

Martin Simoneau · Nadia Richer · Pierre Mercier
Paul Allard · Nomand Teasdale

Sensory deprivation and balance control in idiopathic scoliosis adolescent

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Abstract Balance control is influenced by the availability and integrity of sensory inputs as well as the ability of the balance control mechanisms to tailor the corrective action to the gravitational torque. In this study, to challenge balance control, visual and ankle proprioceptive information were perturbed (eyes closed and/or tendon vibration). We masked sensory inputs in order: (1) to test the hypothesis that adolescent idiopathic scoliosis (AIS), compared to healthy adolescent, relies more on ankle proprioception and/or visual inputs to regulate balance and (2) to determine whether it is the variation or the amplitude of the balance control commands of AIS that leads to greater body sway oscillations during sensory deprivation. By manipulating the availability of the sensory inputs and measuring the outcomes, center of pressure (CP) range and velocity variability, we could objectively determine the cost of visual and/or ankle proprioception deprivation on balance control. The CP range was larger and the root mean square (RMS) of the CP velocity was more variable for AIS than for control participants when ankle proprioception was perturbed. This was observed regardless of whether vision was available or not. The analysis of the sway density curves revealed that the

amplitude rather than the variation of the balance control commands was related to a larger CP range and greater RMS CP velocity for AIS. The present results suggest that AIS, compared to control participants, relies much more on ankle proprioception to control the amplitude of the balance control commands.

Introduction

Scoliosis is the most common type of spinal deformity in North American children (Weinstein 1994). Of these, adolescent idiopathic scoliosis (AIS) makes up about 90% of all cases of scoliosis. While its prevalence is about 2–3% in children aged between 10 and 16 years, girls are more at risk for severe progression in a ratio of 3.6:1.

Although there is no established cause, idiopathic scoliosis has been associated with neurogenic disorder of paraspinal muscles as measured by stretch reflex responses (Trontelj et al. 1979), deficit on a cerebral level (Herman et al. 1985), vestibular imbalance (Sahlstrand and Petruson 1979; Sahlstrand et al. 1979), muscular imbalance between both sides of the spine (Yarom and Robin 1979a, b; Ford et al. 1984), proprioceptive disorders (Barrack et al. 1984; Keessen et al. 1992) and asymmetries in the ventral pons or brainstem dysfunction (Jensen and Wilson 1979; Petersen et al. 1979). All those sensory and motor impairments could lead to balance dysfunction (e.g., Adler et al. 1986; Byl and Gray 1993).

Deficits in the structure and functioning of peripheral systems and morphologic changes are important and might explain the balance dysfunction observed in AIS. A lesion of the posterior column pathways has been suggested as a major factor in scoliosis. In animal studies, scoliosis has been induced by damaging the posterior column pathway at the dorsal root as well as in the thoracic cord (Liszka 1961; Pincott and Taffs 1982). This suggested a sensory integration problem and it led some researchers to investigate whether patients with

M. Simoneau (✉) · N. Richer · N. Teasdale
Faculté de Médecine, Division de kinésiologie,
Université Laval, PEPS, G1K 7P4 Québec, QC, Canada
E-mail: Martin.Simoneau@kin.msp.ulaval.ca
Tel.: +1-418-6562131
Fax: +1-418-6562441

P. Mercier
Clinique d'orthopédie infantile de Québec,
G2K 2B4 Québec, QC, Canada

P. Mercier
Faculté de Médecine, Département de chirurgie,
Université Laval, G1K 7P4 Québec, QC, Canada

P. Allard
Département de kinésiologie, Université de Montréal,
Station Centre-Ville, P.O. Box 6128,
H3C 1J7 Montréal, QC, Canada

idiopathic scoliosis would respond differently than age-matched controls to vibratory stimuli (Wyatt et al. 1986; Barrack et al. 1988; Byl et al. 1997; Olafsson et al. 2002). Results of these studies do not agree. For example, Wyatt et al. (1986) and Barrack et al. (1988) found that AIS had a lower proprioceptive threshold (more sensitive) whereas McInnes et al. (1991) reported that AIS had a significantly higher vibratory threshold (that is, less sensitive) than control subjects. Responses to vibration stimulation evaluate the threshold of the proprioceptive system. This clinical test, however, does not determine the capability of the spinal and cortical reflexes and/or the cognitive structures to transform sensory perception into appropriate motor responses. The ability of AIS to cope with sudden sensory deprivation and transform their sensory perception into appropriate motor commands has been partially investigated.

More than two decades ago, Sahlstrand et al. (1978) examined the effect of eye closure and/or a compliant base of support, subjects stood on a 10-cm thick piece of foam rubber, on balance control in AIS. Their results demonstrated that masking the sensory inputs coming from the mechanoreceptor of the sole (by standing on the compliant surface) and/or occluding visual inputs increased the total sway area of AIS much more than that of the control participants. Standing on a compliant surface, 10-cm thick piece of foam, may be destabilizing by itself (unstable base of support). It is possible that standing on an unstable surface exacerbated the AIS balance control problem.

The analysis of the kinematics of the center of pressure (CP) describes the overall behavior of the CP (e.g., total sway area, range of the CP, root mean square (RMS) velocity of the CP,...) without looking at the balance control commands. Recently, Baratto et al. (2002) have proposed new parameters which provide information on the causes of the overall CP behavior. The analysis of the sway density curve permits determination of whether the kinematics of the sway oscillations are due to greater or more variations of the balance control commands.

In the present paper, we expand on the work of Sahlstrand et al. (1978) by using a different technique, tendon vibration, which masks ankle proprioception and by looking at the underlying cause of greater body sway oscillations observed for AIS. We hypothesize that greater and more variation of the balance control commands would lead to a greater amplitude of the body sway oscillations and variability of the CP velocity in AIS. This hypothesis, if confirmed, would suggest that idiopathic scoliosis interferes with the neural mechanisms allowing the mapping of available sensory inputs into appropriate muscle actions (balance control commands) to regulate balance.

Subjects and methods

Eight scoliosis patients (seven females and one male; mean age: 16.4 years) participated in the experiment.

Scoliosis patients had previously been screened and diagnosed by a pediatric orthopedic surgeon (one of the authors, P. Mercier). No patient was under active treatment, none of the patients had surgery before and no patient presented any neurological sign of pathological importance in the clinical examination. The average Cobb angle was $45.6^\circ \pm 7.5^\circ$ and varied between 33° and 55° . Briefly, Cobb's angle is defined by the relationship between two lines drawn parallel to the top and bottom of the vertebral bodies at the beginning and end of the curve. The angle between these two lines (or lines drawn perpendicular to them) is measured as the Cobb angle. A scoliotic curve exists when the Cobb's angle measures at least 10° . Most curves are considered significant if greater than $25\text{--}30^\circ$. Curves in excess of $45\text{--}50^\circ$ are considered severe. Brace treatment was recommended for three subjects but none of them actually wore the brace. All spinal curves were right thoracic convex. Out of the eight thoracic curvatures, four had a left lumbar compensatory curve ($39 \pm 14.2^\circ$). The control group consisted of ten healthy young girls (average age of 16.5 years). No participant reported any neurological or orthopedic problem. All patients, participants and tutors gave their informed consent according to university protocols.

An AMTI force platform was used to measure the displacement of the CP. The force platform signals were sampled at 200 Hz using a 12-bit A/D converter. Data were collected first from an unloaded platform to determine the zero offset. Ankle proprioception was perturbed by means of vibratory stimulation. The vibrators ($n=4$) consisted of unbalanced masses fixed at both extremities of DC motors rotating at 80 Hz. The amplitude of the mechanical oscillation was 3 mm. The vibrators were fixed to the participant's ankles, on the tendon of soleus, gastrocnemius and tibialis anterior muscles, by means of rubber bands. Applying vibration to a muscle tendon specifically activates the muscle spindle primary endings (Burke et al. 1976; Roll and Vedel 1982). When applied to mutually antagonistic ankle muscles, the vibratory stimulus deprives subjects from the relevant proprioceptive information produced by body oscillations (Roll et al. 1989). The activation and the deactivation of the vibrators were computer controlled. For convenience, we will herein refer to the tendon vibration condition as perturbed proprioception. It is acknowledged that ankle proprioception only is perturbed. For the no-vision condition, participants closed their eyes when the computer released an auditory signal.

Subjects stood barefoot on the force platform with their feet 10 cm apart and the arms along the body. They maintained an upright posture while fixating a small target in their central vision (2 m away at eye level). All subjects performed four different experimental conditions (six trials in each condition for a total of 24 trials). Each trial lasted 15 s. Three sensory deprivation conditions were created by manipulating sensory information: (1) no-vision (NV), (2) perturbed proprioception/vision

(PP-V) and (3) perturbed proprioception/no-vision (PP-NV). In the control condition (CTR), there was no sensory manipulation.

The CP is calculated from the force-plate reaction forces and moments; it includes dynamic components due to the body's acceleration and is related to the neuromuscular parameters controlling the center of mass. The CP data were filtered using a low-pass filter (Butterworth, fourth order, 8 Hz cut-off frequency) with a dual-pass to remove phase shift. The medio-lateral and antero-posterior velocities of the CP were calculated using a central finite difference technique.

The postural stability of AIS and the control participants was assessed by computing the range of the CP and the RMS of the CP velocity along the medio-lateral and antero-posterior axes during the 15 s of upright standing. The range of the CP represents the difference between the maximum and minimum values of the CP along the antero-posterior or medio-lateral axis. A large CP range indicates that the resultant forces are displaced towards the balance stability boundaries of the participant and could challenge their postural stability (Koozekanani et al. 1980; Patton et al. 2000). The RMS of the CP velocity measures the variability of the CP sway path velocity. This variable is the square root of the sum of squares of the CP velocity divided by the number of data samples; hence, smaller values indicate a less variable CP.

To gain an insight into the mechanisms leading to CP kinematics difference among both groups, we analyzed the sway density curve following Baratto et al. (2002). The sway density curve was digitally filtered with a fourth order Butterworth filter (2.5 Hz low-pass cut-off frequency with dual-pass to remove phase shift) in order to perform a better peak extraction. The sway density curve is computed by counting the number of consecutive samples during which the CP remains inside a 2.5 mm radius¹. Then, the sample count is divided by the sampling rate yielding a time dimension for the ordinate axis. Thus, the sway density curve is a time versus time curve illustrating the evolution over time of the stay time of the CP. The peaks of the sway density curve correspond to time instants in which the CP and presumably the associate motor commands are relatively stable. Mean peak represents the time spent by the CP inside the 2.5 mm radius circle centered at the time of peak on the sway density curve. Hence, the amplitude of the peaks estimates the degree of balance stability. On the other hand, the valleys of the sway density curve correspond to time instants in which the CP rapidly switches from one stable position to another. It is assumed that the mean distance between consecutive peaks illustrates the amplitude of the postural commands. Recently, Jacono et al. (2004) have demonstrated that

the CP displacement tends to be stable when the ankle torque is approximately constant and this corresponds to peaks in the sway density curve. On the contrary, the CP tends to shift quickly when the ankle torque has strong peaks and this corresponds to valleys in the sway density curve (page 303—Jacono et al. 2004). According to Baratto et al. (2002), the mean peak (mean of the peaks of the sway density curve) and mean distance (mean distance between peaks of the sway density curve) reflect the capacity of the postural control system to integrate the sensory information and anticipate physiological internal delays to keep the vertical alignment of the whole body.

Statistical analysis

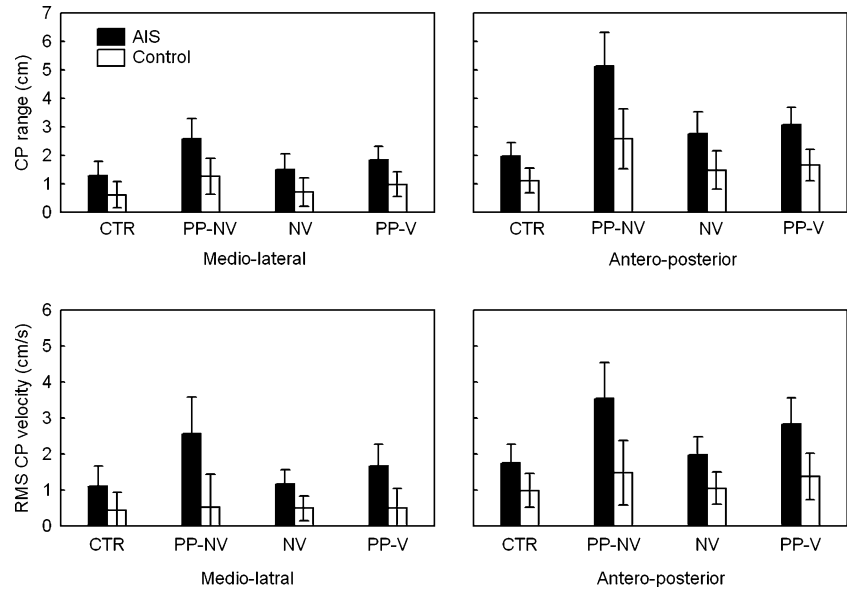
For each experimental condition, the calculated values for each dependant variable were averaged across the six trials. Analyses of variance (ANOVA) with repeated measures were used for statistical comparisons. Whenever the ANOVA reached a significant level, planned comparisons were used to examine the specific effect. The level of significance was set at $P < 0.05$.

Results

The CP ranges along both axes were submitted to a Group \times Condition \times Axis (2 \times 4 \times 2) ANOVA with repeated measures on the last two factors. Results of the ANOVA showed the main effects of Group ($F_{1,16} = 9.65$, $P < 0.01$), Condition ($F_{3,48} = 79.12$, $P < 0.001$) and Axis ($F_{1,16} = 91.42$, $P < 0.001$). Moreover, the interactions of Group by Axis ($F_{1,16} = 6.83$, $P < 0.05$), Group by Condition ($F_{3,48} = 10.31$, $P < 0.001$) and Group by Condition by Axis ($F_{3,48} = 79.12$, $P < 0.001$) were all significant. Overall, Fig. 1 (upper panels) shows that AIS (black bars) exhibited a greater CP range than the control subjects (white bars) for all conditions and for both axes. A decomposition of the triple interaction (Group \times Condition \times Axis) showed that, for the medio-lateral axis, removing vision (NV) or perturbing ankle proprioception only (PP-V) increased the CP range (compared to the control condition) similarly for both groups ($P > 0.05$). When both sources of sensory information were altered (no perturbed ankle proprioception and no-vision; PP-NV), the AIS showed a greater increase in the CP range than the control subjects ($P < 0.05$). As demonstrated by the significant triple interaction, this latter effect was exacerbated for the antero-posterior axis. Compared to the control condition, the increased CP range along the antero-posterior axis for the AIS was 0.31 cm when vision was occluded, 0.87 cm when ankle proprioception only was perturbed and 2.41 cm when both sensory systems were altered. For the same conditions, control participants showed increases of 0.18, 0.43 and 1.11 cm, respectively.

¹The choice of the radius is not critical because away from the optimal values there is a degradation that is reflected in the mild dependence of the sway density curve parameters (Jacono et al. 2004).

Fig. 1 The upper panel presents the group mean for the center of pressure range along the medio-lateral (left panel) and antero-posterior axis for the control (CTR), perturbed proprioception/no-vision (PP-NV), no-vision (NV) and perturbed proprioception/vision (PP-V) experimental conditions. The lower panel illustrates the group mean of the root mean square (RMS) of the center of pressure velocity. The legend for the x-axis is similar to panel A. The error bars represent 95% confidence interval



Data for the RMS CP velocity along both axes (Fig. 1—lower panels) also were submitted to a Group \times Condition \times Axis ($2 \times 4 \times 2$) ANOVA with repeated measures on the last two factors. The ANOVA revealed the main effects of Group ($F_{1,16} = 16.78$, $P < 0.001$), Axis ($F_{3,48} = 20.66$, $P < 0.001$) and Condition ($F_{3,48} = 17.87$, $P < 0.001$) and a significant interaction of Group by Condition ($F_{3,48} = 8.60$, $P < 0.001$). All other interactions were not significant ($P > 0.05$). Results for the RMS CP velocity mimicked those observed for the CP range: (1) overall, AIS showed a greater RMS CP velocity than the control participants for all conditions and for both axes and (2) AIS showed greater RMS CP velocity than the control participants when both sources of sensory information (ankle proprioception and vision; PP-NV) were altered. Compared to the control condition², the RMS CP velocity for the AIS increased by 9.8, 57.3, and 114.0% when vision was occluded (NV), ankle proprioception only was perturbed (PP-V) and when both sensory systems were altered (PP-NV). For the same conditions, control participants showed increases of 8.4, 32.4 and 40.8%, respectively.

Altogether, whether vision is occluded or not, the CP range and RMS CP velocity data demonstrated that AIS expressed an inability to reorganize the weight of the remaining sensory inputs to regulate their body sway oscillations when ankle proprioception was altered. The CP behavior, however, does not reveal the mechanisms underlying these differences. To examine if the AIS balance control deficits resulted from greater amplitude or more variation of the balance control commands, we conducted an analysis of the sway density curve.

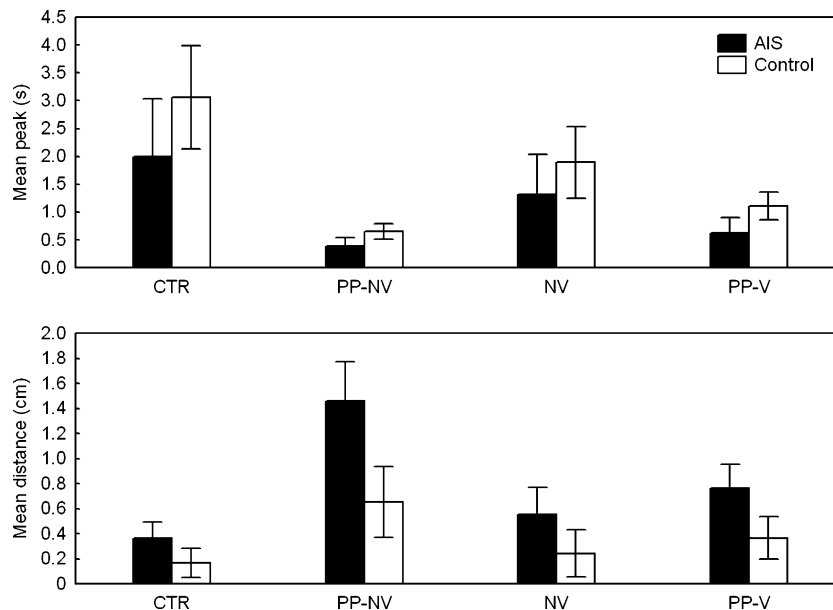
Figure 2 (upper panel) presents the mean peak (the time spent in regions of stability) for the four experi-

mental conditions. Results of the Group \times Condition ANOVA (repeated measures on the last factor) revealed a main effect of Condition ($F_{3,48} = 5.43$, $P < 0.01$). Despite a trend for the AIS to show smaller mean peaks, the main effect of Group ($F_{1,16} = 0.17$, $P > 0.05$) and the Group by Condition interaction were not significant ($F_{3,48} = 1.78$, $P > 0.05$). A comparison of means showed that mean peaks for the perturbed proprioception/no-vision condition were smaller than for all other conditions ($P < 0.001$). The mean peaks for both conditions with perturbed ankle proprioception were not different from each other ($P > 0.05$) and were smaller than for all other conditions ($P < 0.05$). Hence, both groups varied their balance control commands much more when proprioception was perturbed, whether vision was available or not.

With respect to the mean distance between two consecutive regions of stability (Fig. 2—lower panel), the ANOVA (Group \times Condition with repeated measures on the last factor) revealed main effects of Group ($F_{1,16} = 15.34$, $P < 0.01$), Condition ($F_{3,48} = 61.20$, $P < 0.001$) and a significant interaction of Group by Condition ($F_{3,48} = 14.81$, $P < 0.001$). The decomposition of the interaction showed that, when ankle proprioception was perturbed (whether vision was occluded or not; PP-NV and PP-V), the increase in the mean distance between two consecutive region of stability was much greater for AIS (black bars) than for control participants (white bars) ($P < 0.01$). Both groups showed similar increases when vision was removed ($P > 0.05$). Altogether, the results for the mean distance suggest that AIS had greater amplitude of the balance control commands when ankle proprioception was perturbed and this was observed whether vision was occluded or not. It suggests that the greater CP range and the more variable RMS CP velocity observed for AIS when ankle proprioception was perturbed (whether vision is occluded or not) are related to the greater

² $[(\text{RMS2} - \text{RMS1})/\text{RMS1}] \times 100\%$ where RMS2 is the mean RMS CP velocity in the sensory deprivation condition and RMS1 is the mean RMS CP velocity in the control condition.

Fig. 2 The *upper panel* illustrates the group mean for the mean peak for the control (*CTR*), perturbed proprioception/no-vision (*PP-NV*), no-vision (*NV*) and perturbed proprioception/vision (*PP-V*) experimental conditions. The lower panel presents the group mean for the mean distance. The legend for the *x-axis* is similar to the upper panel. The *error bars* represent 95% confidence interval



amplitude in the balance control commands rather than more variation of the commands.

Discussion

During the last decades, several investigators have quantified the vibratory threshold of AIS by means of a biothesiometer in order to evaluate whether scoliosis was associated with dorsum column dysfunction. Results from these studies varied and the biothesiometer now has been deemed unreliable (e.g. McInnes et al. 1991). It is important to recognize that the evaluation of the sensory perception threshold does not evaluate the ability of a person to adapt its motor commands to his/her sensory perception. For example, during upright standing, a person can detect that he/she sways forward with a given velocity. To regain balance, however, he/she will need to select and program the appropriate ankle torque response in order to stop the forward momentum due to gravitational torque and to avoid a fall or a stepping reaction. Biomechanical factors such as the three-dimensional deviation of the spine (shape of the trunk and the changes between body segments) may be related to balance control problems observed in AIS. As the CP range and RMS CP velocity of AIS increase during sensory deprivation due to greater amplitude of the balance control commands, it is unlikely that larger body sway oscillations generally observed in AIS results only from biomechanical factors. The difference between both groups in the control condition suggests that a combination of biomechanical factors and deficits in the sensorimotor mechanisms related to the scaling of the balance control commands exacerbate AIS body sway oscillations.

In this study, we masked sensory inputs in order: (1) to test the hypothesis that AIS, compared to

healthy adolescent, relies more on ankle proprioception and/or visual inputs to regulate balance and (2) to determine whether it is the variation or the amplitude of the balance control commands of AIS that leads to greater body sway oscillations during sensory deprivation. By manipulating the availability of the sensory inputs and measuring the outcomes (CP behaviors), we could objectively determine the cost of visual and/or ankle proprioception deprivation on the balance control of AIS and healthy control participants.

The CP range was larger and the RMS CP velocity was more variable for AIS than for the control participants when ankle proprioception was perturbed. This was observed regardless of whether vision was available or not. Our interpretation is that idiopathic scoliosis interferes with the neural mechanism that weights the remaining sensory inputs. This mechanism is necessary to map these inputs into appropriate balance control commands. The remaining sensory information should come from the sole of the feet, the joints above the ankle and the vestibular apparatus.

In our experiment, to regulate body sway oscillations AIS could not compensate for masked ankle proprioception irrespective of whether vision was available or not. About two decades ago, Diener et al. (1984) showed that ankle proprioception deprivation, in healthy subjects standing freely, had little effect on body sway oscillations with eyes open, but resulted in a larger excursion of the CP with eyes closed. In the present experiment, when ankle proprioception was perturbed, the availability of vision was not sufficient to allow AIS to reduce their CP; they showed a larger CP range, greater RMS CP velocity and balance control commands (mean distance). This observation is important as it suggests that despite the availability of vision AIS, compared to control participants, relied much more on

ankle proprioception to scale the amplitude of their balance control commands.

When ankle proprioception and vision are altered simultaneously, vestibular sensory information is combined with the other remaining sensory information to tailor the balance control commands to the gravitational torque. It has been demonstrated, using sophisticated mathematical models, that vestibular sensory information is less precise than visual and proprioceptive information in conditions where multiple sensory systems provide redundant sensory information (van der Kooij et al. 2001; Peterka 2002). The low precision of the vestibular system is consistent with the larger CP range, much variable RMS CP velocity and greater amplitude of the balance control commands (mean distance) observed for the perturbed ankle proprioception condition in the absence of vision. Experimental data have even shown that the threshold of visual and vestibular systems is higher than the ankle threshold alone (Fitzpatrick and McCloskey 1994). It might be speculated that the CP behavior (greater CP range and RMS CP velocity) and greater balance control commands for AIS, compared to the control participants, could result from the difficulty in reweighting the gain of the vestibular system and the remaining sensory inputs when ankle proprioception was altered regardless of whether vision was occluded or not.

The analysis of the sway density curve provides information on the balance control commands (Baratto et al. 2002; Jacono et al. 2004). We hypothesized that a larger CP range and RMS CP variability of the velocity of the sway path for AIS would be associated to a greater amplitude and variation of the balance control commands. Despite a tendency to show the contrary, the analysis revealed that AIS and the control participants had a similar variation of the balance control commands (similar mean peaks). The greater mean distance between stable regions suggests, however, that when ankle proprioception was perturbed, the amplitude of the balance control commands was greater for AIS than for the control participants. This was observed regardless of whether vision was available or not. The present results suggest that AIS, compared to the control participants, relies much more on ankle proprioception to control the amplitude of the balance control commands.

Idiopathic scoliosis may interfere with the sensorimotor mechanisms that participate in the programming of the amplitude of the balance control commands. It is presently difficult to identify with certitude at which level, within the central nervous system, there would be a dysfunction. Nevertheless, measurements of nerve conduction velocity in the peroneal and median nerves did not support the hypothesis that polyneuropathy is related to idiopathic scoliosis (Sahlstrand and Selden 1980). Maguire et al. (1993) have observed, in all 37 AIS they tested, ipsilateral and contralateral long-latency polysynaptic activity. Surprisingly, in non-idiopathic scoliosis patients with spinal deformities of equal magnitude, this long-latency activity was absent suggesting

that the curve per se is not responsible. Hence, structures other than the spine and the muscles around it should be considered as potential candidates. The brainstem contains sensory and motor nuclei called the reticular formation that relays information to the primary motor cortex and the sensory cortex. Two groups of nuclei in the reticular formation of the pons and the medulla are involved in the control of posture; they facilitate and inhibit spinal reflexes, respectively (Magoun and Rhines 1946). Interestingly, magnetic resonance imaging investigations have shown subtle asymmetries in the ventral pons or corticospinal tract of the AIS (Geissele et al. 1991).

Obviously, it is difficult to evaluate whether the different balance control behaviors observed during testing are the cause or the result of idiopathic scoliosis deformity. Nevertheless, results from the present experiment reveal that the amplitude rather than the variation of the balance control commands is related to the larger CP range and greater CP RMS velocity when ankle proprioception is altered. Finally, this strongly suggests that AIS relies considerably on ankle proprioception to regulate body sway oscillations and to scale the amplitude of their balance control commands.

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