Gait in adolescent idiopathic scoliosis: energy cost analysis

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Abstract Walking is a very common activity for the human body. It is so common that the musculoskeletal and cardiovascular systems are optimized to have the minimum energetic cost at 4 km/h (spontaneous speed). A previous study showed that lumbar and thoracolumbar adolescent idiopathic scoliosis (AIS) patients exhibit a reduction of shoulder, pelvic, and hip frontal mobility during gait. A longer contraction duration of the spinal and pelvic muscles was also noted. The energetic cost (C) of walking is normally linked to the actual mechanical work muscles have to perform. This total mechanical work (W_{tot}) can be divided in two parts: the work needed to move the shoulders and lower limbs relative to the center of mass of the body (COM_b) is known as the internal work (W_{int}), whereas additional work, known as external work (W_{ext}), is needed to accelerate and lift up the COM_b relative to the ground. Normally, the COM_b goes up and down by 3 cm with every step. Pathological

walking usually leads to an increase in W_{tot} (often because of increased vertical displacement of the COM_b), and consequently, it increases the energetic cost. The goal of this study is to investigate the effects of scoliosis and scoliosis severity on the mechanical work and energetic cost of walking. Fifty-four female subjects aged 12 to 17 were used in this study. Thirteen healthy girls were in the control group, 12 were in scoliosis group 1 (Cobb angle [Cb] $\leq 20^\circ$), 13 were in scoliosis group 2 ($20^\circ < \text{Cb} < 40^\circ$), and 16 were in scoliosis group 3 ($\text{Cb} \geq 40^\circ$). They were assessed by physical examination and gait analysis. The 41 scoliotic patients had an untreated progressive left thoracolumbar or lumbar AIS. During gait analysis, the subject was asked to walk on a treadmill at 4 km h^{-1} . Movements of the limbs were followed by six infrared cameras, which tracked markers fixed on the body. W_{int} was calculated from the kinematics. The movements of the COM_b were derived from the ground reaction forces, and W_{ext} was calculated from the force signal. W_{tot} was equal to $W_{\text{int}} + W_{\text{ext}}$. Oxygen consumption ($\dot{V}\text{O}_2$) was measured with a mask to calculate energetic cost (C) and muscular efficiency (W_{tot}/C). Statistical comparisons between the groups were performed using an analysis of variance (ANOVA). The external work (W_{ext}) and internal work (W_{int}) were both reduced from 7 to 22% as a function of the severity of the scoliosis curve. Overall, the total muscular mechanical work (W_{tot}) was reduced from 7% to 13% in the scoliosis patients. Within scoliosis groups, the W_{ext} for the group 1 ($\text{Cb} \geq 20^\circ$) and 2 ($20 \leq \text{Cb} \leq 40^\circ$) was significantly different from group 3 ($\text{Cb} \geq 40^\circ$). No significant differences were observed between scoliosis groups for the W_{int} . The W_{tot} did not show any significant difference between scoliosis groups except between group 1 and 3. The energy cost and $\dot{V}\text{O}_2$ were increased by around 30%. As a result muscle efficiency was significantly decreased by 23% to 32%, but no significant differences related to the severity

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of the scoliosis were noted. This study shows that scoliosis patients have inefficient muscles during walking. Muscle efficiency was so severely decreased that it could be used as a diagnostic tool, since every scoliosis patient had an average muscle efficiency below 27%, whereas every control had an average muscle efficiency above 27%. The reduction of mechanical work found in scoliotic patients has never been observed in any pathological gait, but it is interpreted as a long term adaptation to economize energy and face poor muscle efficiency. With a relatively stiff gait, scoliosis patients also limit vertical movement of the COM_b (smoothing the gait) and consequently, reduce W_{ext} and W_{int} . Inefficiency of scoliosis muscles was obvious even in mild scoliosis (group 1, $Cb < 20^\circ$) and could be related to the prolonged muscle contraction time observed in a previous study (muscle co-contraction).

Keywords Scoliosis · Gait · Energy cost · Pronostic

Introduction

Human walking is an essential daily activity that requires correct joint mobilities and appropriate muscular force to move the body. Both of these parameters engage mechanical work [35] and energy expenditure, which are optimized in normal walking at a spontaneous speed in order to minimize the cost of locomotion [2, 24, 34].

Our previous study focused on changes in gait kinematics between thoraco-lumbar and lumbar Adolescent Idiopathic Scoliosis (AIS) patients and healthy subjects [21]. AIS patients have little reduction in trunk, pelvis, and hip frontal mobility. Surprising, we also noticed a much longer contraction duration of the bilateral lumbar and pelvic muscles (rising from 30% to 50% of the gait cycle). This increase in electrical activity was noticed even for mild scoliosis (Cobb angle [Cb] $< 20^\circ$).

During walking, human beings not only move their lower legs and pelvis, but also raise and lower their center of body mass (COM_b) at each step. Pelvic and hip frontal motion are major determinants that serve to minimize and smooth the vertical displacement of the COM_b [9], allowing optimal oxygen consumption during walking [16]. Disturbances of the vertical displacement of the COM_b in normal conditions (e.g., walking on sand or carrying loads as an African woman) [6, 18] or conditions of pathologic gait (e.g., stiff-knee gait after a stroke or walking with a prosthesis) [10, 12, 27, 28] affect the mechanical work and metabolic cost of the gait [10–13, 18, 22, 27, 29, 30, 33]. More precisely, any handicap increases these two parameters [10, 27, 29, 30, 33, 34]. Both muscular mechanical work, which is assessed by the production of mechanical energy due to the energy changes of the COM_b relative to the ground and of the body

segments relative to the COM_b [4, 5], and the energy expenditure due to the oxygen consumption [32, 34] allow assessment of the efficiency of locomotion. This efficiency is underlined by a locomotor mechanism that can be compared to an inverted pendulum (i.e., a pendulum-like mechanism). At each stride, the COM_b is successively behind or in front of the point of contact with the foot on the ground. It thereby produces gravitational potential and kinetic energy that are continuously converted into one another like a pendulum, and the resulting muscular mechanical work (W_{tot}) requires energy expenditure during walking. This energy expenditure may be measured by the classical indirect calorimetric method that remains the most reliable and practical method based on the rate of O_2 consumption ($\dot{V}O_2$) [25]. From this measure, the physiological work (i.e., the energy per unit distance travelled, also called energy cost or C) may be computed. By comparing the energy cost of walking in patients and healthy subjects, it is possible to evaluate the energetic penalty of gait disability [34]. At a constant speed, an increased energy cost means that the rate of O_2 consumption increases and level of physical effort elevates. For example, there is a progressive rise in the rate of energy expenditure and a doubling of energy cost between normal walking (4 km h^{-1}) and running (8 km h^{-1}) [15].

The problem occurs when the rate of O_2 consumption ($\dot{V}O_2$) approaches its maximum ($\dot{V}O_{2 \text{ max}}$); at this moment, the consumption of oxygen is levelling off as anaerobic oxidation processes occur. These processes result in the accumulation of serum lactate and rapid muscular intolerance to acidosis. Expressed as a percentage of the $\dot{V}O_{2 \text{ max}}$, the rate of oxygen consumption at a normal speed (4 km h^{-1}) requires approximately 20% of the $\dot{V}O_{2 \text{ max}}$ of an untrained normal teen or young adult. The fact that walking taxes less than 50% of the $\dot{V}O_{2 \text{ max}}$ in normal subjects and does not require anaerobic activity accounts for the perception that walking requires little effort in healthy individuals [34]. Indeed, an excessive energy cost reduces the possibility of engaging in activities and participating in social events.

By studying this variable in AIS, it is possible to gain further insight into the mechanisms of pathological walking. The first goal of this study is to evaluate how light gait changes observed in AIS patients affect the mechanical work and energy expenditure during locomotion. The second goal is to determine whether the severity of scoliosis curves influence these parameters.

Materials and methods

Study population

Fifty-four female subjects (13 healthy subjects and 41 untreated progressive AIS patients with comparable height,

weight and body mass index) aged 12 to 17 years were included in the study. The scoliosis patient group had a left thoracolumbar or lumbar main structural curve (types 5 and 6 according to the Lenke classification [19]) and was divided in three subgroups according to the Cobb angle (Cb) range: group 1: $Cb \leq 20^\circ$ ($n = 12$), group 2: $20^\circ < Cb < 40^\circ$ ($n = 13$), and group 3: $Cb \geq 40^\circ$ ($n = 16$) [7]. Girls underwent a complete physical examination to detect any locomotor disorders, neurological abnormalities, and previous spinal treatment or gait assessment. Scoliosis patients were submitted to a radiological examination. Anthropometric and radiological data are summarized in our previous study [21].

Every subject signed up for and participated freely in the study, which was approved by the local ethics board.

Instrumented gait analysis

Gait was assessed by a three-dimensional analysis, which included synchronous mechanical and energetic measurements (Fig. 1).

The mechanical work was computed as follows: the total positive mechanical work (W_{tot}) done by the muscles during walking was divided into the external work (W_{ext}) performed to move the COM_b relative to the surroundings and the internal work (W_{int}) performed to move the body segments relative to the COM_b [35] (Fig. 2).

The external work (W_{ext}) performed by the muscles to accelerate and lift the COM_b was computed from four force transducers located at the four corners of the treadmill. These transducers measured the 3D-ground reaction forces according to Cavagna [3].

The three-dimensional accelerations (a) of the COM_b were computed from the vertical (F_v), lateral (F_l), and forward (F_f) components of the ground reaction forces (F) and mass (m) of the subject ($F = ma$). The mathematical integration of the three-dimensional accelerations gave the

velocity changes of the COM_b in all three directions (V_v , V_l , V_f). From the instantaneous V_v , V_l , and V_f and the body mass (m), we computed the instantaneous kinetic energies ($E_k = 1/2mV^2$) of the COM_b (E_{kv} , E_{kl} , E_{kf}). A second mathematical integration of V_v was performed to determine the vertical COM_b displacement (S_v) and computed the instantaneous gravitational potential energy ($E_p = mgS_v$). The total external mechanical energy (E_{tot}) of the COM_b was calculated as the sum of the kinetic and potential energies. The increments of the E_{kv} , E_{kl} , E_{kf} , and E_p curves represented the positive work (W_{ekv} , W_{ekl} , W_{ekf} , and W_{ep} , respectively) necessary to accelerate the COM_b in the three directions and lift the COM_b during a stride. W_{ext} was obtained by summing the increments of E_{tot} over a stride. W_{ekv} , W_{ekl} , W_{ekf} , W_{ep} , and W_{ext} were expressed in Joules per kilogram body mass and per distance travelled.

The ‘Recovery’, quantifying the percent of mechanical energy saved by a pendulum-like exchange between the gravitational potential energy and kinetic energy of the COM_b (i.e., an index reflecting the effectiveness of the pendulum-like mechanical mode of walking) was calculated using the following equation [3, 5]:

$$\text{Recovery}(\%) = 100 \times \frac{|W_{ek}| + |W_{ep}| - |W_{\text{ext}}|}{|W_{ek}| + |W_{ep}|}$$

In this equation, $W_{ek} = W_{ekf} + W_{ekv} + W_{ekl}$ and each parameter was calculated as the sum of the positive increments from the corresponding E_k , E_p , and E_{tot} curves (Fig. 2).

$W_{ek} + W_{ep}$ is the maximum positive work (W_{ext}) that should be done without energy shift and represents the work actually done [5].

The internal work (W_{int} , the work required to move the limbs relative to the COM_b) was computed from kinematic data following the method described by Willems et al. [35] and Detrembleur et al. [12]. The body was divided into

Fig. 1 Energetic and mechanical measurements. Illustration of energy expenditure (oxygen consumption and energy cost) measured by the classical indirect calorimetric method and mechanical work assessed by the three-dimensional ground reaction force

Fig. 2 Evolution of external and internal mechanical energy as function of time during gait at 4 km h^{-1} . The *upper figure* represents the curves of external energy (expressed in joules per kilogram body mass and per meter travelled) as a function of time. These curves were used to compute the external work (W_{ext}) performed by the muscles to accelerate and lift the COM_b . The E_{kf} curve represents the kinetic energy variations linked to the speed of COM_b displacement in the forward direction. The E_v curve represents the gravitational potential (E_p) and kinetic energy variations (E_{kv}) linked to the speed of COM_b displacement in the vertical direction. The E_{kl} curve represents the kinetic energy variations linked to the speed of COM_b displacement in the lateral direction. The total external mechanical energy (E_{tot}) of the COM_b was calculated as the sum of the kinetic and potential energies. The increments of E_{kf} , E_v , and E_{kl} curves represented the positive work (W_{ekf} , W_{ev} and W_{ekf} , respectively) necessary to accelerate the

COM_b in the three directions and lift the COM_b during a stride. W_{ext} was obtained by summing the increments of E_{tot} over a stride. The a' and b' vertical arrows show the increments of the external mechanical energy curves measured on a healthy subject and an AIS patient with $Cb \geq 40^\circ$. The lower figure represents the curves of internal energy as a function of time. These curves were used to compute the internal work (W_{int}) required to move the limbs relative to the COM_b for the head-arm-trunk (HAT) segment ($E_{i,HAT}$) as well as the *left* and *right lower limb* segments ($E_{i,LLL}$ and $E_{i,RLL}$). When the curves increase, the muscles provide positive work to accelerate the body segments relative to the COM_b . The W_{int} during gait corresponded to the sum of the W_{int} done to move the lower limbs and HAT segments, and it was expressed in joules per kilogram body mass and per meter travelled. The a , b , c , d , e , and f vertical arrows show the increments of the internal mechanical energy curves

seven rigid segments: head-arm-trunk (HAT), thighs, shanks, and feet. The internal mechanical energy of the body segments corresponded to the sum of the rotational and translational energies of these segments due to their

movements relative to the COM_b . For each lower limb, the internal mechanical energy–time curves of the thigh, shank, and foot were summed. The W_{int} of each lower limb and HAT segment was then calculated separately as the

sum of the increments of the respective internal mechanical energy curves. Finally, W_{int} during gait corresponded to the sum of the W_{int} done to move the lower limbs and HAT segments and was expressed in joules per kilogram body mass and per meter travelled.

The metabolic cost of walking was determined by the subject's oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$), which were measured throughout the treadmill test with an ergospirometer (Quark b², Cosmed, Italy) and expressed in $\text{ml kg}^{-1} \text{min}^{-1}$. The mass-specific gross energy consumption rate ($W \text{ kg}^{-1}$) was obtained from the oxygen consumption rate using an energy equivalent of oxygen, taking into account the measured respiratory exchange ratio (RER) [23]. The RER, computed as the ratio between $\dot{V}CO_2$ and $\dot{V}O_2$, always remained less than 1. Each energy measurement started with a rest period in which the subject was standing on the treadmill. Thereafter, they walked until a steady state was reached and maintained for at least 2 min. The Joules of energy expended per liter of oxygen consumed were computed depending on the RER according to the Lusk equation [23]. The energy expended above the resting value (standing subtracted from walking consumption) was divided by the walking speed (4 km h^{-1}) to obtain the net energy cost of walking ($C, \text{J kg}^{-1} \text{m}^{-1}$) [4]. The efficiency (η) of positive work production by the muscles was calculated as the ratio between W_{tot} and C [4].

Protocol

All subjects wore a harness attached to the ceiling to prevent them from falling while walking on the treadmill. The sessions began with a rest period, in which the subjects stood barefoot on the motor-driven treadmill (Mercury LTmed, HP Cosmos®, Germany) [14] for the static calibration of kinematic and energetic variables. Thereafter, the subjects were asked to walk at a constant speed of 4 km h^{-1} for a few minutes until a steady state was reached and maintained for at least two minutes. Then, energetic variables were computed for two minutes. Other variables were simultaneously recorded for twenty seconds and averaged for ten successive strides. The mean of each value was used for statistical analysis. The percentage reduction for some selected variables was calculated as follows: the absolute difference between the mean of the scoliosis group and the mean of the healthy subjects group, divided by the mean of the healthy subject group. The result was then multiplied by 100 to obtain the percentage of change.

Statistical analysis

All the variables that followed (respect) the normal distribution and equality of variance were presented in mean

($\pm$ SD). The other variables were given as medians and quartiles [25–75%]. Statistical analysis was performed using the software SigmaStat version 2.0, SPSS Sciences Software GmbH, Erkrath, Germany. The significance level was set at $P \leq 0.05$.

A one-way analysis of variance (ANOVA) or Kruskal-Wallis One Way Analysis of Variance on Ranks (if normality and equality of variance tests not passed) was performed to compare all gait variables between the group of able-bodied subjects and each of the scoliosis groups. A post-hoc test was used to identify significantly different variables with the Bonferroni correction.

Results

In all scoliosis patient groups, the mechanical work was significantly decreased in comparison to that of healthy subjects (Fig. 2). On average, the external work (W_{ext}) performed by the muscles to accelerate and lift the COM_b and the internal work (W_{int}) required to move the limbs relative to the COM_b were both reduced by 7 to 22% (i.e., reduced from 0.02 to $0.06 \text{ J kg}^{-1} \text{m}^{-1}$, $P < 0.001$) with the severity of the scoliosis curve. Additionally, the total mechanical work (W_{tot}) was reduced by 7 to 13% (i.e., from 0.04 to $0.07 \text{ J kg}^{-1} \text{m}^{-1}$, $P < 0.001$, Table 1). The post hoc test showed a significant reduction as a function of the severity of the curve for W_{ext} except for scoliosis groups 1 ($Cb \geq 20^\circ$) and 2 ($20 \leq Cb \leq 40^\circ$). There was no significant difference for the W_{int} between the three scoliosis groups. A significant difference was found for W_{tot} only between scoliosis groups 1 and 3 ($Cb \geq 40^\circ$).

Among the three spatial components of the W_{ext} , the vertical (W_{ekv}) ($P = 0.009$) and forward (W_{ekf}) ($P = 0.01$) mechanical work were significantly decreased in scoliosis patients but showed no difference between the three scoliosis groups (Table 1).

In all scoliosis patients, the average energy cost was increased by 30% (i.e., from 1.8 to $2.4 \text{ J kg}^{-1} \text{m}^{-1}$, $P < 0.001$) and the $\dot{V}O_2$ progressed from 9.9 to $13.8 \text{ ml kg}^{-1} \text{min}^{-1}$ ($P = 0.001$). The muscle efficiency was significantly decreased by 30% (i.e., from 30.2 to 20.6, $P = 0.001$) when comparing all scoliosis subjects with healthy subjects. There was no significant difference in these energetic variables between the three scoliosis groups (Table 1, Fig. 3).

Discussion

The present study has demonstrated an important increase of energy cost and decrease of muscular efficiency during

Table 1 Results of ANOVA on mechanical and energetic variables in 54 female subjects

	Control group	Scoliosis patients			<i>P</i> value
	Mean (SD)	Mean (SD)			
	(<i>n</i> = 13)	Cb < 20° (<i>n</i> = 12)	20 < Cb < 40° (<i>n</i> = 13)	Cb > 40° (<i>n</i> = 16)	
Mechanics					
W_{ext} (J kg ^{−1} m ^{−1})	0.27 (0.02)	0.25 (0.02)*	0.25 (0.02)*	0.21 (0.02)*	<0.001
W_{int} (J kg ^{−1} m ^{−1}) ^a	0.27 (0.25–0.27)	0.24 (0.22–0.25)*	0.24 (0.22–0.24)*	0.21 (0.19–0.24)*	<0.001
W_{tot} (J kg ^{−1} m ^{−1})	0.55 (0.02)	0.51 (0.02)*	0.5 (0.03)*	0.48 (0.03)*	<0.001
W_{ekf} (J kg ^{−1} m ^{−1}) ^a	0.32 (0.29–0.34)	0.31 (0.29–0.33)	0.30 (0.28–0.34)	0.28 (0.25–0.29)*	0.01
W_{ekv} (J kg ^{−1} m ^{−1})	0.39 (0.04)	0.37 (0.04)	0.35 (0.03)*	0.34 (0.02)*	0.009
W_{ekl} (J kg ^{−1} m ^{−1})	0.01 (0.004)	0.03 (0.1)	0.008 (0.003)	0.03 (0.07)	0.58
Recovery (%)	61.3 (4.7)	65.2 (4.3)	63.6 (5)	62.9 (4.9)	0.26
Energetics					
Energy cost (J kg ^{−1} m ^{−1})	1.8 (0.3)	2.4 (0.4)*	2.3 (0.3)*	2.4 (0.3)*	<0.001
Muscle efficiency	30.2 (3.9)	23.1 (5.9)*	21.8 (3.4)*	20.6 (3.8)*	0.001
$\dot{V}O_2$ (ml kg ^{−1} min ^{−1})	9.9 (0.8)	12.8 (1.6)*	13.8 (2.8)*	13 (3.2)*	0.001
COM _b displacement					
Vertical (m) ^a	0.026 (0.024–0.027)	0.023 (0.021–0.029)	0.021 (0.019–0.025)	0.020 (0.017–0.024)*	0.017

Significant differences are typed in bold and are accepted for *P* value ≤ 0.05

NS Not significant, i.e. *P*-value > 0.05

* Significantly different from the control group

^a Median [25–75%]

gait in AIS patients. These changes are associated with a surprising economy of mechanical work (W_{tot}). This economy was due to the decrease of its two components, the external work (W_{ext}) performed to move the COM_b relative to the surroundings and the internal work (W_{int}) performed to move the body segments relative to the COM_b.

Regarding the external work, a first explanation can be found by examining the forward and vertical components. The forward external work, which is necessary to accelerate the COM_b in a forward direction, was progressively reduced with the severity of the scoliosis curve from 3 to 12.5%. This is likely due to the progressive decrease of the step length (from 0.67 to 0.64 m vs. 0.69 m in healthy subjects). The vertical external work necessary to lift the COM_b was also progressively reduced from 5 to 13% and may be explained primarily by a decrease of the vertical displacement of the COM_b (from 0.023 to 0.020 m vs. 0.026 m in healthy subjects). As previously reported [9, 26], the vertical displacement of the COM_b depends on main kinematic determinants of gait. In our study, the restriction of pelvic and hip motion contributed to reducing the vertical displacement of the COM_b. In our AIS patients, the internal work (W_{int}) necessary to move the body segments relative to the COM_b was also reduced. This reduction may be explained by the decrease of angular speed of the knee and ankle [21]. Effectively, the AIS

patients seem to walk carefully, as if they were carrying a glass full of water. In sum, the decrease of W_{ext} and W_{int} induced a decrease of the total mechanical work (W_{tot}) that was effective even for mild scoliosis curves. It tended to be lower in the more severe scoliosis groups, but this trend was not significant. AIS patients seem to economize their muscular mechanical work. This economy has never been underlined in either experimentally restricted joint motions or other diseases that affect locomotion [10, 11, 20, 22, 29]. In a previous study in healthy subjects, shoulder, pelvis, and hip motion restrictions were observed when able-bodied trunks were experimentally stiffened by bracing for a short period of time [20]. We further observed a 15% increase of W_{ext} , which is mainly explained by a trend toward higher vertical displacement of the COM_b and the loss of the pendular locomotor mechanism. When the body is stiffened for a short period of time (less than 6 h) by an external device that permits less motion freedom than the joints it surrounds, it seems that the human body cannot adapt and then produces higher mechanical work. In contrast, the stiffness in AIS patients is internal and permanent; over the long term, it results in an adaptive phenomenon that can explain the surprising reduction of muscular mechanical work.

When joint restrictions are caused by an orthopedic or neurological disease that mainly affects the lower limbs (e.g., as in amputees or stroke patients) [10, 12], an

Fig. 3 Mechanical work, energy cost, and muscle efficiency. Each subject ($n = 54$) is represented by black points. **a** W_{tot} ($J \cdot kg^{-1} \cdot m^{-1}$) as a function of the Cobb angle curve. **b** energy cost ($J \cdot kg^{-1} \cdot m^{-1}$) as a function of the Cobb angle curve. **c** muscle efficiency as a function of the Cobb angle curve

increase of the external mechanical work due to increased vertical displacement of the COM_b was also observed.

Despite the surprising economic mechanical work observed in our study, O_2 consumption was increased and led to a significant increase in energy cost (+30%) that was

obvious in every scoliosis group as a cut-off system compared to the healthy subjects (Fig. 3b). This increased O_2 consumption was not explained by the muscular mechanical work requiring less O_2 consumption; instead, it can be explained by the bilaterally prolonged activation timing of the pelvi-femoral and lumbo-pelvic muscles [21]. The increase of muscular timing also occurred obviously for the mild scoliosis patients as a cut-off system. This finding suggested the hypothesis that AIS is associated with a significant dysfunction of the lumbo-pelvic muscles.

The prolonged timing of the EMG contraction of lumbo-pelvic and pelvi-femoral AIS muscles was not observed when the spino-pelvic joints were stiffened artificially by a brace in healthy subjects in which wearing a spinal brace experimentally for a short time did not alter muscle efficiency [20]. Thus, this excessive muscular activity in AIS patients that is even obvious in mild AIS patients is not a direct consequence of spine stiffness.

As a result, muscular efficiency (i.e., the efficiency of positive work production by the muscles) was reduced by 30% in comparison to that of healthy girls (Fig. 3c). This variable may also be used as a cut-off system to differentiate affected from non-affected individuals. The loss of AIS muscular efficiency may be explained by an alteration in the timing of the specific spino-pelvic muscles around the scoliosis deformity. This means that muscles consume more O_2 than just to ensure their mechanical work during walking. This finding could raise the hypothesis that the occurrence of very poor muscle efficiency in the lumbo-pelvic region is balanced by an economical reaction of the human body in order to limit the consequences of this phenomenon.

Adolescent Idiopathic Scoliosis patients consume almost a third more O_2 than unaffected, matched girls during the production of this basic activity (i.e., the gait). Normal, self-selected economical gait in our healthy subjects requires on an average $10 \text{ ml } kg^{-1} \text{ min}^{-1}$ of O_2 consumption, which corresponds to 20% of the $\dot{V}O_2 \text{ max}$ of an untrained normal teen or young adult [1]. At a constant speed, the percentage of increase of the energy cost corresponds to the percentage of increase of $\dot{V}O_2$. Thus, the increase of $\dot{V}O_2$ by 30% in scoliosis patients compared to healthy subjects is comparable to a gait at a speed of $6 \text{ km } h^{-1}$ in the following equation: $O_2 \text{ rate} = 0.00100S^2 + 6.2$ [8]. During normal walking, scoliosis patients had to elevate their levels of physical effort. The problem occurs when the range of O_2 consumption approaches its maximum ($\dot{V}O_2 \text{ max}$); at this moment, the input of oxygen levels off and anaerobic oxidation processes result in the accumulation of serum lactate and rapid muscular intolerance to acidosis. The fact that walking taxes less than 50% of the $\dot{V}O_2 \text{ max}$ in normal subjects and does not require anaerobic activity accounts for the perception that walking requires little effort in healthy

individuals [34]. However, scoliosis patients require around 35% of their $\dot{V}O_2$ max—50% more than healthy subjects—just for walking. Therefore, it appears that scoliosis patients exert more physical effort than healthy subjects just to walk. For example, in amputees affected by the loss of joint motion at different levels, the rate of energy expenditure and energy cost increase from the ankle, to the knee, and to the hip respectively by 3% [30], 23% [31], and 32% [34]. AIS patients exhibit nearly the same energy cost as walking with an immobilized hip [17]. It is thus expected that these patients cannot bear a significant increase of effort. Barrios et al. report that AIS patients showed earlier anaerobic threshold and lower aerobic power, expressed by a 25% decrease of their $\dot{V}O_2$ max [1].

This original observation suggests a new hypothesis regarding the aetiopathogenesis of AIS. Namely, it could be due to inefficient muscle or muscular dysfunction. This hypothesis requires further investigation.

Therefore, it would be very interesting to follow the same patients during their own evolution to assess the intra-individual evolution of metabolic and mechanic energy in order to analyze possible correlations with progression of the scoliosis curves. Additionally, it would be very interesting to study activities requiring greater O_2 consumption, such as running and activities necessary for the physical development of adolescents, because such activities are more common in school physical education programs.

Conclusions

Our hypotheses were that (1) the spinal deformations in AIS thoraco-lumbar or lumbar main structural curve patients will negatively impact the gait, increase the mechanical work, and increase the energy cost of walking and (2) the severity of the curves will correlate with the severity of the effects in these parameters. AIS provides a very small gait disability. In fact, the restriction of shoulder, pelvic, and hip motion (with the exception of a careful gait) is so minor that it cannot be visually observed even by an experienced clinician. With regard to the mechanics of walking, however, our investigation paradoxically showed a clear decrease in the muscular mechanical work associated with an increase of energy cost and a decrease in the muscular efficiency. AIS patients exert 30% more physical effort than healthy subjects to ensure habitual locomotion, and this additional effort requires an important increase of oxygen consumption. This excessive energy cost may be a consequence of the bilateral timing activation increase of the lumbo-pelvic and pelvi-femoral muscles. The changes in energy parameters occur even for the mild AIS patients like an on-off switch and could be used to differentiate

affected from non-affected individuals. These changes do not show significant progression in relation to the severity of the scoliosis curves.

These results suggest the hypothesis that the aetiopathogenesis of AIS may be due not only to a mechanical disorder, but also to a muscular disease. More studies are necessary to determine the causes of these excessive scoliosis muscle activities as well as the effects of reconditioning programs and current orthopaedic or surgical treatments.

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