spinal biomechanics, with possible consequences for the initiation and progression of idiopathic scoliosis, spondylolisthesis, Scheuermann's disease, degenerative disc disease or osteoarthritis of the hip.

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