



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

Sébastien Leteneur, Mathias Blandeau, Franck Barbier, Nader Farahpour, Paul Allard

► To cite this version:

Sébastien Leteneur, Mathias Blandeau, Franck Barbier, Nader Farahpour, Paul Allard. Center of pressure palindromes reveals a wobbling standing balance in scoliotic girls. *Clinical Biomechanics*, 2024, 113, pp.106217. 10.1016/j.clinbiomech.2024.106217 . hal-04501129

HAL Id: hal-04501129

<https://uphf.hal.science/hal-04501129>

Submitted on 12 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Abstract

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

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

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

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

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

Introduction

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

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

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

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

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

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

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

Method

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

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

PLEASE INSERT TABLE 1 ABOUT HERE

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

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

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

PLEASE INSERT FIG 1 ABOUT HERE

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

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

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

Results

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

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

PLEASE INSERT TABLE 2 ABOUT HERE

The GATC zone distribution for the complete palindromic strings for each group is shown in Fig.2 and their respective p values are reported in table 3a. Generally, the pattern of CoP for all groups in decreasing order was A (AP), G (Neutral), T (Tilt) and C (ML) consecutively. In able-bodied girls, these zones were all statistically significant from one another ($p\leq0.007$). The CoP GATC proportion in the A (43,2%) and G (33.3%) areas represented 76.5% of all changes and 91.4% if the T zones were included. Subjects with a moderate scoliosis displaced their CoP mostly in the A zones which was significantly larger than those in the other zones ($p\leq0.048$). The shifts in the G and T areas were similar ($p=0.518$) and these were greater than in the C sections ($p\leq0.001$). For these subjects, the repetitions in the A zones were 40.3%, in the G one 51.4% and with the T areas, it was 91.7%. The group with severe scoliosis exhibited similar CoP zone changes as for the moderate scoliotic group. Their CoP zone shifts were mostly in the A zones which were significantly larger than those in the G and C sections ($p\leq0.004$). Shifts in the G and T areas were similar ($p\geq0.900$) and T zone was greater than in the C zones ($p\leq0.001$). These subjects presented 37.3% recurrences in the A and 47.9% in the G areas. With the T zone it was

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

PLEASE INSERT FIG 2 ABOUT HERE

PLEASE INSERT FIG 3 ABOUT HERE

PLEASE INSERT FIG 4 ABOUT HERE

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

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

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

Discussion

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

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

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

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

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

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

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

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

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

Conclusion

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

the base of supports. This subscribes to more than a two-mode standing balance modality.

Generally, standing balance control in girls follows organized pathways in different zones of the base of support rather than privilege an axial directional strategy.

Acknowledgements

The authors wish to express their gratitude to Mrs. Inda Kore for her technical assistance. This work was supported by the ELSAT2020 project, the European Union with the European Regional Development Fund, the French state and the Hauts-de-France Region Council: the authors gratefully acknowledge the support of these institutions.

References

1. Allard P, Chavet P, Barbier F, Gatto L, Labelle H et al. (2004) Effect of body morphology on standing balance in adolescent idiopathic scoliosis. *Am J Phys Med Rehabil* 83: 689–697. doi:10.1097/01.PHM. 0000137344.95784.15. PubMed: 15314533.
2. Allard P, Nault ML, Hinse S, et al: Relationship between morphologic somatotypes and standing posture equilibrium. *Ann Hum Biol* 2001;28:624 –33.
3. Allard, P., Leteneur, S., Watelain, E. and Begon, M. (2017). Urban legends in gait analysis. *Movement and Sport Science* 98, 5-11.
4. Amblard, B., Crémieux, J., Marchand, A.R. et al. Lateral orientation and stabilization of human stance: static versus dynamic visual cues. *Exp Brain Res* **61**, 21–37 (1985). <https://doi.org/10.1007/BF00235617>

- 366 5. Baratto L, Morasso PG, Re C, Spada G (2002) A new look at posturographic analysis in the
367 clinical context: sway-density versus other parameterization techniques. *Motor Control*
368 6:246–270
- 369 6. Beaulieu, M., Toulotte, C., Gatto, L., Rivard, C.-H., Simoneau, M. and Allard, P. (2009)
370 Postural imbalance in non-treated adolescent idiopathic scoliosis at different periods of
371 progression. *European Spine Journal* 18, 38-44.
- 372 7. Bruyneel A-V, Chavet P, Bollini G, Allard P, Mesure S. The influence of adolescent
373 idiopathic scoliosis on the dynamic adaptive behaviour. *Neuroscience Letters*.
374 2008;447:158–63.
- 375 8. Bunnell WP. The Natural History of Idiopathic Scoliosis Before Skeletal Maturity. *Spine*.
376 1986;11:773–6.
- 377 9. Carpenter MG, Franck JS, Winter DA, et al: Sampling duration effects on center of pressure
378 summary measures. *Gait Posture* 2001;13:35–40
- 379 10. Collins, J.J. and De Luca, C.J (1993). Open-loop and closed-loop control of posture: A
380 random-walk analysis of center-of-pressure trajectories. *Experimental Brain Research*, Vol
381 95, pages308–31
- 382 11. Dalleau, G., Allard, M., Beaulieu, M., Rivard, C.-H. and Allard, P. (2007). Free moment
383 contribution to quiet standing in able-bodied and scoliotic girls. *European Spine Journal* 16,
384 1593-1599.
- 385 12. Dufvenberg, M., Adeyemi, F., Rajendran, I. *et al*. Does postural stability differ between
386 adolescents with idiopathic scoliosis and typically developed? A systematic literature review
387 and meta-analysis. *Scoliosis* **13**, 19 (2018). <https://doi.org/10.1186/s13013-018-0163-1>

- 388 13. Federolf, P. A. (2016). A novel approach to study human posture control: “principal
389 movements” obtained from a principal component analysis of kinematic marker data. *J.*
390 *Biomech.* 49, 364–370. doi: 10.1016/j.jbiomech.2015.12.030
- 391 14. Gillet, C., Duboy, J., Barbier, F., Armand, S., Jeddi, R., Lepoutre, F.-X. and Allard, P.
392 (2003) Contribution of the accelerated body masses to able-bodied gait. *American Journal of*
393 *Physical Medicine and Rehabilitation* 82, 101-109.
- 394 15. Goldie, P. A., Bach, T. M., and Evans, O. M., 1989, Force platform measures for evaluating
395 postural control: reliability and validity. *Archives of Physical Medicine and Rehabilitation*,
396 70, 510±517
- 397 16. Gruber AH, Busa MA, Gorton GE, Van Emmerik REA, Masso PD, Hamill J. Time-to-
398 contact and multiscale entropy identify differences in postural control in adolescent
399 idiopathic scoliosis. *Gait & Posture.* 2011;34:13–8.
- 400 17. Hay, D.C. and Wachowiak, M.P. (2017). Analysis of free moment and center of pressure
401 frequency components during quiet standing using magnitude squared coherence. *Human*
402 *Movement Science* Volume 54, August 2017, Pages 101-109
- 403 18. Herman R, Mixon J, Fisher A, et al. Idiopathic scoliosis and the central nervous system: A
404 motor control problem. *Spine* 1985;10:1–12
- 405 19. Haumont, T., Gauchard, G.C., Lascombes, P., Perrin, P.P., 2011. Postural instability in early-
406 stage idiopathic scoliosis in adolescent girls. *Spine (Phila. Pa. 1976)* 36, E847–E854.
407 <http://dx.doi.org/10.1097/BRS.0b013e3181ff5837>.
- 408 20. Jacono, M., Casadio, M., Morasso, P.G. and Sanguineti, V. (2004). The Sway-Density Curve
409 and the Underlying Postural Stabilization Process. *Motor Control*, 8, 292-311.

21. Jamison, M., Glover, M., Peterson, K., DeGregorio, K., King, K., Danelson, K., O’Gara, T. (2022). Lumbopelvic postural differences in adolescent idiopathic scoliosis: A pilot study, *Gait & Posture* 29, 73-77, ISSN 0966-6362, <https://doi.org/10.1016/j.gaitpost.2022.01.002>.
22. Johansson, J. , Jarocka, E. , Westling, G. , Nordström, A. , & Nordström, P. (2019). Predicting incident falls: Relationship between postural sway and limits of stability in older adults. *Human Movement Science*, 66, 117–123. ISSN 01679457. [10.1016/j.humov.2019.04.004](https://doi.org/10.1016/j.humov.2019.04.004)
23. Karami, M.V., Aboutorabi, A., Ebrahimzadeh, K., Arazpour, M., Asare, E. The effect of orthotic interventions on balance performance in adolescent idiopathic scoliosis: A systematic literature review. *Assistive Technology* Pages 260-267 | Accepted 11 Oct 2018, Published online: 02 Jan 2019 <https://doi.org/10.1080/10400435.2018.1539419>.
24. LeBlanc R, Labelle H, Rivard CH, Poitras B (1997) Relation between adolescent idiopathic scoliosis and morphologic somatotype. *Spine* 22:2532–2536
25. Lee, J.-U., Kim, M.-Y., Kim, J. Comparison of static plantar foot pressure between healthy subjects and patients with adolescent idiopathic scoliosis, *Toxicol. Environ. Health Sci.* 6 (2014) 127–132.
26. Lestienne, F.G. and Gurfinkel, V.S. (1988) Posture as an organizational structure based on a dual process: a formal basis to interpret changes of posture in weightlessness. *Progress in brain research*, 76, 307-313.
27. Leteneur, S., Simoneau-Buessinger, É., Barbier, F., Rivard, C.-H. and Allard, P. (2017). Effect of natural sagittal trunk lean on standing balance in untreated scoliotic girls. *Clinical Biomechanics* 49, 107-112.

28. Leteneur, S., Crémoux, S., Allard, P., Simoneau, É.M., Farahpour, N. and Barbier, F. (2019). Frequency coherence analysis of postural balance in able-bodied and in non-treated adolescent idiopathic scoliotic girls. *Clinical Biomechanics* 67, 180-186.
29. Lonstein JE, Carlson M (1984) The prediction of curve progression in untreated idiopathic scoliosis during growth. *J Bone Jt Surg* 66:1061–1071
30. Mandelbrot BB, van Ness JW (1968) Fractional Brownian motions, fractional noises and applications. *SIAM Rev* 10:422-437
31. McIlroy WE, Maki BE: Preferred placement of the feet during quiet stance: Development of a standardized foot placement for the balancing test. *Clin Biomech* 1997;12:66–70
32. Nault ML, Allard P, Hinse S, et al: Relationships between standing stability and body posture parameters in adolescent idiopathic scoliosis. *Spine* 2002;27: 1911–7.
33. Piątek-Krzywicka, E., Borzucka, D. & Kuczyński, M. Postural control through force plate measurements in female AIS patients compared to their able-bodied peers. *Sci Rep* 12, 13170 (2022). <https://doi.org/10.1038/s41598-022-17597-y>
34. Quijoux F, Nicolai A, Chairi I, Bargiotas I, Ricard D, Yelnik A, Oudre L, Bertin-Hugault F, Vidal PP, Vayatis N, Buffat S, Audiffren J. A review of center of pressure (CoP) variables to quantify standing balance in elderly people: Algorithms and open-access code. *Physiol Rep*. 2021 Nov;9(22):e15067. doi: 10.14814/phy2.15067. PMID: 34826208; PMCID: PMC8623280.
35. Rougier, P and Caron, O. Center of gravity motions and ankle joint stiffness control in upright undisturbed stance modeled through a fractional Brownian motion framework. 2000 *J Mot Behav* Dec;32(4):405-13. doi: 10.1080/00222890009601390.

454 36. Sadeghi H, Allard P, Barbier F, Gatto L, Chavet P, Rivard CH, Hinse S, Simoneau M.
455 Bracing has no effect on standing balance in females with adolescent idiopathic scoliosis.
456 Med Sci Monit. 2008 Jun;14(6):CR293-298. PMID: 18509271.

457 37. Sahlstrand T, Ortengren R, Nachemson A (1978) Postural equilibrium in adolescent
458 idiopathic scoliosis. Acta Orthop Scand 49:354–365

459 38. Schmit, J.M., Riley, M.A., Dalvi, A. et al. Deterministic center of pressure patterns
460 characterize postural instability in Parkinson's disease. Exp Brain Res **168**, 357–367 (2006).
461 <https://doi.org/10.1007/s00221-005-0094-y>

462 39. Sharma S. Applied multivariate techniques. University of South Carolina. John Wiley &
463 Sons. Inc, 1996.

464 40. Sim, T., Yoo, H., Lee, D. et al. Analysis of sensory system aspects of postural stability
465 during quiet standing in adolescent idiopathic scoliosis patients. J Neuro Engineering
466 Rehabil **15**, 54 (2018). <https://doi.org/10.1186/s12984-018-0395-6>

467 41. Simoneau, M., Richer, N., Mercier, P., Allard, P. and Teasdale, N. (2006). Sensory
468 deprivation and balance control in adolescent idiopathic scoliosis. Experimental Brain
469 Research 170, 576-582.

470 42. Stokes IAF. Three-dimensional terminology of spinal deformity: A report presented to the
471 Scoliosis Research Society by the Scoliosis Research Society Working Group on 3-D
472 terminology of spinal deformity. Spine 1994;19: 236–48.

473 43. Stylianides. G., Beaulieu, M., Dalleau, G., Rivard, C.-H. and Allard, P. (2012). Iliac Crest
474 Orientation and Geometry in Able-bodied and Non-treated Adolescent Idiopathic Scoliosis
475 Girls with Moderate and Severe Spinal Deformity. ESJ 21, 725-732.

44. Szulc, P., Bartkowiak, P., Lewandowski, J. and Markuszewski, J. The influence of idiopathic scoliosis on load distribution in the foot, *Chirurgia narzadow ruchu i ortopedia polska* 73 (2008) 187–191.
45. Zatsiorsky VM, Duarte M. Instant equilibrium point and its migration in standing tasks: rambling and trembling components of the stabilogram. *Motor Control*. 1999 Jan;3(1):28-38. doi: 10.1123/mcj.3.1.28. PMID: 9924099.
46. Zhu F, Hong Q, Guo X, Wang D, Chen J, Zhu Q, Zhang C, Chen W, Zhang M. A comparison of foot posture and walking performance in patients with mild, moderate, and severe adolescent idiopathic scoliosis. *PLoS One*. 2021 May 17;16(5):e0251592. doi: 10.1371/journal.pone.0251592. PMID: 33999943; PMCID: PMC8128255.

Figure and table legends

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

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

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

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

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

Table 1: Mean and standard deviations (SD) for age, height, mass for the three subject groups 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)
Heigth (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

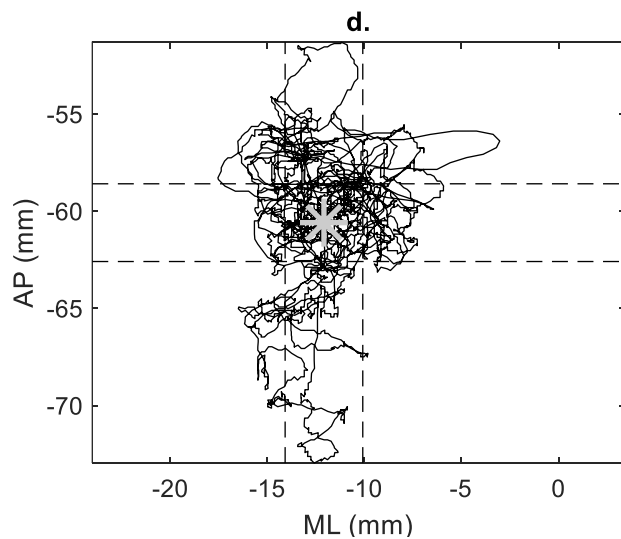
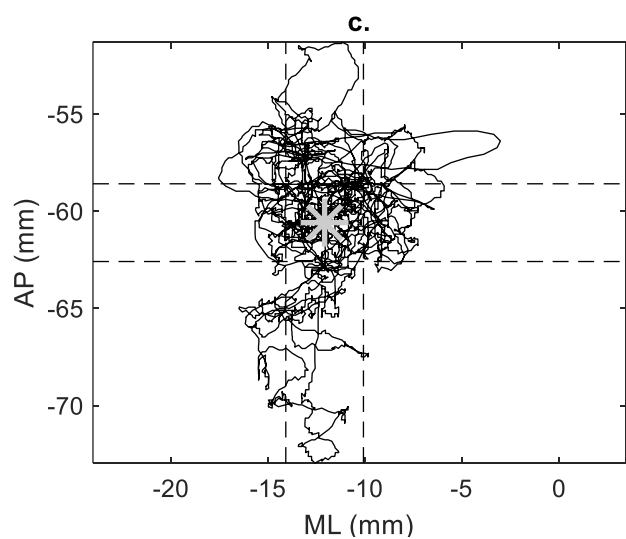
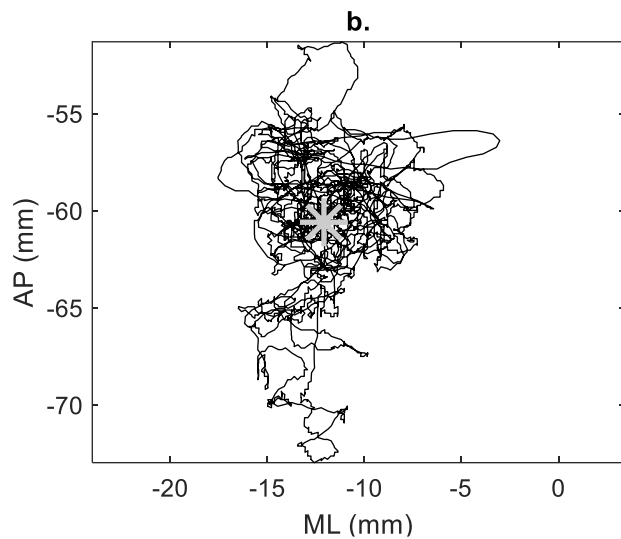
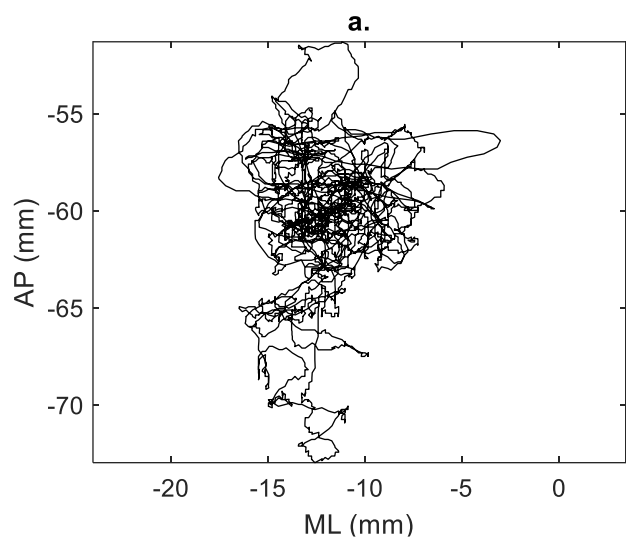
535
536
537

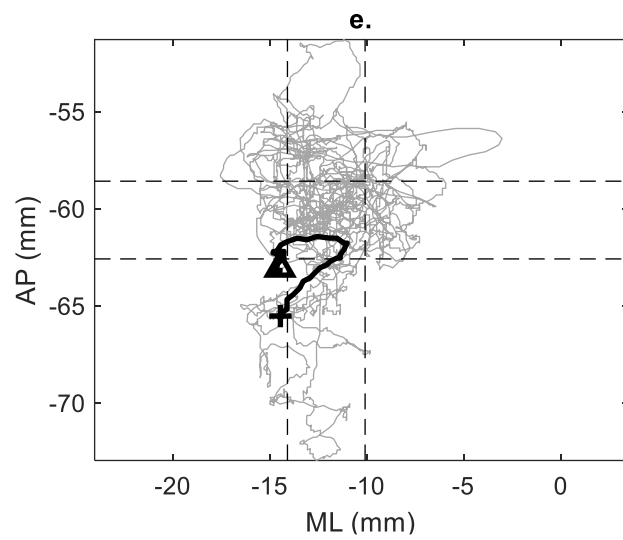
538 Table 4
539
540

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

541
542





544

545 Fig. 1

546

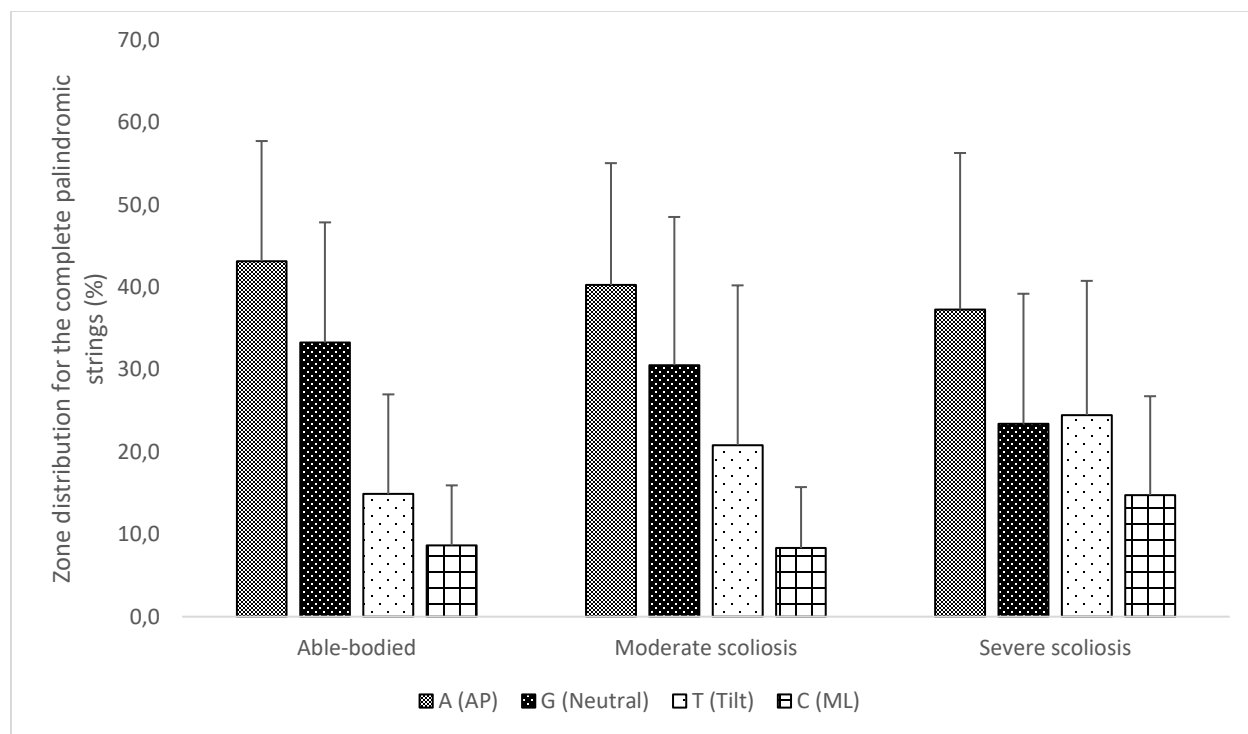


Fig. 2

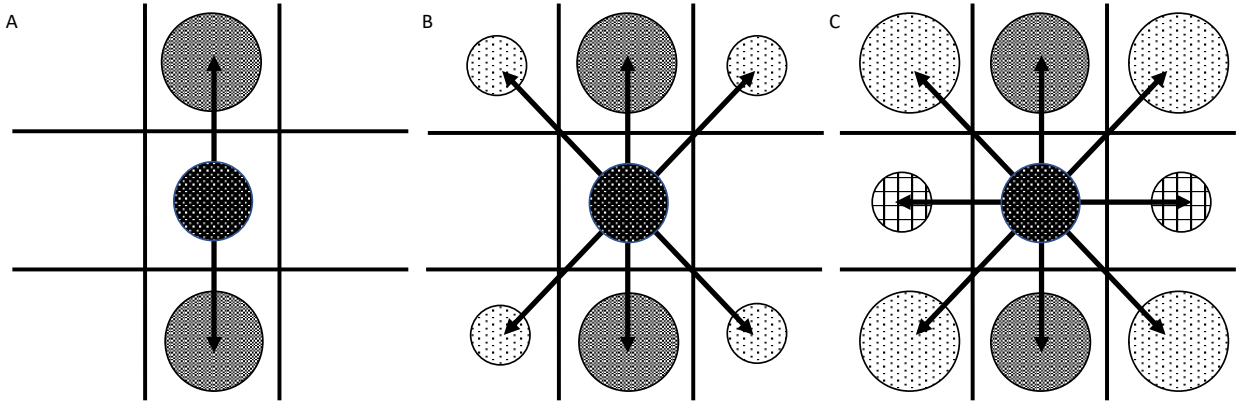


Fig. 3

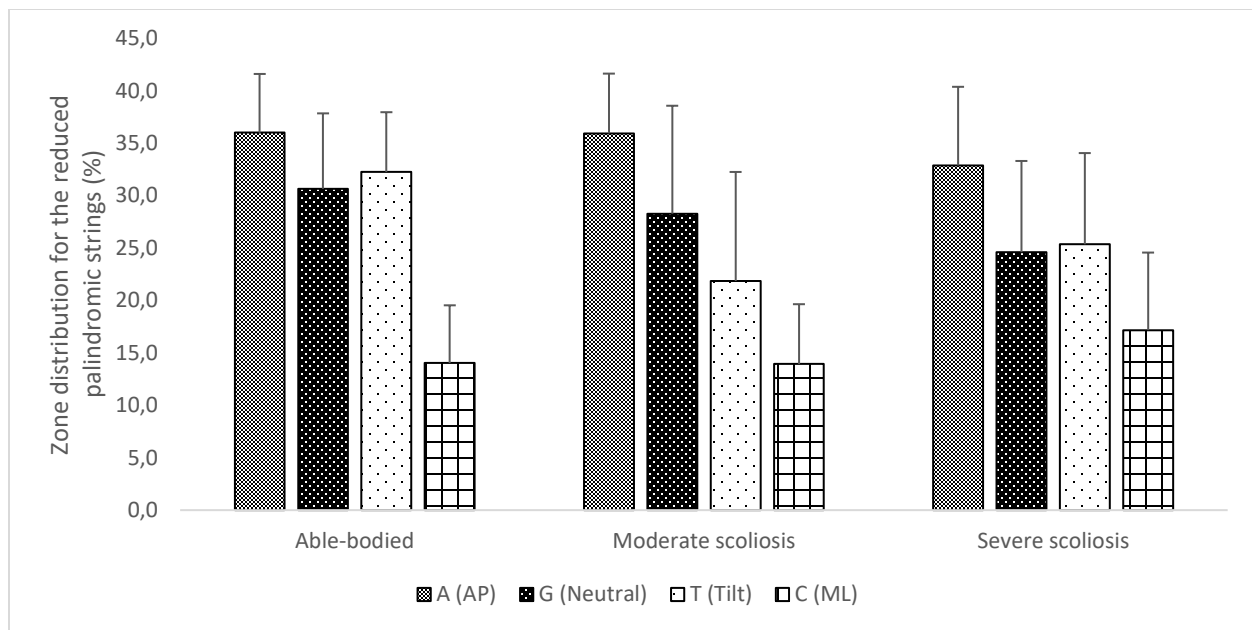


Fig. 4