Eur Spine J (2009) 18:188–195
DOI 10.1007/s00586-008-0864-x

ORIGINAL ARTICLE

Dynamical asymmetries in idiopathic scoliosis during forward and lateral initiation step

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Received: 10 March 2008 / Revised: 14 November 2008 / Accepted: 14 December 2008 / Published online: 8 January 2009

Abstract Adolescent idiopathic scoliosis (AIS) is characterized by morphological trunk modifications acting on body mass distribution. Some specific biomechanical strategies during postural regulation have been reported. Given that spinal deformity is three-dimensional, some strategy analysis resulting from different stepping directions should lead to a better understanding of the dynamic adaptation of behaviour. The aim of this study is to identify dynamic strategies of AIS patients stepping in lateral and forward directions. Ten AIS patients with a right thoracic curve and 15 controlled volunteers have been tested. Ground reaction forces (GRF) have been recorded for right-limb stepping and for left-limb stepping associated to forward and lateral directions. Force amplitudes, corresponding occurrences, impulses of stepping phases and an asymmetry index have been computed. Asymmetry and variability increased in the AIS group, compared to the control group, whatever the stepping direction is. Asymmetry for AIS patients systematically provides an increased left initiation GRF compared to a right initiation. Nevertheless, for both groups, lateral initiation shows the largest asymmetry index reported for a forward initiation. More precisely, adaptive dynamic strategies for the AIS group have been characterized by an asymmetry between right and left limbs for lateral and forward initiation. These results can be explained by the influence of scoliosis pathology on dynamic movements due to spinal deformity. A right thoracic curve leads to an extra weight on the limb, which needs to be moved; consequently, stepping initiation with the right limb was more challenging for patients than stepping with the left limb. For the AIS group, the observed variability can also depend on the ontogenesis of adaptive strategies. Lateral step initiation has to be considered as the most relevant paradigm to study scoliosis and may also serve as a clinical basis for treatment to analyse the dynamic postural control and asymmetry strategies of the scoliosis patient.

Keywords Idiopathic scoliosis · Initiation of gait · Asymmetry · Balance dynamics · Adaptive strategy

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Introduction

Adolescent idiopathic scoliosis (AIS) is considered a common pathology of spinal deformity. Amongst adolescents aged from 10 to 16, the AIS prevalence is 2–4% [5]. Aetiology of this pathology is still unknown even if several origins are evoked such as genetic trouble associated to family history [14], endocrine factors linked to the melatonin pituitary secretion [10], histological factors linked to the modification of muscle fibres percentage, nucleus constitution [16] and neurophysiological factors [26], which have also been reported.

The mechanical consequences of scoliosis are characterized by a three-dimensional deformity of the spine responsible for geometrical and morphological changes of the trunk. This deformity generates postural alterations, sensory perturbations, standing instability and gait modifications [8]. More specifically, Wiener-Vacher and Mazda [29] showed that 67% of patients suffering from AIS presented vestibulo-ocular pathologies even if no relationship between the magnitude of the perturbation sensitivity and the severity of scoliosis curvature had been demonstrated. In contrast, concavity direction and predominance of lateral labyrinthic [15] and visual [24] systems presented some positive correlations. The visual system seemed to be related to scoliosis aetiology; children suffering from a visual disability presented sixfold AIS than children without visual pathology [4]. In addition, the angle between the subjective spatial perception of horizontal and vertical planes increased in the scoliotic group, especially when the curvature was more significant [9]. This suggested that the scoliotic patient organized and stabilized his balance according to an incorrect spatial reference. These sensory issues can be explained by static or dynamic adaptive strategies. The static upright posture results from an increase of both the oscillation range [23] and the centre of pressure displacement [8, 22]. Spinal deformity has no effect on trunk motion but influences movement between body segments (spine and limbs) [22]. AIS girls presented ectomorphic somatotype [1]. Ectomorphic somatotype and one-curvature scoliosis [15] were shown to be both postural instability sources. In a dynamic context, gait studies reported an asymmetry between left and right limbs [11, 25] linked to an increase of the mediolateral ground reaction forces variability [17]. Spinal deformity generates postural perturbations, i.e. troubles whilst performing simple and complex movements. This involves re-organization of information through strategic choices in order to keep a safe static and a dynamic balance [20].

Gait initiation, a transient state from standing posture to gait, has showed some asymmetries in ground reaction forces (GRF) for different pathologies like hemiplegia [2], clubfoot [28], and gonarthrosis patients [27], but no orthopaedic spinal pathology has been tested. As it has been previously demonstrated in gonarthrosis pathology, dynamical GRF control should be asymmetrical and affecting balance regulation.

For healthy adolescent, the initiation gait is characterized by a specific dynamic behaviour fundamental to create an appropriate balance [3]. Morphological AIS modifications of the trunk acting on the mass distribution could be the origin of some asymmetry strategies to regulate balance or movement [19].

Gait initiation could be considered as a relevant paradigm to analyse interactions between plane influence and adaptive postural strategies as AIS frequently presented a predominant trunk deformity in the frontal plane [7, 21].

The aim of this study was to identify dynamic asymmetries during step initiation in the lateral and anterior directions for adolescent girls suffering from scoliosis.

Methods

Two groups participated in the study: 15 young non-scoliotic girls (control group) and 10 scoliotic girls (scoliotic group) with right thoracic or thoraco-lumbar AIS without any compensatory curvature. This specific curvature caused larger modifications in terms of dynamic control compared to the lumbar or compensatory curvature [15]. An orthopaedic surgeon observed each subject to eliminate spinal, neurological and orthopaedic pathologies. He diagnosed and assessed AIS curvature thanks to Cobb's method (angle $\geq 18°$). AIS patients did not undergo prior surgical treatment of spine nor of lower limbs. Both groups had similar age (average 13.18 years $\pm$ 1.7), height (1.57 m $\pm$ 0.08), and weight (48.3 kg $\pm$ 9.3). The experimental protocol was approved by the local research ethics committee (RCB ID: 2006-A00289-42).

The dynamic analysis was performed using two force-plates (strange gauges sensor technique) inserted side by side on the floor, providing GRF data in mediolateral (*Fx*), anteroposterior (*Fy*) and vertical (*Fz*) axes. The foot laterality of the adolescent girls has been assessed via foot dominance testing (posterior push reaction) to identify the dominant and the non-dominant limb. The foot initiating movement was defined as the "dominant foot". All subjects were right-footed. Each subject was asked to step according to the side of limb initiation (dominant vs. non-dominant) and according to the step axis (forward step vs. lateral step). In lateral stepping, there was a target on the floor where subjects were asked to step. Each subject randomly performed five trials per variable (the order of trials was randomized). The sampling frequency of both force-plates was 100 Hz, which is consistent with the literature [2, 12]. The dependent variables were *Fx*, *Fy* and *Fz*.

Data processing was run in successive stages using programming routines (MATLAB v.6, *Matworks*) in order to precisely characterize stepping. The first stage estimated the signal from each force-plate for all steps. Data have then been sorted out as follows: for the forward step—the "stance side" force-plate and the "movement side" force-plate, and for the lateral step—the "initial support" force-plate and the "impact" force-plate. During the lateral step, the upright standing position was kept with both feet on the "initial support" force-plate until the stepping limb contacted the "impact" force-plate. The initial contact on the "impact" force-plate determined t_0. During the forward step, the upright standing position was performed with one foot on each force-plate. The onset of the single-foot phase determined t_0 (Fig. 1).

All GRF data have been synchronized and averaged, from t_0, limited to −1,000 to +1,000 ms time window. Specific *Fx*, *Fy* and *Fz* GRF parameters (magnitude and occurrence) have been extracted to characterize step dynamics. Impulse of GRF components has been computed. Force values, occurrences, impulses and an asymmetry indicator (AI) have been used [6] to identify the difference lower limb strategies between both initiation sides: AI = [(right − left/right) × 100]. A 5% threshold was considered significant to state a dynamic asymmetry between limbs [13]. The comparison between both groups (scoliotic group vs. control group) and direction step (anterior vs. lateral) for all AI (AI(0) symmetry) have been reported in absolute value in function of AI = 0 (perfect symmetry value). Thus, asymmetry level for all parameters has been calculated from AI and reported between minimum and maximum values: AI(0) = [Min; Max]. For the asymmetry direction (right vs. left initiation), the range of AI (AI(*d*) dispersion) has been reported between minimum (negative) and maximum (positive) values: [Min < AI(*d*) < Max].

The Gaussian distribution has been validated by the Wilk–Shapiro statistical test. Analyses of variance (ANOVAs) for each group have been calculated on AI values considering limb initiation and direction of GRF data, GRF magnitude, GRF occurrences and GRF impulses. A Newman–Keuls post hoc test has been used to compare the different variables according to the group. A difference thanks to a *P* value inferior to 0.05 was considered significant.

Results

The difference between scoliotic and control groups has been observed in Table 1 and Fig. 2.

Whatever the direction, AI increased for the scoliotic group (SG) compared to the control group (CG) (CG AI(0) = [|−0.1|; 36.4]; SG AI(0) = [|−0.2|; |−85|], $P < 5.3 \times 10^{-4}$; Fig. 2) in terms of occurrences, impulses, and GRF values (Table 1). For all parameters, SG increase was statistically non-significant for forward stepping versus lateral stepping. For the lateral step, AI(0) increased for SG versus CG-concerned occurrences, impulses and GRF values *Fx*, *Fy* and *Fz* (Table 1).

Asymmetry indicator comparison between SG and CG, whatever the direction, revealed an increased variability of the overall parameters computed for scoliotic patients (10.92% ± −9.71) versus CG (4.83% ± −2.85, $P < 5 \times 10^{-3}$; Fig. 2). The variability of lateral stepping increased for SG (SG 16.80% ± −9.98 vs. CG 6.91% ± −2.67, $P < 1.1 \times 10^{-3}$) in contrast to anterior stepping. The comparison between the two directions revealed a higher

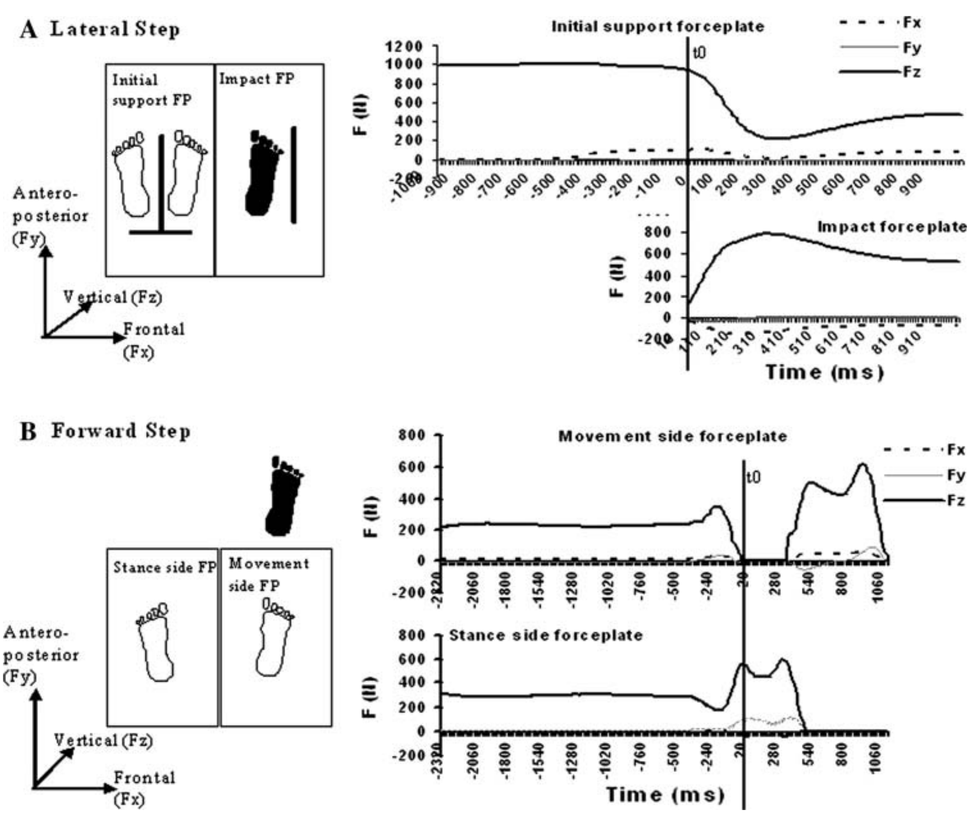

Fig. 1 Experimental setup design for lateral (**a**) and forward (**b**) stepping. *Light* foot corresponds to the initial position. *Dark* foot corresponds to the impact foot on the right side. Lateral step: the three components of ground reaction forces (*Fx* mediolateral, *Fy* anteroposterior and *Fz* vertical) evolution (expressed in N) associated to the time evolution (ms) shown for the lateral step on the initial support force-plate and the impact force-plate. Forward step: the three components of ground reaction forces (*Fx* mediolateral, *Fy* anteroposterior and *Fz* vertical) evolution (expressed in N) associated to the time evolution (ms) shown for the forward step on the stance side force-plate and the movement side force-plate

Table 1 Asymmetry Index [AI(0)] comparison between the control group and the scoliotic group

Step	Group		
	Control group	Scoliotic group	*P* value
Forward and lateral steps			
Occurrences	AI(0) = [0.3; 23.1]	AI(0) = [1.2; 49.1]	$P < 1.6 \times 10^{-3}$
Impulses	AI(0) = [0.1; 36.4]	AI(0) = [0.92; 66.5]	$P < 2 \times 10^{-3}$
Fx	AI(0) = [0.3; 7.89]	AI(0) = [0.2; 13.5]	$P < 5 \times 10^{-3}$
Fy	AI(0) = [0.85; 24.4]	AI(0) = [4.65; 85]	$P < 3.9 \times 10^{-3}$
Fz	AI(0) = [0.4; 10.9]	AI(0) = [0.81; 29.8]	$P < 4.1 \times 10^{-3}$
Forward step			
Occurrences	AI(0) = [0.69; 12.62]	AI(0) = [1.83; 49.91]	NS
Impulses	AI(0) = [0.94; 11.27]	AI(0) = [0.92; 13.58]	NS
Fx	AI(0) = [0.91; 7.89]	AI(0) = [8.13; 10.22]	NS
Fy	AI(0) = [0.85; 7.29]	AI(0) = [4.65; 15.06]	NS
Fz	AI(0) = [0.49; 4.75]	AI(0) = [0.81; 4.68]	NS
Lateral step			
Occurrences	AI(0) = [0.3; 23.1]	AI(0) = [1.2; 29.8]	$P < 5 \times 10^{-3}$
Impulses	AI(0) = [0.1; 36.4]	AI(0) = [4.6; 66.5]	$P < 1.7 \times 10^{-3}$
Fx	AI(0) = [0.5; 8.7]	AI(0) = [0.2; 13.5]	$P < 3.1 \times 10^{-3}$
Fy	AI(0) = [7.9; 24.4]	AI(0) = [8.9; 85]	$P < 2.4 \times 10^{-3}$
Fz	AI(0) = [2.9; 10.9]	AI(0) = [9.4; 29.8]	$P < 3.6 \times 10^{-3}$

All parameters are represented in absolute value. These three stages are represented by (1) forward and lateral steps, (2) forward step and (3) lateral step. The non-significant results ($P > 5 \times 10^{-2}$) are represented by NS

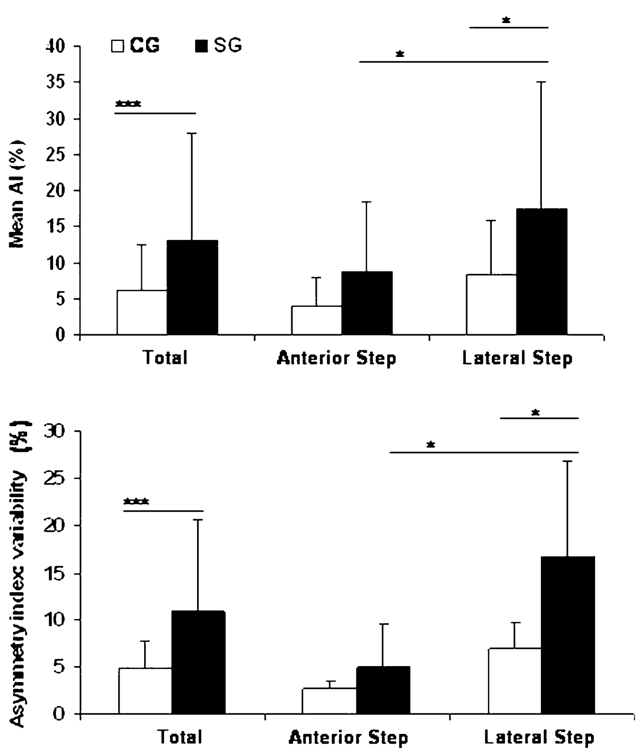

Fig. 2 Asymmetry index (AI) and standard deviation (%) for all parameters in two movements (Total), forward step (Anterior step), lateral step, for control group (CG) in *clear* and, scoliotic group (SG) in *dark*. A statistical difference is represented by "*" ($P < 5 \times 10^{-2}$) or "***" ($P < 1 \times 10^{-3}$)

variability for lateral stepping, only when stepping was performed by scoliotic patients (anterior 5.04% ± −4.45 vs. lateral 16.80% ± −9.98; $P < 4 \times 10^{-3}$).

The comparison between step directions is represented in Table 2.

Lateral stepping globally presented largest AI(0) than forward stepping with AI(0) as SG statistically increased whilst no difference was found for CG (Fig. 2). In addition, impulses, *Fx*, *Fy* and *Fz* of lateral stepping performed by SG revealed larger asymmetries whilst its timing presented a trend to increase with lateral stepping versus forward (Table 2).

The overall parameters of forward stepping performed by SG systematically presented an AI(0) > 5% for the anteroposterior forces (occurrences, impulses and force values) and mediolateral forces (occurrences and force values, excepted for impulses; Table 2). Considering vertical forces, AI(0) was not systematically >5%.

The overall parameters of lateral stepping performed by SG systematically showed AI(0) > 5% for vertical and anteroposterior components of GRF (occurrences, impulses and forces values). For mediolateral forces, the AI(0) was not systematically >5%. CG was characterized during forward and lateral stepping by an AI(0) not systematically >5% whatever the GRF components (impulses, occurrences and forces values; Table 1) were.

Table 2 Asymmetry Index (AI) comparison between forward step and lateral step

Group	Step		
	Forward step	Lateral step	P value
Control group			
All parameters	AI(0) = [0.71; 12.62]	AI(0) = [0.1; 36.4]	NS
Occurrences	AI(0) = [0.69; 12.62]	AI(0) = [0.3; 23.1]	NS
Impulses	AI(0) = [0.94; 11.27]	AI(0) = [0.1; 36.4]	NS
Fx	AI(0) = [0.91; 7.89]	AI(0) = [0.5; 8.7]	NS
Fy	AI(0) = [0.85; 7.29]	AI(0) = [7.9; 24.4]	NS
Fz	AI(0) = [0.49; 4.75]	AI(0) = [2.9; 10.9]	NS
Scoliotic group			
All parameters	AI(0) = [0.81; 49.91]	AI(0) = [0.2; 85]	$P < 9 \times 10^{-5}$
Occurrences	AI(0) = [1.83; 49.91]	AI(0) = [1.2; 29.8]	NS ($P < 7 \times 10^{-3}$)
Impulses	AI(0) = [0.92; 13.58]	AI(0) = [4.6; 66.5]	$P < 3 \times 10^{-4}$
Fx	AI(0) = [8.13; 10.22]	AI(0) = [0.2; 13.5]	$P < 4.2 \times 10^{-3}$
Fy	AI(0) = [4.65; 15.06]	AI(0) = [8.9; 85]	$P < 3.9 \times 10^{-3}$
Fz	AI(0) = [0.81; 4.68]	AI(0) = [9.4; 29.8]	$P < 4.1 \times 10^{-3}$

All parameters are represented in absolute value. Two stages are represented: (1) control group and (2) scoliotic group. Non-significant results ($P > 5 \times 10^{-2}$) are represented by NS

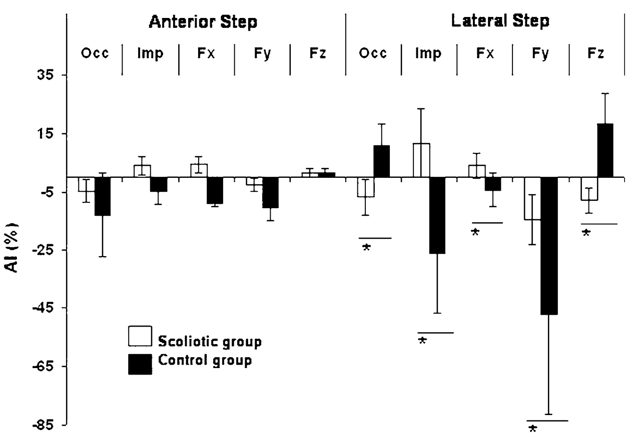

Fig. 3 Direction of the asymmetry for the scoliotic group in *dark* and the control group in *clear* for the anterior step and lateral step. The asymmetry index (*AI*) was computed for GRF parameters: occurrences (*occ*), impulses (*imp*), medio-lateral (*Fx*), antero-posterior (*Fy*) and vertical (*Fz*) components. A statistical difference is represented by "*" ($P < 5 \times 10^{-2}$)

Asymmetry result for right and left limbs is represented in Fig. 3.

The computed AI(*d*) gives some information on the direction of the asymmetry (see "Methods").

Scoliotic group was characterized by a negative AI for 66% of the computed parameters (AI > 5%; Fig. 3). More specifically, the left side revealed an increase in the value of occurrences ($1.2 > \mathrm{AI}(d) > -49.91$), impulses ($0.92 > \mathrm{AI}(d) > -66.5$) and GRF for *Fx* ($-0.2 > \mathrm{AI}(d) > -13.5$) and for *Fy* ($8.9 > \mathrm{AI}(d) > -85$). Conversely, *Fz* increased for the right side ($-0.81 < \mathrm{AI}(d) < 29.8$; Fig. 3).

Control group was characterized by a negative AI in 52% of the measured parameters. In this group, the asymmetry distribution was less pronounced than SG for occurrences ($-23.1 < \mathrm{AI}(d) < 12.62$), impulses ($0.1 < \mathrm{AI}(d) < 36.4$) and GRF for *Fx* ($-7.89 < \mathrm{AI}(d) < 8.7$), *Fy* ($-24.4 < \mathrm{AI}(d) < 6.8$) and *Fz* ($-10.9 < \mathrm{AI}(d) < 4.75$; Fig. 3).

Discussion

The aim of the study is to characterize adaptive strategies adolescents with AIS use when they perform a step initiation in the frontal plane and in the sagittal plane. Results showed for each GRF parameter an increasing AI for the scoliotic group compared to the control group. Computed asymmetry, mirroring adaptive strategy, is more apparent for the lateral step than for the forward step whatever the group is. The SG showed negative AI direction revealing the predominance of left initiation limb versus right initiation limb. Such large asymmetry is the consequence of some adaptive postural strategies, whatever the stepping direction is, reflecting the influence of the spinal curvature.

During gait, Chockalingam et al. [11] have established that the scoliotic patient with non-compensated curve presents larger GRF asymmetry than the patient with a compensated curve. Moreover, these authors did not demonstrate any correlation between asymmetry strategies and the mediolateral component of gait movement. In addition, our results have revealed an asymmetry of the lower limb dynamics highly related to the movement direction. Such an asymmetry, affecting the different parameters of GRF, appears at different phases of the movement whatever the direction is. Strategies observed for both groups presume of a functional biomechanical organization devoted to the optimal control of the mechanical energy associated to orthogonal planes to be controlled [30]. Such motor production is regulated by motor programs linked to the scoliosis curvature automatically inducing additional strategies. Such adaptive morphological deformation strategy is dedicated to adjust low-cost energies [20]. Whatever the testing paradigm is, asymmetry is always more pronounced for scoliotic patients. We have demonstrated that scoliotic patients compensate for the effect of pathological curvature through a specific GRF strategy in terms of time–distance parameters. According to Giakas et al. [17] GRF components for patients suffering from scoliosis are altogether combined to compensate the curvature asymmetry to ensure balance. Controversial results in the literature may be explained by the testing paradigm. i.e. normal gait versus stepping initiation in two plane directions. Differences calculated between the groups may be due to a mechanical modification of mass distribution and segmental inertia, both determining specific motor strategies to be adapted to geometry curvature. Control subjects undergoing the experiment also show a behavioural asymmetry, thus enabling us to think that the asymmetry (dominant vs. nondominant) is not at the origin of the scoliotic process. However, the significant difference observed in both groups show that this asymmetric rise could be the baseline trigger of pathology. To justify this idea, two paradigms exist. The first one would be to recognize the connection between asymmetry level and scoliosis acuteness rise (longitudinal study). The second one would be to measure the evolution of this asymmetry index on young children and see if those with the most asymmetric index develop a scoliosis curve.

The scoliosis geometry progresses with adolescent growth and development which should be reflected on the notification of modified adaptive motor strategies. Larger computed AI variability may be a cue of such a progressive behaviour. These results observed in two orthogonal planes are confirmed by previous studies of gait and standing postures [12, 17]. Ontogenic development of spinal deformity associated with the morphotype of SG and with the consequences of biomechanical aspect [1] may explain the variability of dynamic motor strategies. Orthogonal displacement reflects the influence of mechanical ontogenesis on adaptive behaviour. Our data showed the prevailing variability of lateral stepping versus forward stepping. Moreover, spinal deformity is more noticeable in the frontal plane than in the sagittal one. For lateral stepping, adaptive strategies performed by scoliotic subjects are more related to scoliosis deformity in the frontal plane than in the sagittal one. An increased variability of the movement in the frontal plane may be explained by the absence of prior learning. Scoliosis patients cannot manage to find a new adequate strategy to fit with a new motor task. In contrast, the patient stepping forward benefits from a repeated learning enabling the development of a more specific and stable adaptive strategy. This forward step is an appropriate experimental paradigm to analyse stabilization of motor strategies leading to a functional homogeneous behaviour. However, despite the increased variability, lateral stepping may still be considered as the most relevant paradigm to assess asymmetry between initiation limbs. It explains the patient's adaptive behaviour within the scoliosis group. Lateral stepping allows a better differentiation of scoliotic patients from healthy subjects and lower limb stepping initiation. Studying the movement in different planes for a three-dimensional spinal deformation is thus relevant.

Differences on specific asymmetry strategies expressed via lower limb dynamics are more observable for lateral stepping than for forward initiation. This increased asymmetry in lateral stepping can be explained by the fact that forward initiation is more frequently used in gait than lateral step. For forward initiation, scoliotic subjects have to provide a dynamical strategy over time according to the progression of spine deformation. In contrast, when the subject steps laterally he faces a new dynamical status. The independent analysis of the dynamical parameters show that CG revealed an AI, which is not systematically superior to 5% for forward and lateral stepping whatever the GRF impulses, occurrences and GRF forces are. GRF differences between groups are more acute for lateral stepping. Large asymmetry of GRF gait has already been demonstrated in mediolateral component [11, 18]. Giakas et al. [17] have shown high GRF frequencies for SG and Schizas et al. [25] have shown asymmetry of vertical GRF superior to 4% in SG. These stepping direction results demonstrate no functional asymmetry for CG, which contradicts the results of De Vita et al. [13] for whom asymmetry exists in normal gait. This study shows an AI systematically superior to 5% for anteroposterior and vertical forces meant to step laterally. In contrast, forward stepping presents an AI superior to 5% for anteroposterior and mediolateral forces. We observed that anteroposterior forces are statistically asymmetrical whatever the initiation direction is. These anteroposterior forces, characterized by a permanent asymmetry, mirror the adaptive behaviour of AIS patients, which could compensate trunk morphological asymmetry. According to movement direction, anteroposterior forces combine automatically with mediolateral or vertical forces to control GRF without compromising the dynamical balance. Giakas et al. [17] previously showed in scoliotic patients that anteroposterior forces combined with mediolateral forces during gait, which has also been demonstrated in this study. According to a recent work concerning lateral step initiation [8], anteroposterior forces were defined as the most representative parameter to study the dynamical asymmetry of a motor production in the SG whatever the stepping direction is. The anteroposterior component of GRF is a relevant clinical parameter to compare SG to CG and more specifically to specify the dynamics of lower limbs in stepping initiation. This point does not confirm previous results dealing with dynamics of posture [31] or of gait [17]. These authors indicate major issues in mediolateral component of GRF than the other components (anteroposterior and vertical forces).

Thus, the asymmetry strategies adapt according to plane movements. The patient suffering from scoliosis must manage to find the equilibrium of the movement and the spinal deformation without learning the dynamical strategy to be run. Scoliotic patients present a different behaviour in terms of force control according to the stepping direction. Our data demonstrate the necessity to differentiate a static analysis of posture, a quasi static analysis of initiation gait and a dynamical analysis of normal gait. Initiation gait as the transition phase has to be considered as a whole intrinsic motor behaviour associating specific learning and motor strategies.

Conclusion

This study demonstrates the interest to focus on movement initiation following orthogonal directions for a pathological population presenting a three-dimensional trunk deformity. Whatever the stepping direction was, asymmetrical GRF controlled balance for AIS patients. Stepping forward, as the result of ontogenetic learning, has showed a permanent strategy adaptation due to a permanent lateral stepping use, which reflects a short-term strategy adaptation. The originality of our study lies in the type of movement paradigm, which is not posture neither gait, but initiation stepping as the transition between both. The learning aspect and the movement itself are at stake to understand better the clinical basis and be rehabilitation oriented for the patient care.

It would be interesting to systematically assess movements over two different planes for a pathology combining a three-dimensional spinal biomechanical disorder. This assessment should lead us to a characteristic asymmetry index enabling us to plan a physiotherapy adapted to the pathology and adaptations peculiar to each subject.

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