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► To cite this version:

Sébastien Leteneur, Sylvain Cremoux, Paul Allard, Emilie Simoneau-Buessinger, Georgios A. Stylianides, et al.. Untreated adolescent idiopathic scoliotic girls display altered balance modalities during self-paced voluntary body sways compared to able-bodied girls. *Journal of Bodywork and Movement Therapies*, 2021, 27, pp.1-8. 10.1016/j.jbmt.2021.01.013 . hal-03710412

HAL Id: hal-03710412

<https://uphf.hal.science/hal-03710412v1>

Submitted on 24 May 2023

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Title Page

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Untreated adolescent idiopathic scoliotic girls display altered balance modalities during self-paced voluntary body sways compared to able-bodied girls

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Conflict of interest: none.

1

2

Abstract

3 **Introduction:** This study investigated self-paced voluntary oscillations of scoliotic and
4 non-scoliotic girls. Temporal variables and frequency coherence were calculated for the
5 overall, low and high frequency bandwidths of the center of pressure excursions and free-
6 moment to identify which variables best describe sway balance modalities in both groups.

7 **Methods:** Twenty-three girls with adolescent idiopathic moderate scoliosis (spinal curves
8 to the right) formed the scoliotic group and 19 matched able-bodied girls formed the non-
9 scoliotic group. Each girl performed self-paced voluntary medio-lateral and antero-
10 posterior sways while standing on a force platform. Center of pressure displacements, out
11 of plane deviation and free-moment were measured and their frequency content
12 calculated. The magnitude of the coherence was calculated for each signal pairs for three
13 frequency ranges.

14 **Results:** In both sway conditions, the center of pressure excursion parameters were on
15 average 28% higher for the scoliotic group. Factor analysis revealed that balance
16 modalities were essentially based on frequency coherence pair interactions whereas
17 temporal parameters play a secondary role. However, these balance modalities were
18 altered in the scoliotic group. They relied essentially on 2 additional principal
19 components and 3 additional variables reflecting a fine tuning of the control mechanism
20 to maintain dynamic balance.

21 **Interpretation:** Scoliotic girls appear to be performing a wide ellipsoidal trajectory when
22 performing whole body oscillations. Superfluous variables could be related to the

23 difficulty in preserving balance during body sway tasks and could parasitize the scoliotic
24 dynamic control balance modalities. Self-paced voluntary sways could be an appropriate
25 complementary balance test for untreated scoliotic girls.

26

27 **Key Words:** balance; oscillations; scoliosis

28

Text

29 **Untreated adolescent idiopathic scoliotic girls display altered balance modalities during**
30 **self-paced voluntary body sways compared to able-bodied girls**

31

32 **1. Introduction**

33 Scoliosis is characterized by a three-dimensional spine and rib cage distortion (Koreska et
34 al., 1978) which unsettles standing balance (Gauchard et al., 2001; Nault et al., 2002) and
35 shifts backward the body center of mass (CoM) position and increases its excursion
36 (Dalleau et al., 2011; Damavandi et al., 2009). Spinal deformity not only modifies body
37 segment spatial orientation and their interdependency (Goldberg et al., 2001), but
38 modifies gait initiation strategies (Bruyneel et al., 2009; 2008) as well as walking patterns
39 (Mahaudens et al., 2009; Park et al., 2015; Wu et al., 2019). An expected body
40 perturbation while standing accentuates postural control compensations (Klous et al.,
41 2012). The focus of the attention is then on body sways to maintain postural balance by
42 increasing active intervention to maintain upright steadiness. Voluntary postural sway
43 displacement is a simple approach (Tucker et al., 2010) that could highlight new dynamic
44 balance modalities unreported to this day in adolescent idiopathic scoliosis (AIS),
45 especially as postural rehabilitation of scoliotic patients suffers from a lack of knowledge
46 about the relation between posture and proprioception.

47 During standing, the body oscillates and causes its center of pressure (CoP) to migrate in
48 both the antero-posterior (AP) and medio-lateral (ML) directions. Though it can be
49 modelled as a three-dimensional inverse pendulum rotating about the ankles (Barbier et

50 al., 2003), medio-lateral control is achieved by the hips and trunk while antero-posterior
51 balance occurs at the ankles (Shumway-Cook and Woollacott, 2012). The excursion of
52 the CoP is as well associated with an effort from the free moment acting about the
53 vertical axis for postural stabilization (Dalleau et al., 2007; Esposti et al., 2010). When a
54 whole-body action is performed such as in gait initiation, postural adjustments are
55 detected (Klous et al., 2012; Wang et al., 2005). Voluntarily shifting of the body CoM
56 within the standing base of support also occurs in daily activities and is link to falls
57 (Robinovitch et al., 2013). A decrease in stability reduces the performance in these tasks
58 and disturbs balance reactions produced when the CoM is shifted towards the limits of
59 standing stability (Cleworth et al., 2018). However, in daily activities subjects use a range
60 of control balance strategies, not limited to the ankles (Runge et al., 1999). This allows
61 for changes in balance strategies under a critical margin of stability (Lorenzo and
62 Vanrenterghem, 2015). Voluntary body sway needs to be tested since its direction can
63 favor either a hip strategy or stimulates an ankle strategy in association with the free
64 moment compensations. It is reasonable to assume that changes in dynamic balance could
65 be present in a self-paced voluntary body sway along medio-lateral and antero-posterior
66 directions while standing and is exacerbated by a spinal deformation.

67 To estimate if subjects with multiple sclerosis (MS) alter the use of the ankle and hip
68 strategy to manage antero-posterior postural sway at different frequencies, body segment
69 interactions were assessed during quiet standing (Huisinga et al., 2018). Frequency
70 coherence analyses performed on trunk and legs accelerations revealed that MS subjects
71 utilize a mixed ankle-hip sway modality. This method was also applied to characterize
72 the interaction between the CoP displacement and the free moment in able-women and

73 men (Hay and Wachowiak, 2017) and later in adolescent idiopathic scoliosis (Leteneur et
74 al., 2019) during quiet standing. Such a method could be used to describe dynamic
75 balance modalities during self-paced voluntary body oscillations.

76 The general purpose of this study is to determine, if during an imposed activity,
77 particularly self-paced voluntary body sways, there is an organized balanced modality
78 and if it is affected by the sway direction. Specifically, the first objective is to test if the
79 temporal parameters of the body sway and the frequency coherences calculated for the
80 overall, low and high frequency bandwidths between the CoP excursion and its
81 corresponding free moment observed during self-paced voluntary oscillations of scoliotic
82 and non-scoliotic girls are similar. The effect of the direction of the voluntary sway also
83 needs to be tested since medio-lateral and antero-posterior oscillations favors different
84 balance modalities. Finally, we wish to identify which of the temporal and frequency
85 coherence variables best describe sway balance modalities in the scoliotic and non-
86 scoliotic girls during the body sways. **It was hypothesized that untreated adolescent**
87 **idiopathic scoliotic girls display altered balance modalities during self-paced voluntary**
88 **body sways compared to able-bodied girls.** This approach could lead to new advances in
89 proprioception and postural retraining programs for the rehabilitation of scoliotic
90 patients. This study should allow to characterize the balance modalities related to the
91 control mechanisms used by scoliotic patients to maintain their dynamic standing balance
92 despite their postural troubles.

93 **2. Materials and methods**

94 A group of 23 girls diagnosed with moderate adolescent idiopathic scoliosis according to
95 the criteria defined by Bunnel (Bunnel, 1986) participated in this study (named SCO in
96 the figures and tables). Their mean age was 12.9 years (SD 1.8 years) while their height
97 and body mass were 155.2 cm (SD 10.0 cm) and 43.2 kg (SD 10.3 kg), respectively. The
98 scoliotic girls were recruited by an orthopedic surgeon from the hospital scoliosis clinic.
99 The average Cobb angle was 26.2° (SD 11.8°) and ranged between 11° and 49° and all
100 spinal curves were to the right. No patient was under active treatment at the time of this
101 study. All of the recruited girls completed the experiments and were included for data
102 analysis. A group of 19 able-bodied girls, **matched in age, height and body mass with the**
103 **scoliotic girls**, formed the non-scoliotic group (named AB in the figures and tables) and
104 were recruited from family members and friends. This able-bodied group was comparable
105 in age (13.0 years, SD 1.4 years, $P=0.897$), height (156.1 cm, SD 7.1 cm, $P=0.761$) and
106 body mass (45.5 kg, SD 7.7 kg, $P=0.430$) to the scoliotic group. No girl had any form of
107 scoliosis and all were in general good health. Any subject with a limb length discrepancy
108 of more than 1 cm, wearing a foot orthosis or who displayed any signs of postural,
109 orthopedic or neurological disorders was excluded from the study (it concerned 2 of the
110 initially eligible able-bodied girls). All the girls and their parents signed the informed
111 assent form approved by the institutional ethics committee. All the experiments were
112 conducted in a motion capture laboratory by the same researcher expert in the field,
113 between January and March 2018. Prior to the experimentation, all procedures were
114 explained to each subject and data acquisition took approximately an hour.

115 Subjects were asked to perform self-paced voluntary medio-lateral and antero-posterior
116 sways while standing on an AMTI force platform (Model OR6-5, Newton, MA, USA).

117 Self-paced oscillations were preferred to conditioned by visual or acoustic cues given by
118 a metronome because these could perturb the dynamic balance in scoliotic girls (Herman
119 et al., 1985). With the feet barefoot, they positioned themselves with the midline of their
120 heels spaced by 15 cm with the arms positioned loosely along their sides (McIlroy and
121 Maki, 1997). They stood with the feet parallel to each other as not to unduly increase the
122 base of support during the lateral oscillation condition.

123 The girls were requested to perform a whole-body sway completing half a cycle to reach
124 their maximal forward lean. This was followed by a maximal backward body lean. These
125 maximally forward and backward sways were repeated until at least 5 complete cycles
126 were performed at the girls own rhythm to complete a trial. Similarly, subjects were
127 instructed to sway sideways as far as possible to reach their maximal right or left lean
128 followed by a maximal lateral lean in the opposite direction at their own pace. At least 5
129 maximal back and forth lateral sways were required. A trial was rejected if a subject
130 either took a forward or lateral step to regain balance, if the trunk leaned rather than the
131 whole-body or if subjects rotated their trunk or shoulders during the self-imposed
132 voluntary sways. A minimum of 10 second rest was given between trials to reduce
133 fatigue. Data were sampled at a frequency of 64 Hz (Nault et al., 2002) and lasted about
134 60 s. Prior to experimentation, participants were given verbal directives and examples on
135 how to perform the ML and AP body sways. Then, they completed a series of practice
136 trials to become familiar with oscillations conditions.

137 For all trials, the AP and ML center of pressure positions were calculated with respect to
138 the center of the force plate at each time instant. The free moment (T_z) acting at the CoP
139 was calculated from the vertical moment and the moments resulting from the antero-

140 posterior and medio-lateral forces (Dalleau et al., 2007). Tz represents the vertical torque
141 on the feet that reflects the oscillation around the vertical axis associated to the standing
142 imbalance. From the AP and ML CoP displacements, 6 temporal parameters were
143 calculated for each sway directions. The sway ratio corresponds to the ratio of the time to
144 oscillate in a particular direction such as forward over the time taken to return
145 (backwards). It is expressed in percentage. For a given sway direction, the mean range of
146 the CoP in the AP and ML directions and the mean range of the free moment were
147 calculated. The out of plane deviation is the total CoP excursion perpendicular to the
148 direction of the sway. In other words, the ML deviation is calculated during the voluntary
149 AP sway. Similarly, the RMS CoP value is calculated along the perpendicular axis of the
150 sway direction and represents the variability of the displacement along a given axis.

151 To obtain the frequency coherence pairs, the CoP excursion in the AP and ML directions
152 and their corresponding free moments were processed as individual signals as shown in
153 Fig. 1 A to C. These signals were filtered with a zero-lag 4th order Butterworth low-pass
154 filter having a 20 Hz cut-off frequency. Then, each signal was divided into epochs of
155 variable duration according to the maximum of the oscillations. The number of extracted
156 epochs was variable across the participants; however, no group difference was revealed
157 during ML oscillations (8.38 ± 2.13 epochs; $t_{50} = 0.33$; $P = 0.74$; Cohen's $d = 0.09$) or AP
158 oscillations (8.85 ± 2.04 epochs; $t_{50} = 0.19$; $P = 0.85$; Cohen's $d = 0.05$). Each signal was
159 then normalized over time using spline interpolation to obtain epochs of similar number
160 of observations. The reader is referred to (Fauvet et al., 2019) for further details on this
161 procedure. Finally, the average value was removed to each signal to obtain zero-centered
162 epochs of CoP_{AP}, CoP_{ML} and Tz signals as shown in Fig. 1 D to F.

163

164

PLEASE INSERT FIG 1 ABOUT HERE

165

166 The wavelet auto-spectrum of each zero-centered epoched signal is depicted in Fig. 2 A
167 to C and the wavelet cross-spectrum between each zero-centered epoched signal are
168 shown Fig. 2 D to F. They were obtained with a Morlet wavelet transform (Gasq et al.,
169 2015; Leteneur et al., 2019) yielding a 0.97 Hz to 9.68 Hz frequency band in 0.04 Hz
170 steps. The wavelet magnitude-squared coherences, $R_{X,Y}^2(\omega, u)$, are shown in Fig. 2. The
171 wavelet cross-spectrum normalized by the wavelet auto-spectrum of each signal was
172 obtained by

173

$$R_{X,Y}^2(\omega, u) = \frac{|S_{X,Y}(\omega, u)|^2}{S_X(\omega, u)S_Y(\omega, u)}$$

174 where $S_{X,Y}(\omega, u)$ is the wavelet cross-spectrum between X and Y signals (either CoP_{AP} ,
175 CoP_{ML} and Tz signals) and $S_X(\omega, u)$ and $S_Y(\omega, u)$ are the wavelet auto-spectrum of each
176 X and Y signals at frequency ω and time u .

177 To properly quantify the magnitude of the $\text{CoP}_{\text{ML}}\text{-CoP}_{\text{AP}}$, $\text{CoP}_{\text{ML}}\text{-Tz}$ and $\text{CoP}_{\text{AP}}\text{-Tz}$
178 coherence pairs, values were averaged only where significant correlations between two
179 signals were detected as significant on the wavelet cross-spectrum (Bigot et al., 2011;
180 Fauvet et al., 2019). For each signal pairs, the magnitude of the coherence was averaged
181 over the entire time period for three frequency bands: overall frequency band (1.00-
182 8.00 Hz), low frequency band (1.00-3.00 Hz) and high frequency band (3.00-8.00 Hz). In

183 comparison to previous studies (Hay and Wachowiak, 2017; Leteneur et al., 2019) the
184 lowest frequency bound was higher due to the short epoch duration (4.05 ± 1.19 s ranging
185 from 2.21 s to 9.56 s for ML oscillations; 3.82 ± 0.98 s ranging from 2.35 s to 7.68 s for
186 AP oscillations) constraining the lowest frequency bound to $1/d$ (~ 0.45 Hz) where d is the
187 time period.

188

189

PLEASE INSERT FIG 2 ABOUT HERE

190

191 An independent one-way ANOVA was performed on the sway ratio, the mean range of
192 the CoP in the AP and ML directions and Tz, the out of plane deviation or the
193 displacement in the perpendicular direction of the sway and the RMS CoP along the
194 perpendicular axis of the sway direction for each voluntary sway conditions as well as the
195 9 coherence values (3 pairs and 3 frequencies) to compare the able-bodied and the
196 scoliotic groups. Another one-way ANOVA was performed to compare the magnitude of
197 the coherence values between the medio-lateral and antero-posterior voluntary sway
198 conditions for each signal pairs. A Bonferroni correction procedure was applied to
199 control Type 1 error by adjusting the P values in the analysis (Holland and Copenhaver,
200 1988) and a P value of 0.05 or smaller was considered statistically significant. Finally, a
201 factor analysis was carried out for each subject to estimate the relative contribution of the
202 coherence relationships for the able-bodied and scoliotic girls for values measured in the
203 ML and AP sway conditions. Factors with an eigenvalue greater than 1 and variables
204 with a loading factor of 0.7 or above were considered as statistically significant (Leteneur

205 et al., 2019; Sadeghi, 2000). Finally, Cohen's d coefficient was calculated for statistically
206 significant parameters to estimate size effect. The threshold was set at 0.8 (Cohen, 1992;
207 1988).

208 **3. Results**

209 The average Cohen's d coefficient was 1.16 for all statistically significant parameters.

210 Results for the medio-lateral and antero-posterior self-paced voluntary oscillations in the
211 time domain are presented in Fig. 3. In both subject groups, the mean sway ratio was not
212 statistically significant at about 86% ($P>0.364$). For the ML sway condition, the AP
213 deviation ($P=0.011$), the range ML ($P=0.008$) and the range AP ($P=0.037$) were
214 significantly higher for the scoliosis group by 38%, 24% and 21% respectively. For the
215 antero-posterior sway, the ML deviation ($P=0.002$) and the range ML ($P=0.005$) were
216 statistically higher for the scoliotic group by 25% and 30% respectively.

217

218 PLEASE INSERT FIG 3 ABOUT HERE

219

220 There was no significant difference in the coherence values between the able-bodied and
221 scoliotic groups. It appears that regardless of the spinal deformity similar modalities were
222 used to maintain sway balance in both groups. However statistical differences were noted
223 when comparing the medio-lateral and antero-posterior self-paced sway conditions for
224 each subject groups as shown in Fig. 4. Significant coherence values appear only in the
225 overall and the low frequency ranges.

226 For the able-bodied subjects, the All CoP_{AP}-Tz ($P = 0.004$) and the Low CoP_{AP}-Tz
227 ($P = 0.002$) were much higher during the medio-lateral sway condition whereas the All
228 CoP_{ML}-Tz ($P = 0.001$) and Low CoP_{ML}-Tz ($P = 0.001$) have higher coherence values in the
229 antero-posterior self-imposed oscillations. Similar results were obtained for the scoliotic
230 girls. During the ML sway condition, the All CoP_{AP}-Tz ($P = 0.001$) and the Low CoP_{AP}-Tz
231 ($P = 0.001$) were much higher while the All CoP_{ML}-Tz ($P < 0.000$) and Low CoP_{ML}-Tz
232 ($P < 0.001$) have higher coherence values during the antero-posterior voluntary sway.

233

234 PLEASE INSERT FIG 4 ABOUT HERE

235

236 Factor analysis results for the ML and AP sway conditions are presented in Tables 1 and
237 2 respectively. For the self-paced ML oscillations two principal components (PC) on both
238 the temporal and coherence values were necessary to explain 90% of the variance in the
239 able-bodied girls whereas three PCs were needed to describe 90% of the variance in the

240 scoliotic girls. For the able-bodied girls, medio-lateral sway is mostly characterized by
241 coherence values associated with the free moment or proprioception in the PC1 while it is
242 mainly related to the CoP positions coherence pairs or posture in PC2. The first three PCs
243 of the scoliotic group contains a complex mix of coherence pairs involving the free
244 moment and the CoP positions. The scoliotic girls assume an adaptive balance modality
245 based on proprioception but requires an additional number of PCs and variables in a
246 disorganized grouping of variables.

247

248 PLEASE INSERT TABLE 1 ABOUT HERE

249

250 The variables and their factor loading for the antero-posterior sway condition of the able-
251 bodied and scoliotic girls are shown in Table 2. Five principal components values were
252 necessary to explain 85% of the variance in the able-bodied girls whereas six were
253 needed to describe the same variance in the scoliotic girls. This reflects the difficulty as
254 well as the complexity to perform voluntary antero-posterior sways in both subject
255 groups. The first three PCs of the non-scoliotic group are structured into a ranked sway
256 balance modality. The first PC emphasizes the role of the frequency coherence pairs
257 whereas the second PC is associated with the temporal variables. PC3 underlines the
258 frequency coherence between Tz and the CoP positions. The remaining two PCs which
259 explain about 9% of the variability consist of a combination coherence pairs and temporal
260 parameters.

261 The first three PCs for the scoliotic girls mainly consist of coherence frequency pairs.
262 The significant factors loading of the temporal variables are present in the fourth to the
263 six PCs. These results showed that the able-bodied group favored a well-ordered sway
264 balance modality while performing self-paced antero-posterior sway whereas the
265 scoliotic girls rely on the interaction between sway position and free moment to maintain
266 their dynamic balance.

267

268 PLEASE INSERT TABLE 2 ABOUT HERE

269

270 **4. Discussion**

271 The first objective was to determine if scoliotic and non-scoliotic girls display similar
272 temporal and frequency coherence patterns during self-paced voluntary medio-lateral and
273 antero-posterior body sways. Scoliotic girls appear to be performing a wide ellipsoidal
274 trajectory when executing whole body oscillations and that in both sway conditions
275 (Figure 3). Their CoP excursions exhibit a longer out of plane deviation than that of able-
276 bodied girls. This can be explained in part by the difficulty in achieving whole body
277 sways with a center of mass located closer to their heels (Nault et al., 2002) favoring a
278 backward trunk lean compared to non-scoliotic girls (Leteneur et al., 2017).

279 Body sway of scoliotic girls was under a greater control of the free moment than in able-
280 bodied girls (Dalleau et al., 2007) in quiet standing. This interaction between the free
281 moment and the antero-posterior CoP displacements was reported in adults (Hay and
282 Wachowiak, 2017) as well as in scoliotic girls during standing balance (Leteneur et al.,

283 2019). Since trunk rotation was shown to alter standing balance (Pau et al., 2018), self-
284 paced voluntary sways combined with out of plane deviation further disrupt body
285 postural compensations. In the present study, the spinal deformity did not sufficiently
286 solicit the frequency coherence pair interactions during the voluntary body sway
287 conditions, since no significant difference was found between the subject groups (Figure
288 4): the significant differences concerned the same pairs in both groups (All CoP ML-Tz,
289 All CoP AP-Tz, Low CoP ML-Tz, Low CoP AP-Tz). However, there were significant
290 differences in the frequency coherence pairs when comparing medio-lateral to antero-
291 posterior voluntary body sway conditions. All significant differences were related to the
292 dependence of the free moment on the out of plane deviation rather than on the sway
293 direction (Figure 4). It seems that in pursuing a unidirectional sway, the path followed by
294 the center of mass to keep it within the safety margins of the base of support for fear of
295 falling (Adkin et al., 2002) prevailed over the dynamic balance control modalities. The
296 latter could be related to non-statistically significant compensatory actions to maintain
297 steadiness when comparing both subject groups.

298 The final objective was to identify which of the temporal and frequency coherence
299 variables best identify balance modalities according to the scoliotic and non-scoliotic
300 groups and sway directions. Only a few PCs were required to describe medio-lateral (2
301 for able-bodied and 3 for AIS group) voluntary sway compared to antero-posterior (5 for
302 able-bodied and 6 for AIS group) oscillations (Tables 1 and 2). This could be explained
303 by a number of reasons. During the antero-posterior oscillations, the center of mass
304 excursion is longer; the whole-body inclination is more pronounced and the trunk being
305 the dominant body segments produces larger external forces (Gillet et al., 2003) and the

306 forward excursion is greater than the backward since the trunk CoM is closer to the heels,
307 especially in scoliotic girls (Allard et al., 2004). Furthermore during standing,
308 stabilization is under the control of an ankle intrinsic stiffness which increases quickly as
309 the center of pressure moves toward the toes and the limits of stability (Amiri and
310 Kearney, 2019). The ankle intrinsic stiffness could be a major contributing control factor
311 in AP sways but absent during medio-lateral oscillations. All these factors increase the
312 demand on postural control balance and could account for a greater number of PCs as
313 well as variables in explaining antero-posterior voluntary sway (Tables 1 and 2). These
314 reflect the difficulty, but also a fine tuning in the control mechanism to maintain dynamic
315 balance.

316 Generally, physical treatments for scoliosis concentrate either on posture (Penha et al.,
317 2017) or proprioception (Hazime et al., 2012; Pialasse et al., 2016). To our knowledge,
318 no one as yet addressed self-paced voluntary ML and AP sways as a means to assess
319 dynamic balance in able-bodied and untreated scoliotic girls. During voluntary body
320 sway, dynamic balance modalities are similar between subject groups. Factor analysis
321 identified that they were essentially based on frequency coherence pair interactions
322 whereas temporal parameters play a secondary role (Tables 1 and 2). However, these
323 balance modalities are altered in AIS for both sway conditions. The scoliotic group relies
324 on more PCs (3 for ML and 6 for AP) than able-bodied girls (2 for ML and 5 for AP) but
325 also on additional variables. Superfluous modalities could be related to the difficulty in
326 preserving balance during body sway tasks and could parasitize the scoliotic dynamic
327 control balance modalities. This was suggested by Lorenzo and Vanrentherghem, 2015 in
328 a study on the effect of antero-posterior body sway frequency and verbal restraint on

329 mechanical and perceived postural stability. No clear effect on perceived instability was
330 reported while noticeable alterations in mechanical indicators of stability were observed
331 with increase in voluntary sway frequency. Results of the present study suggest that such
332 balance parasites associated to sway balance should be subdued in retraining the motor
333 program in AIS rehabilitation.

334 Our results are limited to untreated scoliotic girls with right thoracic curves only. In
335 literature the scoliotic population could consist of a variety of curve types (Schmid et al.,
336 2016) and a wide range of severity in the spinal deformity (Park et al., 2015). Moreover
337 many studies concerned boys and girls (Ma et al., 2020) ; (Patel et al., 2018) or different
338 forms of scoliosis (Roy et al., 2020). A particular care was given to have a homogenous
339 scoliotic group considering that the type of curvature and its location was found to
340 modify upright balance control (Pasha and Baldwin, 2018). The methodology used in the
341 present study may be reinvested in further studies about specific or pathologic
342 populations, such as in people who present spine deformities resulting from traumatic
343 injuries or in chronic low back pain sufferers. Other experimental protocols could also
344 determine if the present observations are only of mechanical origin or if they present also
345 a neurological component.

346

347 **5. Conclusions**

348 Self-paced voluntary body sway is a challenging task in keeping the center of mass
349 within the safety margins of the base of support for fear of losing balance. Scoliotic girls
350 appear to be performing a wide ellipsoidal trajectory when performing whole body

351 oscillations and that in both sway directions. Yet, the dynamic balance modalities
352 characterized by the frequency coherence pairs during body sway are similar between
353 subject groups. AP voluntary sways appear to be more demanding than ML sway and
354 differences could be attributed to a longer CoM excursion and the presence of an ankle
355 intrinsic stiffness. A greater number of PCs and variables were reported for the AP
356 oscillations in scoliotic girls for both sway conditions. This could reflect variability or a
357 fine tuning of the control mechanism to maintain dynamic balance. Self-paced voluntary
358 oscillations intensify this imbalance and could lead AIS girls to resort to superfluous or
359 supplementary variables to those associated with proprioception that parasite their
360 dynamic balance. It appears that self-paced voluntary medio-lateral and antero-posterior
361 sway conditions could be an appropriate complementary balance test for untreated
362 scoliotic girls.

363 **6. Clinical relevance**

- 364 • Self-paced voluntary sways could be an appropriate balance test for untreated
365 scoliotic girls.
- 366 • Scoliotic girls performed a wide ellipsoidal trajectory when executing whole body
367 oscillations.
- 368 • Balance parasites should be subdued in retraining the motor program in AIS
369 rehabilitation.

370

Acknowledgements

371 The authors wish to express their gratitude to Mrs. Inkiètépas Insinrvera for her technical
372 assistance. This work was supported by the ELSAT2020 project, the European Union
373 with the European Regional Development Fund, the French state and the Hauts-de-
374 France Region Council.

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522

523 Table 1 Significant factors and their respective loading values for a self-paced voluntary medio-lateral sway are given for the able bodied (AB) and scoliotic
524 (SCO) groups. The statistically significant principal components of the factor analysis are presented. Values equal or above 0.7 are in bold. ML and
525 AP represent the medio-lateral and antero-posterior axes respectively, T_Z the free moment. All: overall frequency band (1.00-8.00 Hz), Low: low
526 frequency band (1.00-3.00 Hz), High: high frequency band (3.00-8.00 Hz).

AB	Principal components		SCO	Principal components		
	1	2		1	2	3
All CoP _{AP} -T _Z	0,955	0,292	Sway ratio	-0,984	0,036	0,126
Low CoP _{AP} -T _Z	0,954	0,297	Low CoP _{ML} -CoP _{AP}	0,962	-0,096	0,128
All CoP _{ML} -T _Z	0,940	0,182	All CoP _{ML} -CoP _{AP}	0,962	-0,096	0,128
Low CoP _{ML} -T _Z	0,940	0,182	AP deviation	0,947	-0,127	0,244
Range T _Z	0,790	-0,220	All CoP _{AP} -T _Z	0,905	-0,170	-0,384
High CoP _{ML} -T _Z	0,171	0,985	Low CoP _{AP} -T _Z	0,905	-0,170	-0,384
High CoP _{ML} -CoP _{AP}	-0,171	-0,985	All CoP _{ML} -T _Z	-0,309	0,819	0,274
Low CoP _{ML} -CoP _{AP}	0,166	0,894	Low CoP _{ML} -T _Z	-0,309	0,819	0,274
All CoP _{ML} -CoP _{AP}	0,166	0,894	High CoP _{ML} -T _Z	-0,452	-0,799	0,372
Range ML	0,649	0,718	High CoP _{ML} -CoP _{AP}	0,337	-0,754	-0,105
			High CoP _{AP} -T _Z	0,035	0,021	-0,954
			Range T _Z	-0,003	0,204	0,951

527 Table 2 Significant factors and their respective loading values for a self-paced voluntary antero-posterior sway are given for the able bodied
528 (AB) and scoliotic (SCO) groups. The statistically significant principal components of the factor analysis are presented. Values equal or
529 above 0.7 are in bold. ML and AP represent the medio-lateral and antero-posterior axes respectively, T_z the free moment. All: overall

AB

Principal components

SCO

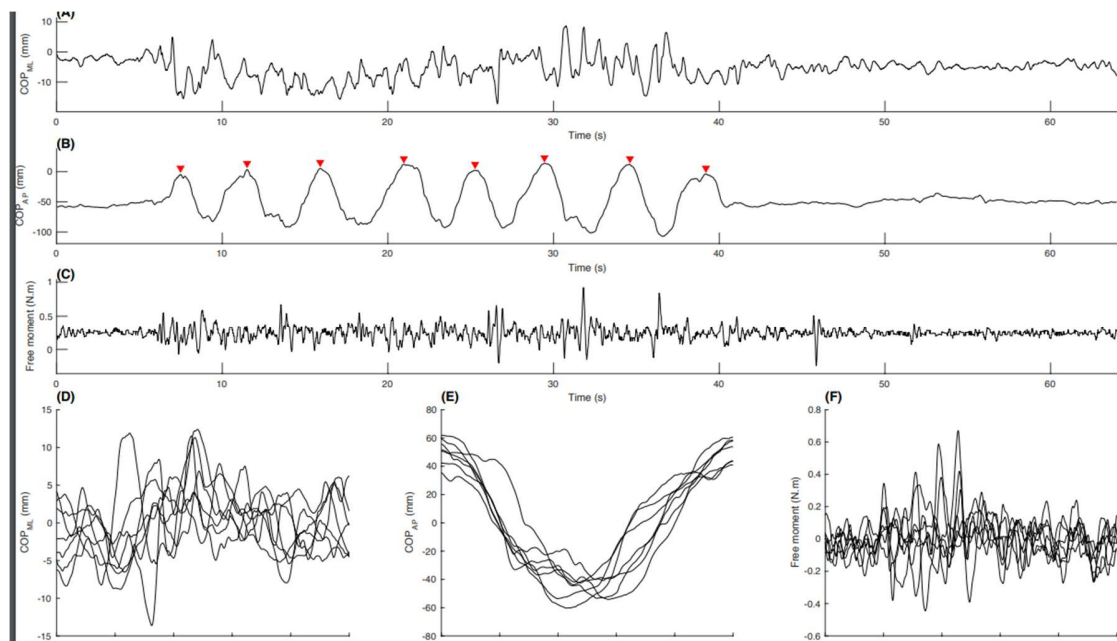
Principal components

530 frequency band (1.00-8.00 Hz), Low: low frequency band (1.00-3.00 Hz), High: high frequency band (3.00-8.00 Hz).

	1	2	3	4	5		1	2	3	4	5	6
Low CoP _{ML} -CoP _{AP}	0,933	-0,053	0,268	0,012	-0,103	All CoP _{AP} -Tz	0,869	-0,146	0,108	-0,134	-0,094	0,265
All CoP _{ML} -CoP _{AP}	0,933	-0,053	0,268	0,012	-0,103	Low CoP _{AP} -Tz	0,869	-0,146	0,108	-0,134	-0,094	0,265
Low CoP _{AP} -Tz	0,794	0,448	-0,309	0,047	0,113	All CoP _{ML} -CoP _{AP}	0,829	-0,231	-0,044	0,234	0,094	-0,237
All CoP _{AP} -Tz	0,794	0,448	-0,309	0,047	0,113	Low CoP _{ML} -CoP _{AP}	0,829	-0,231	-0,044	0,234	0,094	-0,237
RMS ML	0,098	0,923	0,034	0,139	-0,009	Range ML	0,583	0,205	0,019	0,235	-0,175	0,440
Range ML	0,144	0,833	0,070	0,234	0,061	Low CoP _{ML} -Tz	-0,204	0,937	-0,081	0,103	0,012	-0,080
Range Tz	0,007	0,602	0,535	0,104	-0,315	All CoP _{ML} -Tz	-0,229	0,934	-0,082	0,087	0,148	-0,097
High CoP _{AP} -Tz	-0,059	-0,029	-0,851	0,224	0,047	High CoP _{AP} -Tz	0,010	-0,031	0,990	-0,046	-0,014	0,021
High CoP _{ML} -Tz	0,054	0,078	0,754	0,206	-0,087	High CoP _{ML} -CoP _{AP}	0,066	-0,107	0,986	0,003	0,048	0,011
ML deviation	-0,002	0,328	-0,100	0,879	-0,066	Range Tz	0,286	-0,034	0,138	0,795	-0,328	-0,172
Range AP	0,279	0,369	0,010	0,718	-0,029	Range AP	-0,164	0,149	-0,235	0,760	0,189	0,305
Low CoP _{ML} -Tz	-0,385	-0,360	0,230	0,585	0,539	ML deviation	0,169	0,332	0,028	0,611	0,456	0,252
All CoP _{ML} -Tz	-0,379	-0,357	0,252	0,563	0,559	Sway ratio	-0,097	0,069	-0,034	-0,081	-0,863	0,022
High CoP _{ML} -CoP _{AP}	0,074	-0,071	-0,083	-0,094	0,897	High CoP _{ML} -Tz	-0,185	0,203	-0,006	-0,074	0,768	-0,116
Sway ratio	0,048	-0,286	0,401	-0,071	-0,696	RMS ML	0,068	-0,179	0,022	0,096	-0,059	0,814

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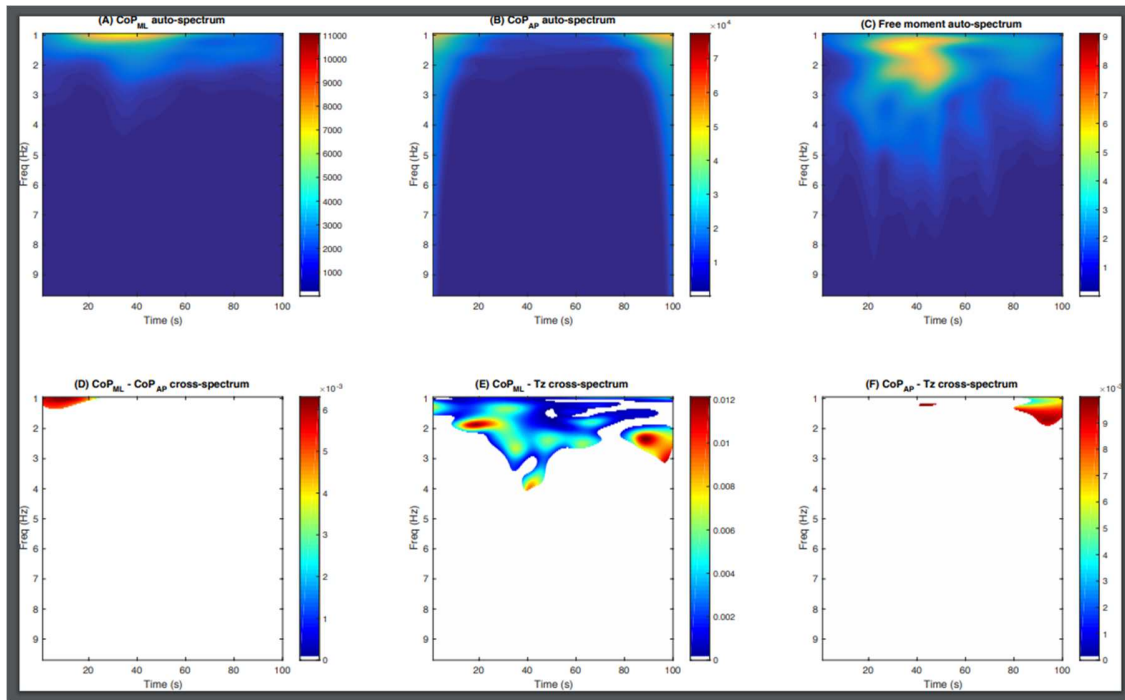
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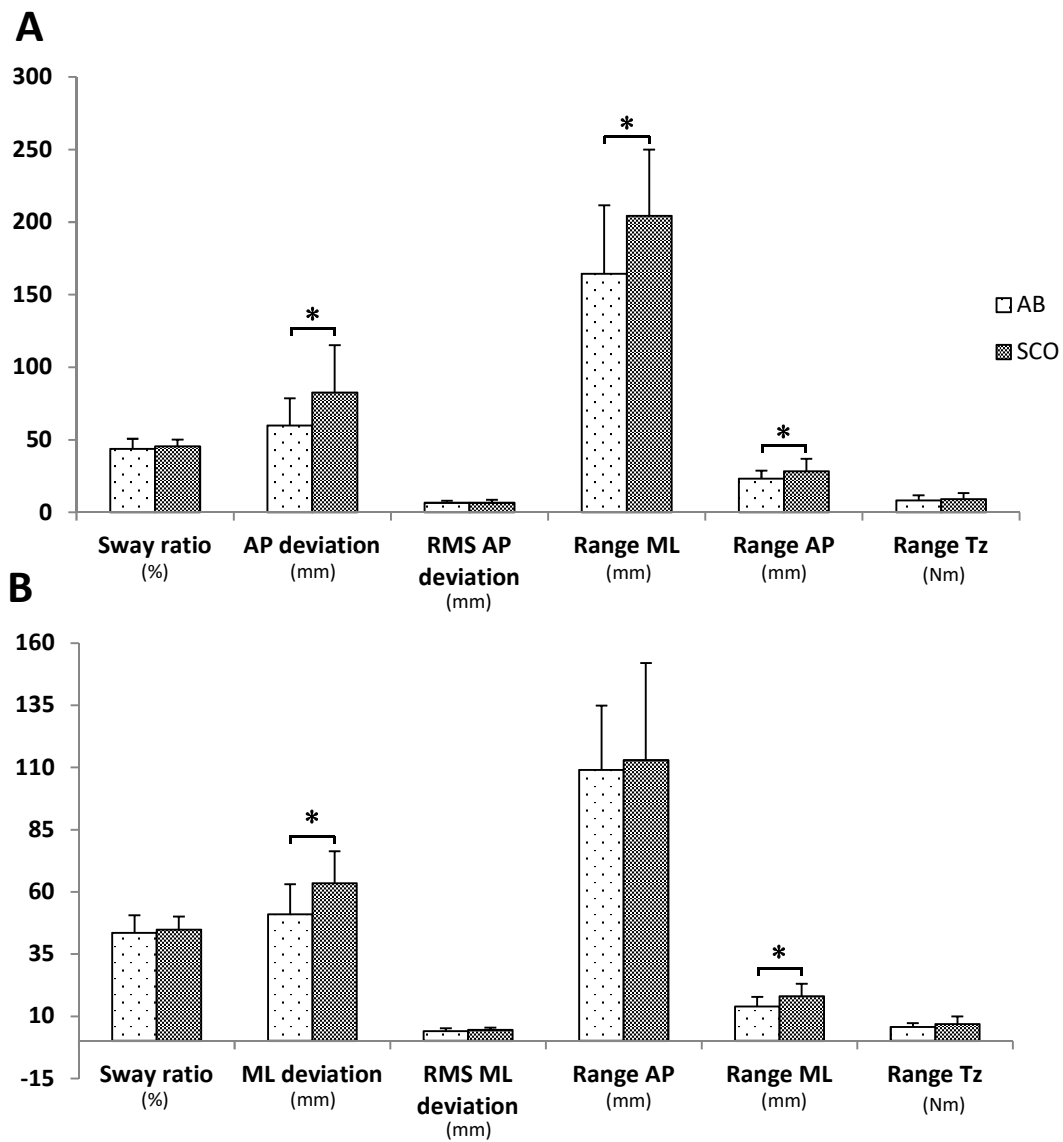
535 **Fig. 1** Displacements of the CoP_{ML} (A, D) and CoP_{AP} (B, E) and free moment acting at the CoP
 536 around the vertical axis (C, F) for a representative able-bodied participant performing a
 537 voluntary antero-posterior oscillation. In (B), the red triangles indicate the local maxima
 538 of the CoP_{AP} used to define the oscillation epochs. In (D, E, F), the black lines depict
 539 each epoch of the latter signals after zero-centering and time normalization.



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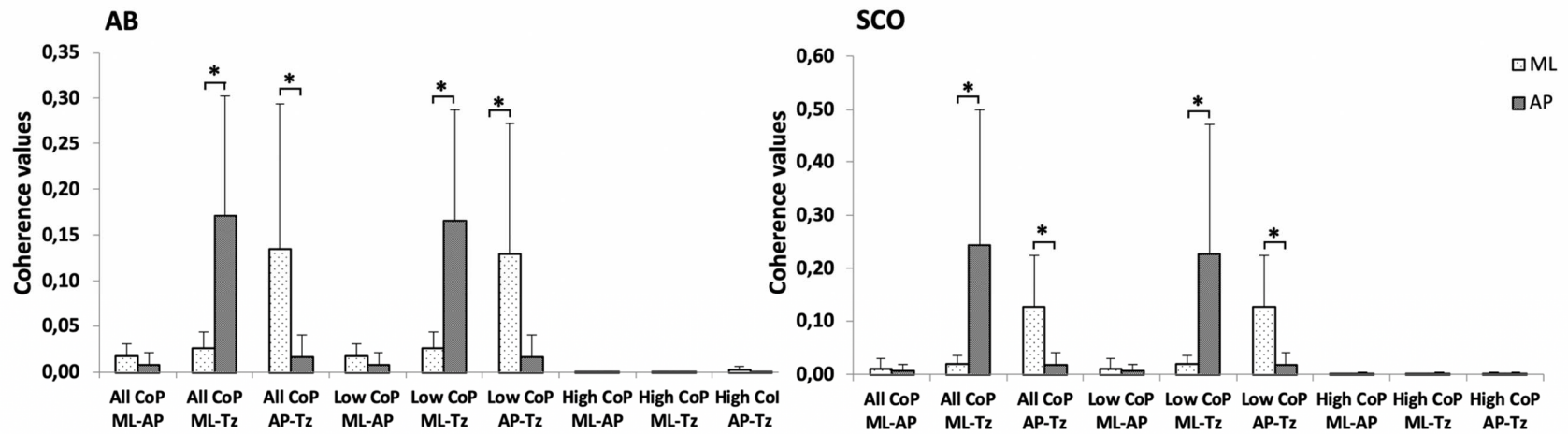
542 Fig. 2 First row: Wavelet auto-spectra of the CoP_{ML} (A), CoP_{AP} (B) and free moment (T_z) (C)
 543 signals of one representative able-bodied participant. Second row: significant wavelet
 544 magnitude-squared coherence between CoP_{ML} and CoP_{AP} (D), CoP_{ML} and free moment
 545 (E) CoP_{AP} and free moment (F) signals depicted in the first row. All non-significant
 546 values are whitened. The magnitude of the coherence for each pair was quantified as the
 547 mean of significant magnitude-squared coherence over the entire time range in three
 548 different frequency ranges (1-8.00 Hz, 1-3.00 Hz, 3.00-8.00 Hz) respectively representing
 549 the overall, low and high frequency ranges.



550

551

552 Fig. 3 Mean of the temporal parameters for able-bodied (AB) and scoliotic girls (SCO) for
 553 medio-lateral (A) and antero-posterior (B) voluntary sway conditions. ML: medio-lateral,
 554 AP: antero-posterior, T_Z: free moment. Note: for display purpose only, range T_Z values
 555 were multiplied by a 10 factor. *: $P < 0.05$.



556

557

558 Fig. 4 Means and their corresponding standard deviation of the coherence values for able-bodied subjects (AB) and scoliotic girls (SCO). CoP:

559 Center of Pressure, ML: medio-lateral, AP: antero-posterior, Tz: free moment, All: overall frequency band (1.00-8.00 Hz), Low: low

560 frequency band (1.00-3.00 Hz), High: high frequency band (3.00-8.00 Hz). *: $P < 0.05$.