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## Center of pressure palindromes reveals a wobbling standing balance in scoliotic girls

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1  
2 **Center of pressure palindromes reveals a wobbling standing balance in scoliotic girls**

3  
4 **Abstract**

5 **Background:** This study characterized the center of pressure planar displacement by palindromic  
6 strings. The objective is to test if the center of pressure pathway of able-bodied girls and those  
7 with a moderate and severe scoliosis displayed similar palindromic tendencies.

8 **Methods:** The CoP excursions of 21 able-bodied girls were compared to 14 girls with a moderate  
9 scoliosis and 14 girls with severe one. Each girl was asked to stand upright on a force platform  
10 for 64s. A crisscross grid of nine areas was centered around the mean center of pressure position  
11 (G) to define three other zones to use the MATLAB built-in nucleotide sequence analysis  
12 function. These were the antero-posterior extremities A, the coronal extremities C and the tilted  
13 or the four corners of the crisscross grid, T. The center of pressure positions were associated to  
14 any of the 4 zones using the GATC acronym.

15 **Findings:** For all groups center of pressure pattern in decreasing order was A, G, T and C. Able-  
16 bodied girls favored the A zones. Girls with moderate scoliosis displaced their center of pressure  
17 mostly in the A zones with shifts in the T sections ( $P \leq 0.001$ ). Girls with severe scoliosis,  
18 additionally displaced their center of pressure in the C zones ( $P \leq 0.001$ ).

19 **Interpretation:** An ankle modality characterized able-bodied girl's standing balance. Girls with a  
20 moderate scoliosis privilege the palindromic zones in the antero-posterior extremities with  
21 excursions in the corners of the base of support, girls with severe scoliosis further relied on the  
22 medio-lateral zones, suggesting a wobbling standing balance.

23 **Key words:** Center of pressure, palindromes, scoliosis, quiet standing, balance, wobbling  
24

## 25 **Introduction**

26 The center of pressure (CoP) excursion is a means to assess the quality of balance stability  
27 during quiet standing by providing information on the neuro-muscular control (Federolf, 2016).  
28 It is evaluated by all-encompassing parameters such as the mean CoP position, and CoP length,  
29 range and speed often calculated separately in the anterior-posterior (AP) and medio-lateral (ML)  
30 directions. These experimental descriptors of the CoP displacements provide a global assessment  
31 of standing balance (Jacono et al., 2004) in able-bodied children (Allard et al., 2001) and adults  
32 (Quijoux et al., 2021) as well in individuals with standing imbalance such as in Parkinson's  
33 disease (Schmit et al., 2006) and scoliosis (Nault et al., 2002). The quantification of the CoP  
34 displacement is also performed in the early detection of balance degradation to prevent falls in  
35 the elderly (Johansson et al., 2019). However, most of these CoP features characterize the overall  
36 performance of standing balance by the CoP trajectory as if stability is achieved along an axis  
37 independently of the other. The pathway followed by the CoP being too close or not to the border  
38 of the base of support that needs to be adjusted to prevent a fall remains unknown.

39  
40 Different organisational modalities were proposed to regulate the process of postural control in  
41 upright standing. One is based on the frequency range of body sway where the first system  
42 operates below 2 Hz while the second intervenes above 4 Hz. (Amblard et al., 1985). Another  
43 refers to a reference CoP positions where standing balance is preserved and to a second reference  
44 equilibrium position about a preselected reference point (Lestienne and Gurfinkel, 1988). These  
45 are related with rambling and trembling by Zatsiorsky and Duarte (1999). The center of pressure  
46 displacement can also be modelled as a combination of deterministic and stochastic mechanisms  
47 using fractional Brownian motion, fBm (Mandelbrot and van Ness, 1968). During quiet standing,

48 open- and close-loop systems were associated with a CoP moving away from a relative  
49 equilibrium point and it's returned to define standing balance in a group of able-bodied young  
50 male adults (Collins and De Luca, 1993). These studies still described the CoP excursions along  
51 the AP or the ML directions separately or by single value parameters.

52  
53 A better understanding of the CoP travel during standing is obtained by its structural  
54 characteristics or sway density plot calculated in the horizontal plane (Baratto et al., 2002). The  
55 number of consecutive samples during which the CoP remains inside a pre-determined radius  
56 conveys a progression over the stay time of the CoP within the area. The radii can vary between  
57 2 and 5 mm (Jacono et al., 2004) but a radius of 2.5 mm is often selected (Simoneau et al., 2006;  
58 Beaulieu et al. 2009). Yet, the horizontal path sequence taken by the CoP with respect to its  
59 equilibrium point and its migration within the sway area during quiet standing remains to be  
60 quantified.

61  
62 It appears that the CoP oscillates about a reference balance position with irregular shifts outside  
63 this zone to eventually return to an equilibrium location. These back-and-forth CoP motions  
64 within different portions of the base of support could follow a sequential path. We assume that  
65 these sequential paths could reflect postural modalities in standing balance (Baratto et al., 2002;  
66 Zatsiorsky and Duarte, 1999) contrary to random CoP shifts as proposed by some authors  
67 (Collins and Luca, 1993; Rougier and Caron, 2000). If so, they could be characterized by  
68 palindromic strings. A palindrome is a set of numbers, letters or words that remains intact when  
69 read backwards such as KAYAK and TACO CAT. These could be construed as CoP oscillations  
70 following a pathway with respect to an equilibrium point within the subject's base of support. If

71 the sway area delimited by the CoP excursions was divided into zones, these could be attributed  
72 a letter. This way, the CoP pathway could be described as a series of letters associated to an area  
73 of the base of support and those that repeats themselves forward and backward constitute a  
74 palindromic string. Each string is a sequence of the CoP positions or stay time within a zone of  
75 the base of support. The palindromic strings could reflect balance modalities not only associated  
76 with the AP or ML orientations but along a pathway covering the surface circumscribed by the  
77 CoP displacements.

78

79 To the best of our knowledge, no previous study characterised balance stability through  
80 palindromic analysis of the CoP pathway. It is hypotized that subjects with impair balance would  
81 have different palindromic strings and repetitions in areas lying outside the equilibrium zone  
82 compared to able-bodied subjects. The objective of this study is to test if the CoP pathway of  
83 able-bodied girls and those with a moderate and severe untreated scoliosis displays similar  
84 palindromic tendencies. Subjects with marked differences in scoliosis severity could emphasize  
85 standing imbalance modalities absent in those with a lesser one. Specifically, the purpose is to  
86 determine if the distribution of the palindromic zones with and without string reduction (which  
87 process is defined in details below) is similar within and between able-bodied girls and those  
88 with moderate and severe untreated scoliosis. The first condition emphasizes the repetition or  
89 stay time within a palindromic zone while the second underlines the CoP shifts from one zone to  
90 another.

91

92 **Method**

93 The control group consisted of 21 able-bodied girls. Their average age was  $13.1 \pm 1.4$  years and  
94 they had a mean height of  $156.8 \pm 6.9$  cm with an average mass was  $45.9 \pm 7.7$  kg. Girls with an  
95 history of neurological or orthopaedic problems, such as a recent injury or surgery, affecting  
96 their standing balance were excluded from the study. Twenty-eight girls diagnosed with  
97 adolescent idiopathic scoliosis as according to the criteria defined by Bunnel (1986) formed the  
98 experimental group. No subject was under active treatment at the time of this study. They all  
99 presented a right thoracic curve with a mean value of  $28.1^\circ \pm 11.7^\circ$  ranging from  $11^\circ$  and  $49^\circ$ .  
100 Their average age ( $12.7 \pm 1.8$  years), height ( $153.8 \pm 10.2$  cm) and mass ( $43.2 \pm 9.7$  kg) were not  
101 statistically different from the able-bodied girls ( $p \geq 0.242$ ). Subjects with a limb length  
102 discrepancy of more than 1 cm or wearing foot orthoses were not considered for this study. An  
103 informed consent form approved by the hospital ethics committee were given by all the girls and  
104 their parents.

105

106 The scoliotic girls were then arbitrarily divided into two groups according to the median Cobb  
107 angle (Stylianides et al., 2012) to distinguish moderate ( $< 28^\circ$ ) from severe ( $> 28^\circ$ ) scoliosis  
108 (Bunnel, 1986; Lonstein and Carlson, 1984). Table 1 summarizes the mean demographic features  
109 of the able-bodied girls and those in the untreated scoliotic groups. There was no statistical  
110 difference for age ( $p \geq 0.242$ ), height ( $p \geq 0.061$ ) and mass ( $p \geq 0.148$ ) between the three groups  
111 while there was one for the Cobb angle ( $p < 0.001$ ).

112

113

PLEASE INSERT TABLE 1 ABOUT HERE

114 For the experiment, participants were asked to stand upright on a force platform (AMTI OR6-5,  
115 Newton, MA). The feet position was standardized so that the girl's heels were apart by about 23

116 cm and feet pointing 15 degrees externally (McIlroy and Maki, 1997). With their arms on their  
117 sides, subjects focused on a target placed at eye level and at a distance of 1.2 m. To test their  
118 standing balance three trials were performed for 64s each with the sampling frequency set at 64  
119 Hz (Allard et al., 2001; Nault et al., 2002). A one-minute rest period was given between each  
120 trial (Carpenter et al. 2001).

121  
122 The center of pressure displacements along each axis was calculated from unfiltered forces and  
123 moments (Allard et al., 2004). A neutral or equilibrium zone needs to be determined from the  
124 CoP displacements as shown in Fig. 1a. For each trial, it was defined by a circle centered at the  
125 mean CoP position (Fig. 1b) having a radius of 2.5 mm (Jacono et al., 2004; Simoneau et al.,  
126 2006; Beaulieu et al., 2009). The neutral zone is labelled G and represents the center of balance  
127 or the center of gravity. A 2.5mm square was created centered at the mean CoP position so that  
128 its corners are on the neutral circle zone. Both horizontal and vertical square edges were  
129 extended to form a crisscross grid of nine areas with the G zone in the middle as depicted in Fig.  
130 1c.

131 PLEASE INSERT FIG 1 ABOUT HERE

132 To be able to utilize the MATLAB built-in nucleotide sequence analysis function (R2022b  
133 software, Bioinformatics Toolbox, The MathWorks, Natick, MA, USA), the nine zones were  
134 reduced to four as shown in Fig. 1d. Determining the position of the CoP is based on the creation  
135 of a logical vector with 4 values: 0 represents the CoP inside the neutral zone, 1 represents the  
136 CoP outside the neutral zone along the ML axis, 2 represents the CoP outside the neutral zone  
137 along the AP axis and 3 represents the CoP outside the neutral zone along both AP and ML axes.  
138 Subsequently values 0, 1, 2 and 3 were respectively attributed to characters G, C, A, T.

139

140

141 These consisted of the neutral zone, G, and three imbalance areas located around G. The A zones  
142 corresponds to the extremities of the antero-posterior direction, the C zones for coronal or the  
143 ends of the medio-lateral orientation and the T zones for tilted or diagonal areas located at the  
144 corners of the crisscross grid. The CoP instantaneous position can be associated to any of the 4  
145 zones using the GATC characters. The palindromic strings reflect the position of the CoP in a  
146 zone, the stay time in each zone by its repetitions and its excursion into others areas while  
147 maintaining standing balance. The palindromic sequence then describes the balance strategy by  
148 the pathway taken by the CoP excursions not only in the AP or ML directions but over the  
149 surface circumscribed by its displacements.

150

151 The interest of this study lies in the ability to determine the sequence of zone fluctuations from  
152 G, to A, T and C zones in any order. Maintaining the CoP inside a zone for a few seconds  
153 resulted in multiple repetitions or stay time. To further simplify the palindromic sequence, the  
154 string was reduced by retaining only zone changes. For example, the sequence  
155 “GGGAAAAATTTTATTTAAAAGGGG” was reduced to “GATATAG”. In summary the  
156 palindromic sequences are calculated over the entire duration of the acquisition. An example of a  
157 single palindromic pathway is shown in Fig. 1e starting at the triangle and ending at the plus sign.  
158 Then those which contain repetitions were reduced by retaining only zone changes. Furthermore,  
159 only the palindromes above length 4 within the sequence vector were analyzed to avoid random  
160 CoP excursions. In other words, it is assumed that reduce palindromes such as TAT or GAG  
161 reflect CoP erratic zone changes not associated with standing balance modality. This study



162 focuses on the behaviour of the CoP moving outside the neutral zone. Hence, only the  
163 palindromes not going back inside the neutral zone were considered with the only exception  
164 when it started and ended in the neutral zone (e.g. GATATAG was kept where ATAGATA was  
165 not). Consequently, reducing the repetitions of the palindromic strings emphasized the CoP shifts  
166 from one zone to another. Both the complete and the reduced palindromic strings were retained  
167 for further analyses. The number and the length of each palindrome were calculated for the  
168 complete and reduced strings for all standing trials. Afterwards the distribution in each zone was  
169 calculated from palindromic sequences and not from the trial duration.

170

171 The output of the MATLAB *palindromes* function were CoP zones (GATC) of the palindromic  
172 sequences. The GATC zones were calculated for each string before and after reduction. Data  
173 were generally normally distributed (Sharma, 1996). MANOVA test was used to compare the  
174 relative GATC distribution between able-bodied and moderate and severe scoliosis groups. Also,  
175 GLM repeated measure ANOVA was used to compare the mean number and length of the  
176 palindromic sequence and the frequency in percentage of the palindromic zones in each group.  
177 These analyses were also performed on the complete and reduce strings. Bonferroni tests were  
178 used to control type one error in multiple comparisons for a significance level set at  $p < 0.05$  for  
179 all comparisons.

180

## 181 **Results**

182 The mean number and length of the complete and reduced palindromic strings for each group is  
183 given in Table 2. There are about 3700 palindromic strings with a mean length of 57 characters  
184 in the complete sequence for each group. The large number of palindromes is due to the

185 repetition of palindromes within the palindromes. With their reduction the mean number is 20  
186 having an average length of 9 characters. The able-bodied girls had 85 more palindromes than  
187 the moderate scoliosis group ( $p=0.001$ ) for the complete string while it had 11 less compared to  
188 the same group ( $p=0.001$ ) for the reduced string. There was no other significant difference  
189 between the groups ( $p>0.150$ ) in numbers and lengths of palindromes. The reduction eliminated  
190 the repetition of the palindromes especially in the able-bodied group. Because the number and  
191 length of the sequences are still too high to determine individual or mean group values, only the  
192 GATC were retained for further analyses.

193 PLEASE INSERT TABLE 2 ABOUT HERE

194 The GATC zone distribution for the complete palindromic strings for each group is shown in  
195 Fig.2 and their respective p values are reported in table 3a. Generally, the pattern of CoP for all  
196 groups in decreasing order was A (AP), G (Neutral), T (Tilt) and C (ML) consecutively. In able-  
197 bodied girls, these zones were all statistically significant from one another ( $p\leq 0.007$ ). The CoP  
198 GATC proportion in the A (43,2%) and G (33.3%) areas represented 76.5% of all changes and  
199 91.4% if the T zones were included. Subjects with a moderate scoliosis displaced their CoP  
200 mostly in the A zones which was significantly larger than those in the other zones ( $p\leq 0.048$ ). The  
201 shifts in the G and T areas were similar ( $p=0.518$ ) and these were greater than in the C sections  
202 ( $p\leq 0.001$ ). For these subjects, the repetitions in the A zones were 40.3%, in the G one 51.4% and  
203 with the T areas, it was 91.7%. The group with severe scoliosis exhibited similar CoP zone  
204 changes as for the moderate scoliotic group. Their CoP zone shifts were mostly in the A zones  
205 which were significantly larger than those in the G and C sections ( $p\leq 0.004$ ). Shifts in the G and  
206 T areas were similar ( $p\geq 0.900$ ) and T zone was greater than in the C zones ( $p\leq 0.001$ ). These  
207 subjects presented 37.3% recurrences in the A and 47.9% in the G areas. With the T zone it was

208 85.2%. It appears that able-bodied girls essentially moved their CoP in the anterior-posterior  
209 zones followed by the G section as show in Fig. 3a. The scoliotic girls carried out comparable  
210 zone changes but concomitantly with a crisscross or tilted orientation as depicted in Fig. 3b.

211

212 PLEASE INSERT FIG 2 ABOUT HERE

213 PLEASE INSERT FIG 3 ABOUT HERE

214 PLEASE INSERT FIG 4 ABOUT HERE

215

216 Fig. 4 illustrates the relative contribution of each GATC components of the reduced palindromic  
217 strings for the able-bodied and scoliotic girls and their respective p values are reported in table  
218 3b. Reducing the repetitions in a section affect the GATC distribution in the others. Here, the  
219 CoP shifts in the A (AP) zones were diminished by about 5% while those in the T (Tilt) and C  
220 (ML) zones increased by about 6% and 5% respectively when compared to the whole  
221 palindromic strings. With string reduction, the number of repetitions in the A zones remained the  
222 highest ( $p \leq 0.009$ ) in the AB group. For the moderate scoliosis group, the T areas were similar to  
223 the G zone ( $p \geq 0.900$ ). The C areas had the smallest CoP changes ( $p \leq 0.037$ ). With this  
224 modification, the able-bodied girls followed the same trend of CoP zone changes as the girls with  
225 a moderate scoliosis whose pattern remained unchanged (Fig 3b) with string reduction. The  
226 severe scoliotic group displayed the greatest GATC alterations. The frequency of CoP changes in  
227 the A and T zones were similar ( $p = 0.343$ ) and the later was no different from the G section  
228 ( $p \geq 0.900$ ). The C zones shifts were similar to the G area ( $p = 0.358$ ) but different from the others  
229 ( $p \leq 0.010$ ). Fig 3c represents the CoP zone changes for the severe scoliosis group.

230

231 The distribution of the CoP positions in the GATC zones were comparable between groups for  
232 the complete and reduced palindromic strings and their respective p values are reported in table  
233 4. The frequency of the CoP changes in the GATC zones for the complete palindromic sequences  
234 was from the highest to the lowest, A (AP) with 40%, G (Neutral) with 29% T (Tilt) with 20%  
235 and C (ML) at 11%. This relative contribution in the frequency of the CoP changes was  
236 significant ( $p \leq 0.007$ ) between groups with the exception of the A zones ( $p = 0.172$ ). There was a  
237 greater CoP recurrence in the G zone for the able-bodied girls than for those with a severe  
238 scoliosis ( $p = 0.006$ ). The severe scoliotic group had more CoP changes in the T zones ( $p = 0.006$ )  
239 than the able-bodied girls. The severe scoliotic girls also had a higher CoP change in the C zones  
240 than those in the two other groups ( $p \leq 0.003$ ). Generally, the severe scoliotic group performed  
241 less CoP shifts in the G area and more in the C and T zones.

242

243 The incidence of the CoP shifts in the reduced palindromic strings between groups followed a  
244 similar pattern to the complete sequence. However, the distribution in the four zones differed.  
245 From to the highest to the lowest the distribution was A (AP) with 34%, G (Neutral) with 27% T  
246 (Tilt) with 26% and C (ML) at 13%. It was significant between the groups only in the T zones  
247 ( $p = 0.001$ ) where the able-bodied girls had a smaller number of CoP shifts than those in the  
248 scoliotic groups ( $p \leq 0.037$ ). The able-bodied girls had a tendency to move away from the T zones  
249 into to the A and G zones compared to the severe scoliotic girls.

250

## 251 **Discussion**

252 Traditionally the CoP excursions in standing posture are described by its mean position, speed,  
253 range, etc. (Goldie et al., 1989). These measurements characterize the unidirectional features of

254 the CoP movements while the sway area conveys the extent of imbalance spread. This study  
255 proposes a new approach to describe the CoP bi-dimensional positions in four sections of the  
256 sway area and their recurrences within these zones using palindromic sequencing. The existence  
257 of palindromic strings supports the notion of a moving reference point with respect to which the  
258 body's equilibrium is maintained (Lestienne and Gurfinkel, 1988; Zatsiorsky and Duarte, 1999;  
259 Baratto et al., 2002). The GATC sequences address how the CoP excursions are organized  
260 especially in scoliotic subjects where greater standing imbalance was reported (Sahlstrand et al.,  
261 1978; Herman et al., 1985).

262  
263 The distribution of the GATC before and after palindromic string reduction is distinctive for each  
264 subject group. It appears that the able-bodied girls display an ankle balance modality. This is  
265 suggested by greater CoP zone changes aligned with the AP orientation. This throws light on the  
266 relatively absence of medio-lateral imbalance in able-bodied girls (Bruyneel et al. 2008). A less  
267 adaptable standing balance postural control strategy in AIS was associated with a large ML range  
268 (Gruber et al., 2011). This concurs with a statistically significant rearward displacement of the  
269 CoP and a non significant one in the ML sway (Sadegui et al., 2008; Dufvenberg et al., 2018).  
270 The lesser CoP ML directional shift could be the result of the medio-lateral plane contribution of  
271 the crosswise T CoP zone GATC changes rather than a unidirectional ML CoP sway. The later  
272 was present in the scoliotic groups but had the smallest ML GATC proportion. The palindromic  
273 sequences suggest a wobbling body motion in these girls characterized by the oblique CoP shifts  
274 within the areas of the base of support.

275

276 Compensatory standing balance strategies brought about by the vestibular and somatosensory  
277 systems reflect challenged motor commands (Sim et al, 2018). To control their posture AIS girls  
278 are thought to generate hips or trunk rotations to maintain their center of mass over the midline  
279 position (Leteneur, et al, 2019). If so, then the ankle strategy could be insufficient when standing  
280 balance is challenged by increase body motions (Karami et al., 2019). This could lead to  
281 problems with the perception of body axes and cause a balance deficit (Piątek-Krzywicka et al.,  
282 2022). Geometric and morphologic changes in the scoliotic trunk and rib cage are responsible for  
283 postural adjustments particularly in body segments rotations (Stokes, 1994) where the trunk is  
284 the principal contributor of external forces acting in the horizontal plane (Gillet et 2003; Allard  
285 et al., 2017). Morphological trunk deviations (Allard et al., 2004) as well as asymmetrical iliac  
286 crests orientation and geometry (Stylianides et al., 2012) can perturb CoP displacements  
287 resulting in larger standard deviations and ranges of the CoP excursion in the scoliotic group.  
288 Moreover, rotational sway of the trunk about its vertical axis due to the free moment was more  
289 noticeable in scoliotic girls (Dalleau et al.; 2007). This can be the result of a difference in foot  
290 pressure between left and right feet in scoliotic girls (Lee et al., 2014; Szulc et al., 2008; Zhu et  
291 al., 2021). We suggest that the scoliotic groups adapted a wobbling standing balance by mean of  
292 their hip, ankle and free moment. The palindromic strings support this assumption where  
293 scoliotic subjects mainly shift their CoP in the AP and Tilt zones in a wobbling manner rather  
294 than along a purely AP or ML direction.

295

296 Any relationship between the CoP sway components could be more complex than a linear  
297 correlation (Hay and Wachowiak, 2017). The palindromic strings suggest at least a two-mode  
298 standing balance modality previously reported (Collins and Luca, 1993; Rougier and Caron,

299 2000; Zatsiorsky VM, Duarte; 1999). Altered head position and a smaller pelvic range of motion  
300 in AIS (Jamison et al., 2022) exacerbated standing balance in scoliotic patients and worsens it by  
301 the extent of their spinal deformity (Haumont et al., 2011; Leteneur et al., 2017). This could lead  
302 to more than a two-mode balance process. Generally, the severe scoliotic group principally  
303 displayed a GATC distribution in the extremities of the crisscross grid and less in the neutral  
304 zone. This could account for their greater sway area (Beaulieu et al., 2009). It appears that  
305 standing balance control in scoliotic girls follows a pathway rather than postural sways along  
306 either axis, independently or concomitantly.

307

308 The lack of statistical difference between the non-scoliotic and mild AIS scoliotic subjects was  
309 reported in gait studies (Zhu et al., 2021) but also in posturographic parameters between girls  
310 with a mild scoliosis and those for whom a body brace has been prescribed (Sadeghi et al., 2009;  
311 Beaulieu et al., 2009). Similar results were observed in this study for the reduced palindromic  
312 strings where CoP repetitions were excluded. The reduced palindromic string emphasizing zone  
313 changes revealed that scoliotic girls behaved differently. Girls with a moderate scoliosis  
314 presented crosswise palindromic zones while the severe group performance deteriorated and  
315 unlike the other groups involved the ML areas. Though scoliotic girls were not under active  
316 treatment, our results suggest that not only inadequate postural balance commands are present  
317 earlier than anticipated but are also worsened as scoliosis progresses. Perturbations of the  
318 sensory integration system was also associated with curve progression and early intervention  
319 targeting functional deficits was recommended to lessen scoliosis progression (Zhu et al., 2021).  
320 Our results recommend earlier than proposed rehabilitation programs aimed at improving motor

321 control modulation and flexibility in standing balance as well as enhancing proprioception while  
322 repositioning the CoP displacement zones in scoliotic girls.

323

324 This study focused only on right thoracic curve. Though the present study contributes to our  
325 understanding of standing balance management, the palindromic string analysis was restricted to  
326 four zones covering the sway area. These zones did not distinguish between the anterior and  
327 posterior zones and between the right and left sections as well as between the four corners of the  
328 crisscross grid. Furthermore, the dimensions of these zones resulted from the radius selected to  
329 define the neutral or equilibrium zone. A smaller radius would decrease this equilibrium area and  
330 increase the imbalance zones while larger radii would offer a greater stability zone making it  
331 more difficult to identify standing imbalance modalities. The palindromic sequence analysis is a  
332 novel approach that needs to be further explored. Nonetheless, it revealed that the CoP  
333 displacements follow organized pathways over the base of support with recurrences in the GATC  
334 zones in the management of standing balance in able-bodied and scoliotic girls.

335

### 336 **Conclusion**

337 The existence of palindromic strings in standing posture supports the assumption of organized  
338 balance processes. Able-bodied subjects seem to primary favor palindromic zones located along  
339 the antero-posterior orientation suggesting an ankle balance modality. Girls with a moderate  
340 scoliosis still privilege the palindromic zones in the antero-posterior extremities with excursions  
341 in the corners of a crisscross grid. Girls with severe scoliosis further relied on the extremities of  
342 the medio-lateral zones when the palindromic string repetitions were excluded. It appears that  
343 scoliotic groups adapted a wobbling standing balance where the CoP shifts to different areas of



344 the base of supports. This subscribes to more than a two-mode standing balance modality.  
345 Generally, standing balance control in girls follows organized pathways in different zones of the  
346 base of support rather than privilege an axial directional strategy.

347

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353

354

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- 486

Figure and table legends

487

488

489 **Fig. 1:** Steps for creating the neutral zone around a CoP trajectory, a) CoP trajectory b) mean  
490 CoP definition represented by a dot, c) neutral zone creation, d) identification of CoP position  
491 regarding to the neutral zone, e) COP trajectory (grey) and fifty-one values of COP (black)  
492 starting from the triangle to the plus sign resulting in an example of a palindromic string  
493 sequence: TTT TTT TTT TAA AAA AAA AAA AAA GGG GGG GGG GGG CCC CCC CCT  
494 TTT TTT. The dashed lines delimit the eight zones of the CoP outside the neutral zone. The  
495 letters in the figure are defined in the text.

496

497 **Fig. 2:** GATC distribution (%) over the complete palindromic string for each group. Statistically  
498 significant differences were not reported on the figure for clarity purpose.

499

500 **Fig. 3:** Schematic illustrations of the highest frequency CoP shifts where the size of the circle is  
501 representative to its frequency in each zone while the double headed arrows indicate the antero-  
502 posterior (vertical), medio-lateral (horizontal) and crisscross (X-shape) zone orientations. The  
503 GATC letters are defined in the text. A: able-bodied, B: moderate scoliosis, C: severe scoliosis

504

505 **Fig. 4:** GATC distribution (%) over the palindromic string after reduction for each group.

506 Statistically significant differences were not reported on the figure for clarity purpose.

507

508 **Table 1:** Mean and standard deviations (SD) for age, height, mass for the three subject groups  
509 and Cobb angle and range for the two scoliosis groups. AB: able-bodied.



510

511 **Table 2:** Mean (SD) number and length for the complete and reduced palindromic strings  
512 of able-bodied and scoliosis groups.

513

514 **Table 3:** p values of the statistical comparisons between the relative contribution of each  
515 component of the complete (a) and reduced (b) palindromic strings. G: neutral zone. A: antero-  
516 posterior direction. C: coronal or medio-lateral orientation. T: tilted or diagonal areas. AB: able-  
517 bodied.

518

519 **Table 4:** p values of the statistical comparisons between the distribution of the CoP positions in  
520 the four zones for the complete and reduced palindromic strings. G: neutral zone, A: antero-  
521 posterior direction, C: coronal or medio-lateral orientation, T: tilted or diagonal areas. AB: able-  
522 bodied.

523

524

525 Table 1

|                      | AB          | Moderate scoliosis | Severe scoliosis |
|----------------------|-------------|--------------------|------------------|
| Age (years)          | 13.1 (1.4)  | 12.2 (2.0)         | 13.1 (1.4)       |
| Height (cm)          | 156.8 (6.9) | 149.6 (10.1)       | 157.4 (10.1)     |
| Mass (kg)            | 45.9 (7.7)  | 40.0 (8.2)         | 45.8 (10.1)      |
| Cobb angle (°)       |             | 17.7 (5.7)         | 36.4 (6.6)       |
| Cobb angle range (°) |             | 5.7                | 15.0             |

526

527

528

529 Table 2

|                    | Number complete | Number reduced | Length complete | Length reduced |
|--------------------|-----------------|----------------|-----------------|----------------|
| AB                 | 3746.7 (106.8)  | 14.5 (36.9)    | 62.6 (10.9)     | 7.9 (3.1)      |
| Moderate scoliosis | 3661.4 (139.7)  | 26.0 (40.4)    | 52.8 (16.2)     | 9.5 (4.0)      |
| Severe scoliosis   | 3699.2 (130.2)  | 21.1 (21.9)    | 55.3 (19.6)     | 8.4 (3.7)      |

530

531

532

533 Table 3  
 534

a

| Within groups | Complete strings | AB    | Moderate scoliosis | Severe scoliosis |
|---------------|------------------|-------|--------------------|------------------|
| G             | C                | 0.000 | 0.000              | 0.108            |
|               | A                | 0.007 | 0.048              | 0.004            |
|               | T                | 0.000 | 0.518              | 0.900            |
| C             | G                | 0.000 | 0.000              | 0.108            |
|               | A                | 0.000 | 0.000              | 0.000            |
|               | T                | 0.000 | 0.000              | 0.001            |
| A             | G                | 0.007 | 0.048              | 0.004            |
|               | C                | 0.000 | 0.000              | 0.000            |
|               | T                | 0.000 | 0.001              | 0.068            |
| T             | G                | 0.000 | 0.518              | 0.900            |
|               | C                | 0.000 | 0.000              | 0.001            |
|               | A                | 0.000 | 0.001              | 0.068            |

b

| Within groups | Reduced strings | AB    | Moderate scoliosis | Severe scoliosis |
|---------------|-----------------|-------|--------------------|------------------|
| G             | C               | 0.000 | 0.021              | 0.358            |
|               | A               | 0.008 | 0.039              | 0.009            |
|               | T               | 0.009 | 0.900              | 0.900            |
| C             | G               | 0.000 | 0.021              | 0.358            |
|               | A               | 0.000 | 0.000              | 0.007            |
|               | T               | 0.000 | 0.037              | 0.010            |
| A             | G               | 0.008 | 0.039              | 0.009            |
|               | C               | 0.000 | 0.000              | 0.007            |
|               | T               | 0.007 | 0.026              | 0.343            |
| T             | G               | 0.009 | 0.900              | 0.900            |
|               | C               | 0.000 | 0.037              | 0.010            |
|               | A               | 0.007 | 0.026              | 0.343            |

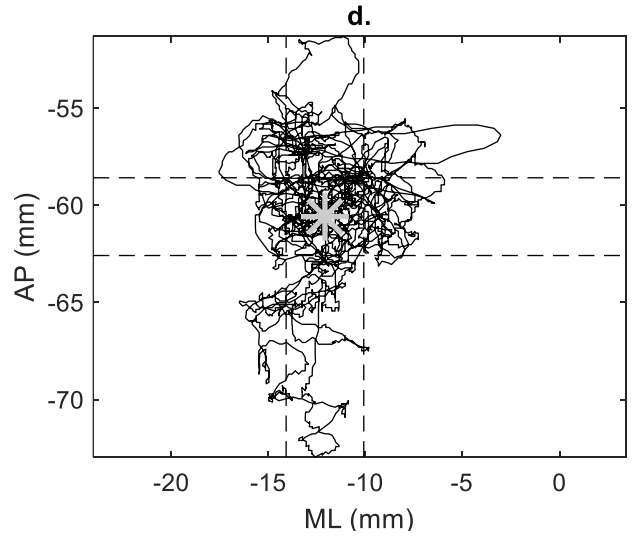
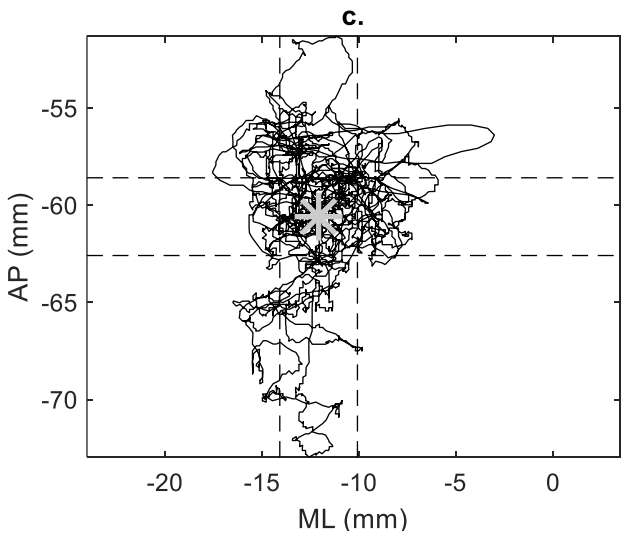
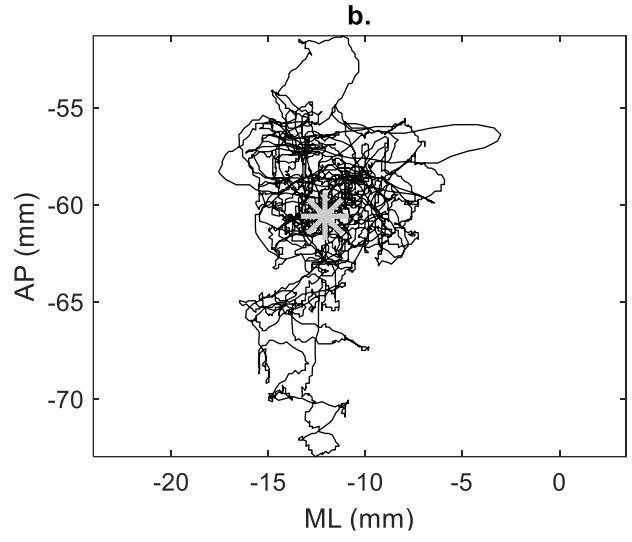
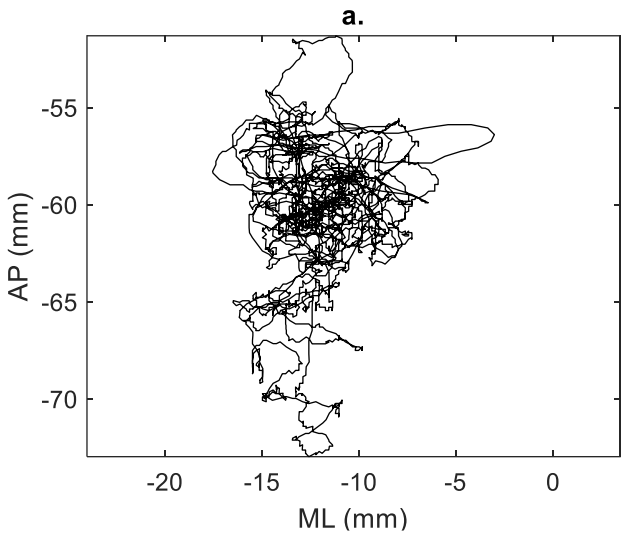
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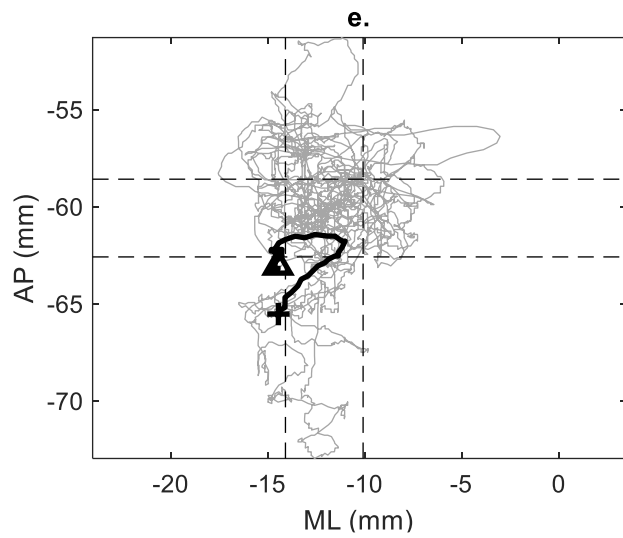
538 Table 4  
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| Between groups     | Complete strings   | G     | C     | A     | T     |
|--------------------|--------------------|-------|-------|-------|-------|
| AB                 | Severe scoliosis   | 0,006 | 0,002 | 0,189 | 0,006 |
|                    | Moderate scoliosis | 1,000 | 1,000 | 1,000 | 0,159 |
| Severe scoliosis   | AB                 | 0,006 | 0,002 | 0,189 | 0,006 |
|                    | Moderate scoliosis | 0,126 | 0,003 | 1,000 | 0,852 |
| Moderate scoliosis | AB                 | 1,000 | 1,000 | 1,000 | 0,159 |
|                    | Severe scoliosis   | 0,126 | 0,003 | 1,000 | 0,852 |

| Between groups     | Reduced strings    | G     | C     | A     | T     |
|--------------------|--------------------|-------|-------|-------|-------|
| AB                 | Severe scoliosis   | 0,114 | 0,400 | 0,412 | 0,037 |
|                    | Moderate scoliosis | 1,000 | 1,000 | 1,000 | 0,001 |
| Severe scoliosis   | AB                 | 0,114 | 0,400 | 0,412 | 0,037 |
|                    | Moderate scoliosis | 0,787 | 0,524 | 0,604 | 0,761 |
| Moderate scoliosis | AB                 | 1,000 | 1,000 | 1,000 | 0,001 |
|                    | Severe scoliosis   | 0,787 | 0,524 | 0,604 | 0,761 |

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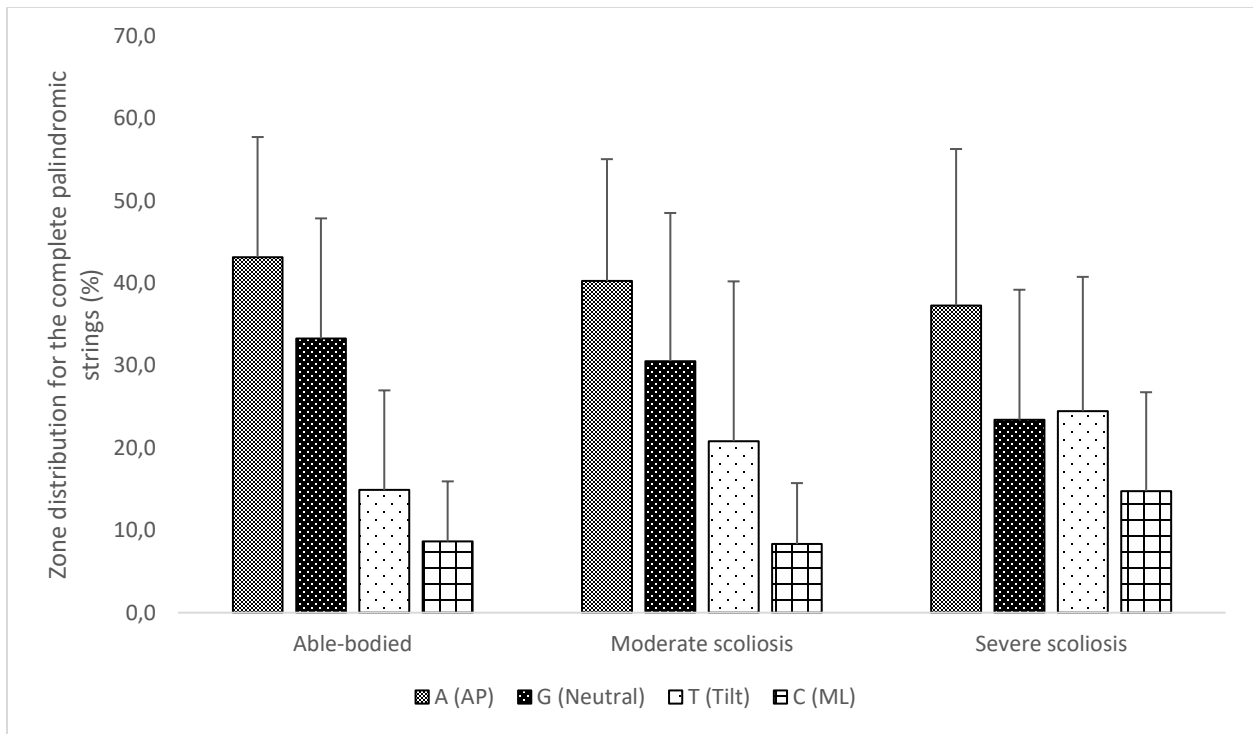




544

545 Fig. 1

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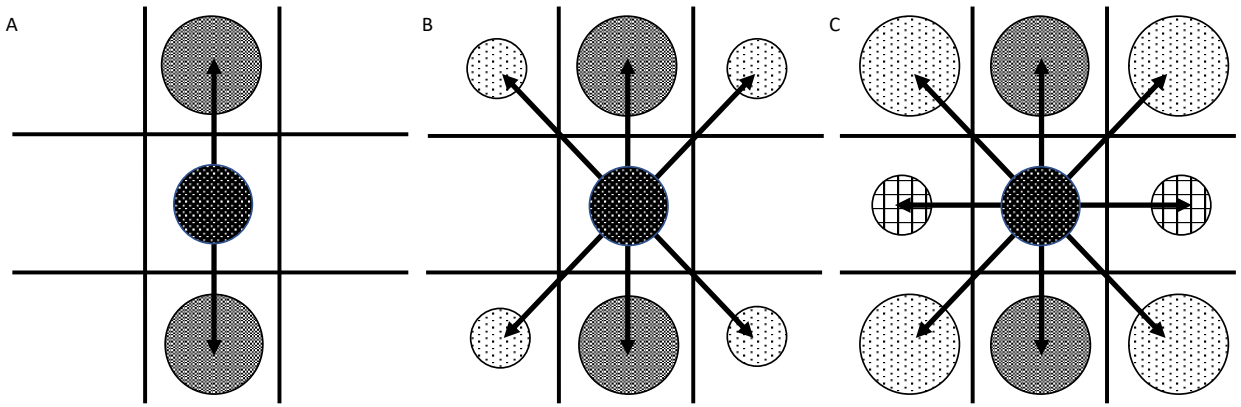
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548 Fig. 2

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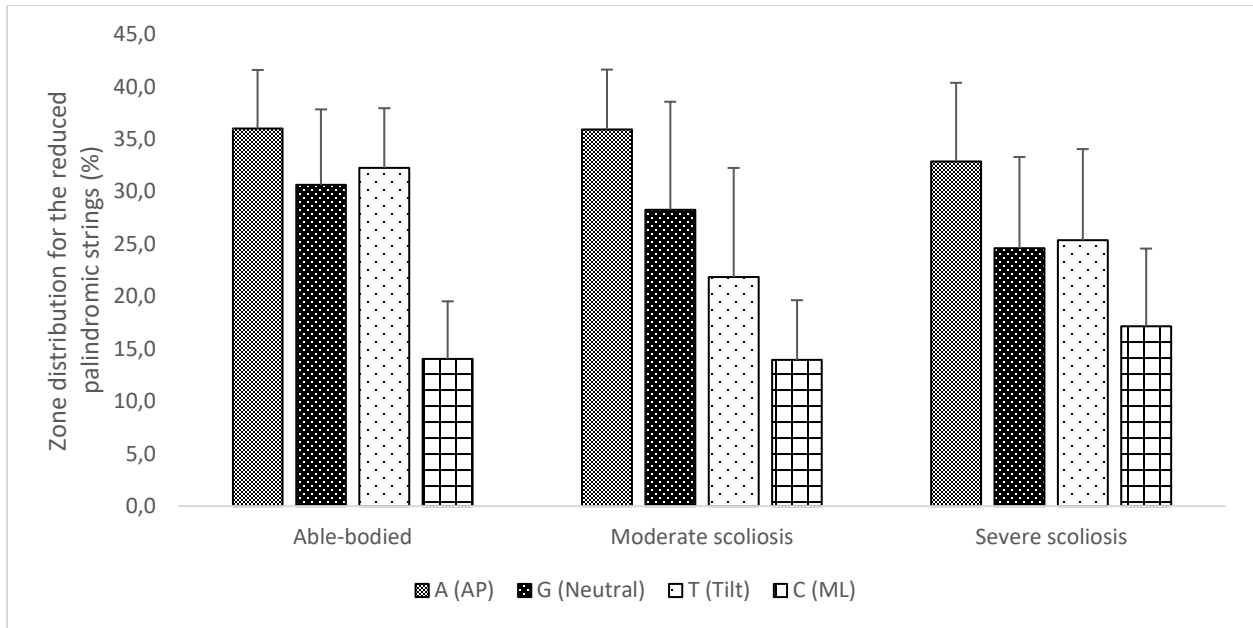


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552 Fig. 3

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556 Fig. 4

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