

Basic Study

Spinal alignment evolution with age: A prospective gait analysis study

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Author contributions: All authors contributed equally to this work.

Institutional review board statement: The Spine unit review board reviewed this study and gave his approval.

Institutional animal care and use committee statement: No animal has been involved in this study.

Conflict-of-interest statement: No conflict of interest.

Data sharing statement: Authors agreed to share data with the editor.

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Manuscript source: Invited manuscript

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Received: July 25, 2016

Peer-review started: July 29, 2016

First decision: September 2, 2016

Revised: November 10, 2016

Accepted: December 27, 2016

Article in press: December 28, 2016

Published online: March 18, 2017

Abstract

AIM

To describe, using gait analysis, the development of spinal motion in the growing child.

METHODS

Thirty-six healthy children aged from 3 to 16 years old were included in this study for a gait analysis (9 m-walk). Various kinematic parameters were recorded and analyzed such as thoracic angle (TA), lumbar angle (LA) and sagittal vertical axis (SVA). The kinetic parameters were the net reaction moments (N.m/kg) at the thoracolumbar and lumbosacral junctions.

RESULTS

TA and LA curves were not statistically correlated to the age (respectively, $P = 0.32$ and $P = 0.41$). SVA increased significantly with age ($P < 0.001$). Moments in sagittal plane at the lumbosacral junction were statistically correlated to the age ($P = 0.003$), underlining the fact that sagittal mechanical constraints at the lumbosacral

junction increase with age. Moments in transversal plane at the thoracolumbar and lumbosacral junctions were statistically correlated to the age ($P = 0.0002$ and $P = 0.0006$), revealing that transversal mechanical constraints decrease with age.

CONCLUSION

The kinetic analysis showed that during growth, a decrease of torsional constraint occurs while an increase of sagittal constraint is observed. These changes in spine biomechanics are related to the crucial role of the trunk for bipedalism acquisition, allowing stabilization despite lower limbs immaturity. With the acquisition of mature gait, the spine will mainly undergo constraints in the sagittal plane.

Key words: Sagittal balance; Spine biomechanics; Gait analysis; Thoracic kyphosis; Spine growth

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Core tip: Many postural changes occur during childhood, including the adaptation of the spine to maintain an erect posture. The aim was to describe, using gait analysis, the development of spinal motion during growth. Various kinematic parameters were recorded in 36 healthy children. Thoracic kyphosis and lumbar lordosis were not found to increase during childhood whereas sagittal vertical axis increased with age. The kinetic analysis showed a decrease of torsional constraint while sagittal constraint increased. These changes in spine biomechanics are related to the crucial role of the trunk for bipedalism acquisition, allowing stabilization despite lower limbs immaturity.

Pesenti S, Blondel B, Peltier E, Viehweger E, Pomero V, Authier G, Fuentes S, Jouve JL. Spinal alignment evolution with age: A prospective gait analysis study. *World J Orthop* 2017; 8(3): 256-263 Available from: URL: <http://www.wjgnet.com/2218-5836/full/v8/i3/256.htm> DOI: <http://dx.doi.org/10.5312/wjo.v8.i3.256>

INTRODUCTION

With the acquisition of bipedalism, many anatomical and postural changes occurred in humans^[1-3]. Among these changes, an adaptation of the spine has been necessary to maintain an erect position, in combination with an adaptation of the pelvis and the lower limbs^[4-6]. Although gait acquisition is apparently complete by the age of 3, adaptation to erect posture continues until the end of growth. According to Peterson *et al*^[7], mature gait patterns are visible in children only from the age of 12.

With the development of modern tools for gait analysis, it is possible to obtain a precise evaluation of the kinematic and kinetic for different segments of the human body. While many of these tools have been developed for lower limbs analysis, various authors have demonstrated

their accuracy for trunk dynamic analysis^[8-10]. Many studies have described the evolution of spinal curvatures with radiological or other methods^[11,12]. Using these tools, it has been shown that thoracic kyphosis and lumbar lordosis increase with age.

To our knowledge, there is no evidence in literature about this development using gait analysis tools. Moreover, gait analysis provides dynamic data such as constraints applied to spinal joints, these parameters having never been discussed in literature before. The hypothesis of this work was that spinal motion changes all along growth. The aim of this study was to describe, using gait analysis, the development of spinal motion in the growing child.

MATERIALS AND METHODS

Study design

To obtain a homogenous pediatric cohort, only healthy volunteers were included in this prospective study after informed consent. Inclusion criteria were children aged from 3 to 16 years old, without known disease and volunteers to participate to the study. Exclusion criteria were every history of orthopedic or neurologic disorders, major orthopedic trauma or allergy to the components used for gait analysis.

Anthropometric data

For each participant, the following anthropometric data were collected for gait analysis: Age, weight, height, lower limb length and knee and ankle diameters.

Gait analysis

All measurements were obtained using an optoelectronic system (Vicon, Oxford, United Kingdom) with six high-resolution cameras with infrared light and a sampling frequency of 100 Hz which recorded the position of passive retroreflective markers and two force platforms (AMTI, United States). This protocol included all the markers necessary to obtain parameters of a standing posture and to calculate the force of external efforts in the different intersegmental centers, as described by Blondel *et al*^[13], according to the International Society of Biomechanics^[14,15].

Subjects were equipped with a set of 28 retroreflective markers as described in Table 1 and Figure 1. These markers allowed an analysis of different body segments such as head and neck, the scapular girdle, the thorax and thoracic spine, the abdomen and lumbar spine, the pelvis and the lower limbs.

Before the beginning of gait analysis, a short trial was performed to check the good positioning of the markers according to the analysis of knee valgus/varus^[16].

For gait analysis, subjects were asked to walk at a self-selected speed, barefoot, on a flat and straight 9 m-walkway. A minimum of seven trials was recorded to collect kinematic and kinetic data.

The data collected by the 6 high-resolution cameras were converted into a 3D model using NEXUS software

Table 1 Optoelectronic markers placement following anatomical landmarks according to Blondel *et al*^[13] gait analysis protocol

Parameters	
Head	Vertex: 1 Nasion: 1 Tragus: 2
Trunk - thorax	Acromion: 2 Manubrium: 1 Xiphoid: 1 C7: 1 T6: 1 T9: 1
Trunk - abdomen	T12: 1 L3: 1 S1: 1
Pelvis	ASIS: 2
Lower limbs - thighs	Femoral shaft: 2 Lateral femoral condyle: 2
Lower limbs - legs	Tibial shaft: 2 Lateral malleolus: 2
Lower limb - feet	Calcaneus: 2 2 nd metatarsal head: 2



Figure 1 Gait analysis model used for trunk motion assessment. Retroreflective markers were placed according to anatomical landmarks, such as described by Blondel *et al*^[13] (Table 1). Six markers were used for spine motion.

Table 2 Kinematic parameters measured during gait analysis

	Frontal	Sagittal	Transversal
Overall balance		SVA Ad	
Shoulders			APA
Thoracic spine		TA	
Lumbar spine		LA	
Pelvis		Pelvic version	
Lower limbs	Knee Varus/valgus	Hip flex/ext Knee flex/ext	

SVA: Sagittal vertical axis; APA: Angle pelvis-acromion; TA: Thoracic angle; LA: Lumbar angle.

Table 3 Kinetic parameters measured during gait analysis

	Frontal moments	Sagittal moments	Transversal moments
Thoracolumbar junction	Lateral bending	Flexion-extension	Torsion
Lumbosacral junction	Lateral bending	Flexion-extension	Torsion

(Vicon Motion Systems, Oxford, United Kingdom) for the lower limbs and data were integrated to MATLAB software for trunk analysis.

The characteristic moments of the beginning and the end of the double stance phase were used to compare subjects.

For kinetic analysis, calculations were made from anthropometric reference tables^[17].

Gait parameters

Kinematic parameters during gait are described hereafter and summarized in Table 2 and Figure 2: (1) Sagittal Vertical Axis Adimensioned (SVA Ad): distance between

the marker "S1" and the vertical line passing by the marker "C7". This value was weighted by the height of the subject to be comparable between subjects, regardless to age and height ($SVA\ Ad = SVA/Height$). This parameter reflects trunk position during gait: A great value of SVA indicates that the trunk is leaning forward; (2) angle pelvis-acromion (APA): Angle defined in the transverse plane between the line joining the 2 "Acromion" markers and the line joining the 2 "anterosuperior iliac spine" markers. The APA-rom (range of motion) was calculated as the difference between the maximum and the minimum values of the APA during a gait cycle^[18]; (3) thoracic angle (TA): Angle between the "C7"- "T7" line and the "T9"- "T12" line; and (4) lumbar Angle (LA): Angle between the "T12"- "L3" line and the "L3"- "S1" line.

Kinetic parameters are detailed in Table 3. In frontal plane, moments applied to the spine are relative to lateral bending movements, in sagittal plane they are flexion-extension movements and in transversal plane, they were consecutive to torsional movements. These data were dimensioned (*i.e.*, divided by the weight) to be comparable between individuals, independently from their body mass.

Statistical analysis

Gait data were analyzed to compare subjects in a continuous analysis according to age. A Pearson Product Moment Correlation Coefficient (r) was used to determine differences between subjects according to age. Level of significance was set at 5% for every statistical analysis.

RESULTS

Demographic data

From October 2012 to October 2013, 36 subjects were included in this study. Mean age of the population was

Table 4 Details of demographic and anthropometric data

Subject No.	Sex	Age (yr)	Height (cm)	Weight (kg)	Lower limb length (cm)		Knee diameter (cm)		Ankle diameter (cm)	
					Right	Left	Right	Left	Right	Left
1	F	3.3	880	11	420	420	55	55	45	45
2	F	3.4	1060	17	510	510	80	80	60	60
3	M	3.9	935	14	500	500	70	70	44	44
4	F	3.9	1050	19	520	520	80	80	60	60
5	M	4.1	1080	18	550	550	70	70	50	50
6	F	4.6	1090	16	650	650	50	50	45	45
7	F	5.8	1135	19	570	570	70	70	50	50
8	M	6.1	1150	19	575	575	80	80	60	60
9	F	7.0	1345	27	670	670	90	90	65	65
10	F	7.2	1200	21	570	570	70	70	50	50
11	F	7.4	1160	21	585	585	80	80	60	60
12	M	7.7	1370	34	730	730	110	110	70	70
13	F	7.7	1300	31	680	680	95	95	70	70
14	F	7.8	1280	26	650	650	90	90	70	70
15	M	8.0	1340	27	680	680	90	90	70	70
16	M	8.1	1330	28	685	685	95	95	65	65
17	M	8.5	1360	33	710	710	90	90	55	55
18	M	8.8	1400	40	720	720	110	110	70	70
19	F	8.9	1380	37	720	720	100	100	65	65
20	M	9.1	1320	24	680	680	80	80	60	60
21	M	9.2	1420	26	750	760	55	55	50	50
22	F	9.3	1524	38	820	820	100	100	65	65
23	M	9.5	1395	36	750	750	110	105	65	65
24	F	10.0	1360	29	710	710	70	70	55	55
25	F	10.6	1370	39	740	740	95	95	60	60
26	F	10.8	1425	32	750	750	90	90	65	65
27	F	11.0	1530	41	810	810	105	105	70	70
28	M	11.1	1520	51	850	850	100	100	70	70
29	F	11.1	1463	47	740	740	105	105	70	70
30	F	11.3	1610	46	840	840	105	105	70	80
31	M	11.9	1390	34	700	700	85	85	60	60
32	F	12.5	1470	35	740	740	100	100	70	70
33	F	12.7	1570	54	900	900	115	110	75	70
34	F	13.9	1690	47	925	925	100	100	70	70
35	M	15.5	1650	48	830	830	85	85	65	65
36	M	15.6	1770	87	930	930	100	100	70	70

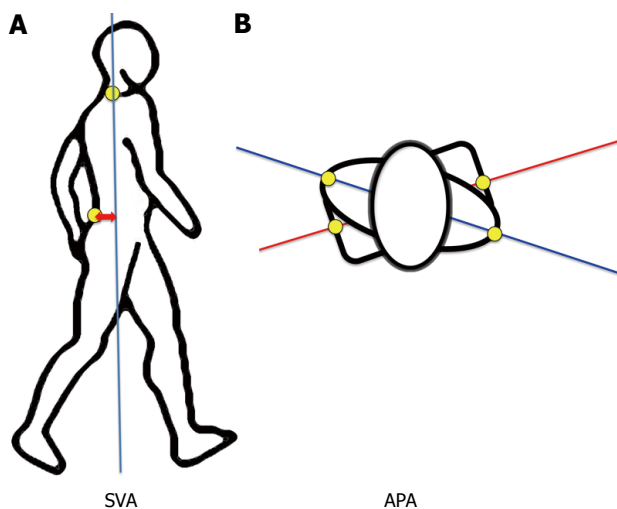


Figure 2 Sagittal vertical axis and angle pelvis-acromion. A: SVA was defined as the distance between the marker "S1" and the vertical line passing by the marker "C7". This parameter reflects trunk position during gait: A great value of SVA indicates that the trunk is leaning forward; B: APA was defined as the angle between the line joining the 2 "Acromion" markers and the line joining the 2 "anterosuperior iliac spine" markers. SVA: Sagittal vertical axis; APA: Angle pelvis-acromion.

8.8 years old (3.3 to 15.6 years old). Demographic and anthropometric data are shown in Table 4.

Gait analysis: Kinematics

Sagittal plane: TA and LA curves were not statistically different (respectively, $r = 0.06$ and $r = 0.023$, $P = 0.32$ and $P = 0.41$, Figure 3).

SVA Ad was significantly correlated to the age ($r = 0.488$, $P < 0.001$), revealing a progressive anterior increase of the projection of the C7 marker with regards to the S1 marker (Figure 4).

Transversal plane: There was a non-significant negative correlation between APA-rom and age ($r = -0.063$, $P = 0.71$).

Gait analysis: Kinetics

Sagittal plane: Results showed that flexion-extension moments at the lumbosacral junction were statistically correlated to age ($r = 0.356$, $P = 0.003$). In other words, mechanical sagittal constraints at the lumbosacral junction increase during growth. At the thoracolumbar

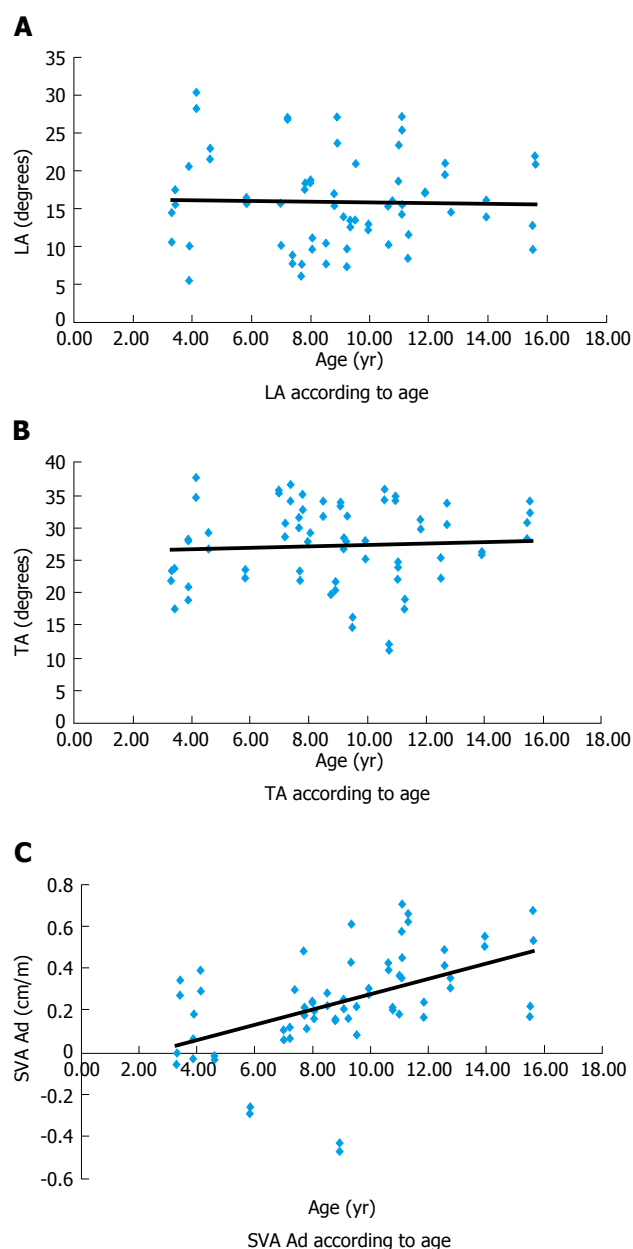


Figure 3 Continuous analysis of kinematic parameters according to the age. A: TA; B: LA; C: SVA. TA: Thoracic angle; LA: Lumbar angle; SVA: Sagittal vertical axis.

junction, sagittal constraints were not significantly correlated to age ($r = 0.189$, $P = 0.13$, Figure 5).

Transversal plane: Results demonstrated that torsion moments at thoracolumbar and lumbosacral junctions were statistically correlated to age ($r = -0.613$ and $r = -0.563$, $P = 0.0002$ and $P = 0.0006$). In other words, transversal mechanical constraints at thoracolumbar and lumbosacral junctions decrease with age (Figure 6).

DISCUSSION

This study is the first to analyze spinal motion in children *via* gait analysis tool. Changes occur in spine motion in children with the acquisition of a mature gait

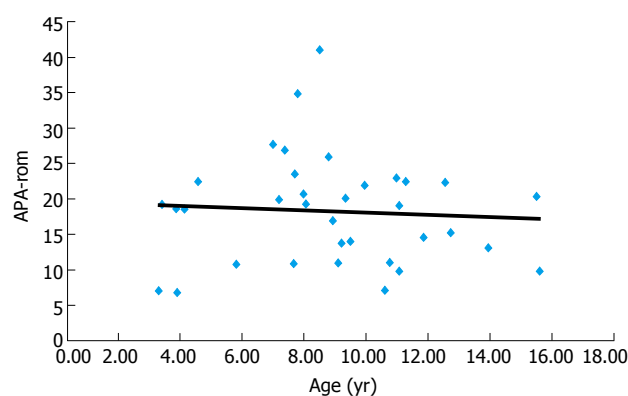


Figure 4 Continuous analysis of angle pelvis-acromion-rom according to the age. APA: Angle pelvis-acromion.

even if dynamic parameters of the spine during growth seem to be established before the age of 3.

So far, only few studies have studied dynamic development of the spine according to age *via* gait analysis^[19]. The studies from Wagner *et al*^[20] and Farfan^[21] showed that the presence of a lumbar spinal curvature concave toward the back is a necessary biomechanical condition for a stable erect posture, enabling an economic muscular functioning despite the posterior position of the spine. Lumbar lordosis thus appears as being a fundamental prerequisite to bipedalism, explaining its early appearance during childhood. Parameters determining bipedalism are acquired very early during growth^[21,22]. However, some skeletal parameters which are not involved in the acquisition of bipedalism are variable and change until the end of growth. Some of these parameters are even found to be genetically predetermined during fetal life. This is, for example, the case of the morphology of the femoral trochlea^[23] or the lumbar lordosis^[24], which are genetically predetermined in humans. Their early kinematic setting is an element explaining the ability to bipedalism.

The spine appears to be of fundamental importance in the adaptation of the skeleton to bipedalism and we can define a real "spinal motor of bipedalism"; the spine being the first skeletal element to adjust its posture and functioning to bipedalism as the main element of locomotion^[25]. The lower limbs adapt secondarily, around the age of 7, with a progressive pelvic anteversion, a progressive extension of the hips and the knees, lately mature.

Some radiographic and morphologic studies have evaluated the development of spinal curvatures during growth^[11,12]. These studies revealed that from the age of 3 years until skeletal maturity, there is a linear enhancement of the thoracic kyphosis and lumbar lordosis. According to us, these changes do not reflect the adaptation of the skeleton to bipedalism, but an adaptation to the major constraints applied to the trunk during growth. In other words, formation of overlying sagittal curvatures to the lumbar lordosis with the appearance of thoracic kyphosis and cervical lordosis is related to biomechanical adaptation to an increase of load on the

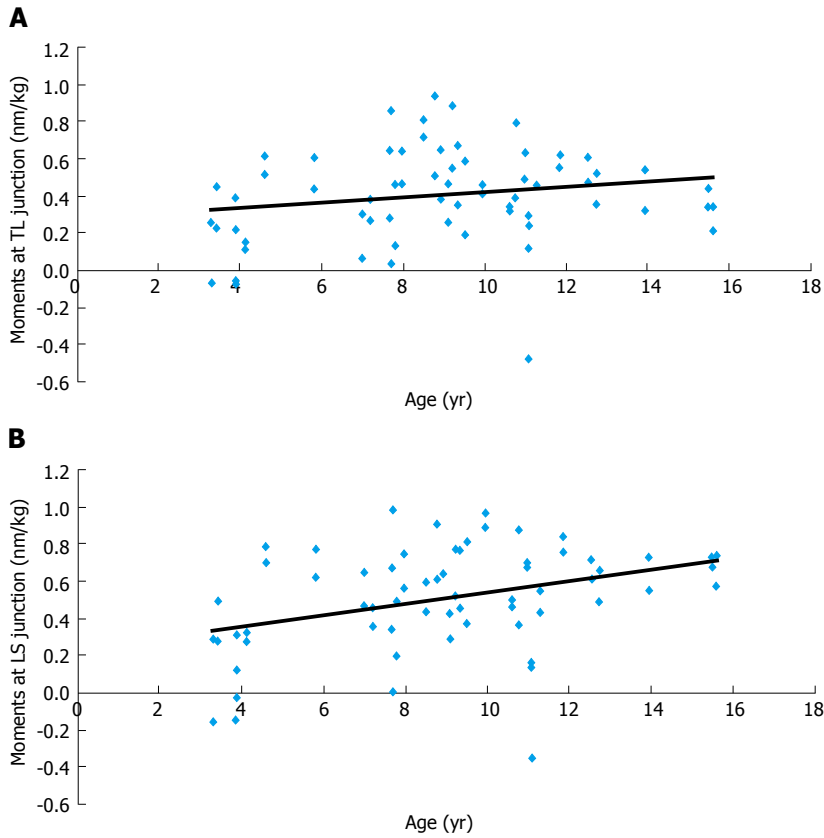


Figure 5 Sagittal kinetic parameters of the trunk according to the age. A: TL; B: LS. Frontal plane constraints are relative to flexion-extension movements. TL: Thoracolumbar; LS: Lumbosacral.

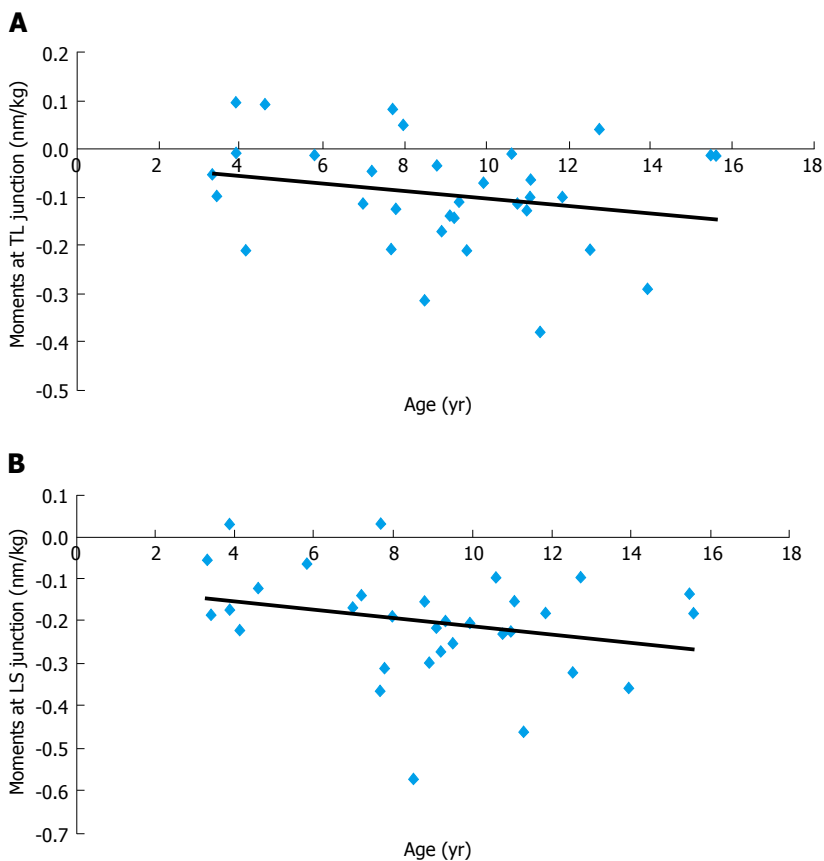


Figure 6 Transversal kinetic parameters of the trunk according to the age (continuous analysis). Transversal plane constraints are relative to torsional movements of the trunk. TL: Thoracolumbar; LS: Lumbosacral.

spine.

Most of the parameters used in this study for kinematic analysis, such as SVA, were chosen according to previous works^[18]. These parameters seemed to be good descriptors because they are the dynamic equivalent of radiographic parameters. Thoracic angle and lumbar angle were meant to be the equivalent of thoracic kyphosis and lumbar lordosis, which are 2 radiographic parameters used in clinical practice.

Results from this study suggest that the sagittal efforts applied on the spine increase significantly with age leading to increased flexion-extension constraints at the lumbosacral junction. This phenomenon can be explained by the accentuation of spinal curvatures with age as a response to the increased load on the spine, deporting the lumbar spine forward and thereby increasing the lever arm and the moment applied to the underlying lumbosacral junction.

With regards to the kinetic parameters in the transverse plane, our results showed a significant reduction in torsional constraints at the thoracolumbar and lumbosacral junctions during growth. Although lumbar lordosis is acquired from fetal life, the central maturation processes coordinating the acquisition of a mature gait for the lower limbs appear only around the age of 7. Before this turning point, the lower limbs do not have a mature kinematics allowing balance and stability for satisfactory and stable erect posture. These results are in line with the posturographic study from Peterson *et al.*^[7] who have shown that sensory systems ensuring a satisfactory balance for maintaining erect station were efficient only from the age of 12. Thus, the spine undergoes greater constraints to compensate this permanent balance research. Large constraints applied to the spine and their reduction with age are a sign of the compensation by the trunk of a lack of stability due to lower limbs and sensory system immaturity. Prior to the acquisition of a definitive and mature bipedalism, the trunk is fundamental for the possibility of early bipedalism.

Furthermore, the significant increase of SVA during growth could be related to the same conclusion. The low value of SVA in young children reflects the need to keep the shoulders over the pelvis to stabilize the erect posture. With maturation and the acquisition of a final biped balance, the subject is projected more forward, then changing the direction of the constraints on the spine from the transverse plane to the sagittal plane.

These findings allow a better comprehension of the importance of constraints in the lumbar spine and can be a source of explanation for specific degenerative disorders of this anatomical region.

The small number of subject in each age group may be at the origin of a lack of statistical power and may explain the lack of significant difference. However, in similar series, changes in lower limb parameters are clearly established, these parameters being definitively acquired after the age of 7^[26-31]. The protocol used for trunk assessment has been validated before in the study by Blondel *et al.*^[13]. This protocol is designed for clinical use and a low number of markers is a clear advantage

in that case. The authors have demonstrated that 6 markers were sufficient to assess trunk kinematics and kinetics precisely. Moreover, there was a wide amount of variability. Including a greater number of subjects may increase statistical power and allow to highlight differences in sagittal kinematic parameters.

The biomechanical model developed by Blondel *et al.*^[13] in adults has enabled us to achieve the first dynamic study of spine development with age. The comparison of age groups and continuous analysis did not highlight major kinematic evolution of spinal curvatures during skeletal maturation. The acquisition of the lumbar lordosis and thoracic kyphosis is a morphological characteristic that probably appears very early in children, before the age of 3.

The kinetic analysis revealed a progressive decrease in torsional constraints applied on the spine while the constraints in flexion-extension increase with age. These changes allow stabilization of erect posture despite the immaturity of the lower limbs. With the acquisition of mature gait, the spine will mainly undergo constraints in the sagittal plane. These changes point out the major role of the trunk during the acquisition of bipedalism.

COMMENTS

Background

Although gait acquisition is apparently complete by the age of 3, adaptation to erect posture continues until the end of growth. Many studies have described the evolution of spinal curvatures with radiological methods. Using gait analysis tools, it is possible to obtain a precise analysis of the evolution of spinal alignment with age.

Research frontiers

Even if the sample size is quite limited, this study provides interesting information about evolution of spinal dynamics with growth. This study may help to understand changes in gait in spinal disorders.

Innovations and breakthroughs

Results from this study confirm the technical feasibility of the protocol in young children. Using this methodology, it was possible to evaluate net moments applied to spinal junctions. To the authors' knowledge, this the first study to provide dynamic data of the spine of healthy children.

Applications

By providing normative data, this study may help to understand the changes that occur in children with spinal disorders. It could also help to evaluate the behavior of the spine in children after spinal surgery.

Peer-review

Although the sample size is relatively small, this is an interesting study.

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