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To cite this version:

Sebastien Leteneur, Sylvain Cremoux, Paul Allard, Emilie Simoneau-Buessinger, Nader Farahpour, et al.. Frequency coherence analysis of postural balance in able-bodied and in non-treated adolescent idiopathic scoliotic girls. Clinical Biomechanics, Elsevier, 2019, 67, pp.180-186. 10.1016/j.clinbiomech.2019.05.012 . hal-03462893

HAL Id: hal-03462893
https://hal-uphf.archives-ouvertes.fr/hal-03462893

Submitted on 20 Dec 2021

Title:

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Abstract word count: 250 words

Main text word count: 3023 words

Declarations of interest: none

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Abstract

Background: This study test if the frequency coherence calculated for the overall, low and high frequency bandwidths of the center of pressure excursions and free-moment calculated during standing balance are similar between scoliotic and non-scoliotic girls and if the coherence values within each frequency band are comparable for a given group of girls.

Methods: Twenty-nine girls with adolescent idiopathic scoliosis formed the scoliotic group and 22 able-bodied girls formed the non-scoliotic group. Each girl maintained a quiet upright stance on a force plate. Three trials were performed at a sampling frequency of 64 Hz for 64s. Mean anterio-posterior, medio-lateral center of pressure positions and free-moment were measured and their frequency content calculated. The magnitude of the coherence was calculated for each signal pairs for three frequency ranges.

Results: The magnitude of the medio-lateral center of pressure/free-moment coherence in the low and high frequency bands was significantly different between the groups. Within each group, the magnitude of the medio-lateral center of pressure/free-moment coherence was significantly higher than the other two coherence pairs at low frequencies ($P<0.001$). Factor analysis revealed that able-bodied girls exhibited a mixed standing balance modality consisting of posture (center of pressure) and proprioceptive information (free-moment). Scoliotic girls adopted an adaptive modality mostly based on proprioception information to maintain their standing balance.

Interpretation: Scoliotic girls systematically depend on the free-moment to modulate their antero-posterior center of pressure displacements. These results suggest a postural reeducation program aimed at improving proprioception while repositioning the mean center of pressure by postural corrections.

Key Words: scoliosis; posture; proprioception.

Introduction

The quality of upright posture and standing balance is usually assessed by the center of pressure (CoP) position and its displacements. The mean antero-posterior (AP) and medio-lateral (ML) positions of the CoP are associated with body posture (Winter, 1995) whereas the free moment acting at the CoP is representative of upper limbs and trunk control around the vertical axis to maintain standing balance (Beaulieu et al., 2009; Dalleau et al., 2007) Changes in sensory, task, or perturbation conditions affect the CoP excursions (Creath et al., 2005) requiring an effort from the free moment for postural stabilization (Esposti et al., 2010). To our knowledge, no one has studied the relationships between the free moment and CoP displacements in the frequency domain during quiet standing of subjects with scoliosis. Evaluating the spectral relationship between postural parameters such as the CoP positions and proprioceptive information gained through the free moment in subjects with scoliosis could orient clinicians to favor either or both balance modalities in the physical reeducation program and in adapting body braces to prevent scoliosis progression.

Even though spectral analysis was used to evaluate quiet standing (Creath et al., 2005; Zhang et al., 2007), only Hay and Wachowiak (Hay and Wachowiak, 2017) applied this method to assess the interaction between ML and AP centers of pressure and the free moment. Their spectral analysis was performed on data collected from a group of able-bodied adults comprising equally of women and men. They calculated the interaction or frequency coherence between signal pairs comprising of the combination of the ML and AP centers of pressure and the free moment. High coherence values between the CoP displacements and the free moment in different frequency bandwidths suggested adaptations from different parts of the body to regulate upright balance posture.

It is reasonable to assume that a similar approach could be applied to elucidate complex interactions especially in populations such as adolescents with idiopathic scoliosis. The three-dimensional deformation of the spine (Sahlstrand et al., 1978), pelvis distortion (Begon et al., 2015) and body morphology (Allard et al., 2004) are associated with an increased displacement in center of pressure towards the ankle explaining in part their hypokyphotic posture. These morphologic and postural changes lead to standing imbalance (Nault et al., 2002) requiring a corrective torque applied by the trunk and other body segments limbs to counteract standing balance destabilization (Dalleau et al., 2007). Proprioceptive information induces a corrective torque generated through the action of active feedback-control mechanisms (Simoneau et al., 2006a) by the free moment.

Hay and Wachowiak (Hay and Wachowiak, 2017) estimated the degree of the interaction between the CoP and free moment signal pairs by calculating the mean squared coherence as a function of frequency. Then they calculated the confidence interval of each signal to identify the frequencies where statistical differences were present. Following this confidence interval analysis, results were reported to occur at two frequency ranges, namely at low frequencies below 0.5 Hz and at higher frequencies ranging from 0.5 Hz to 1.5 Hz. Based on this study, our approach was to perform a coherence analysis on signals taken at different predetermined frequency bandwidths, namely overall and below and above 0.5 Hz. This has the advantage of focusing the coherence analysis in specific frequency bandwidths rather than identifying them once the coherence analysis is performed.

The objectives of this work were to test if the coherence calculated for the overall, low and high frequency bandwidths between the CoP excursion and its corresponding free moment observed during standing balance of scoliotic and non-scoliotic girls are similar and if the coherence values within each frequency band are comparable within each group of girls. Furthermore, factor analysis was used to identify the frequency coherence variables which best identify balance modalities in the scoliotic and non-scoliotic girl data sets. This approach would allow to evaluate both proprioception and postural corrections that can be proposed in the rehabilitation of scoliotic patients.

Methods

A group of 29 girls diagnosed with adolescent idiopathic scoliosis according to the criteria defined by Bunnel (Bunnel, 1986) participated to this study. Their mean age was 12.7 years (SD 1.8 years) while their height and weight were 153.7 cm (SD 10.7 cm) and 43.0 kg (SD 9.5 kg), respectively. The average Cobb angle was 27.4° (SD 11.3°) and ranged between 11° and 49° and all curves were to the right. No patient was under active treatment at the time of this study. A group of 22 able-bodied girls formed the non-scoliotic group. None had any form of scoliosis and all were in general good health. A subject with a limb length discrepancy of more than 1 cm, wearing a foot orthosis or who displayed any signs of postural, orthopedic or neurological disorders was excluded from the study. This group was comparable in age (13.1 years, SD 1.4 years, *P*=0.285), height (156.8 cm, SD 6.9 cm, *P*=0.204) and weight (45.9 kg, SD 7.7 kg, *P*=0.233) to the scoliotic group. All the girls and their parents signed the informed consent form approved by the hospital ethics committee.

The quality of quiet standing was determined by having each girl maintain a quiet upright stance on an AMTI force plate (Model OR6-5, Newton, MA, USA) with the feet barefoot and positioned with the heels spaced by 23 cm and the toes pointing externally by 15° (McIlroy and Maki, 1997) Each girl focused their eyesight on a target placed at 1.2 m ahead and located at eye level (Allard et al., 2004; Dalleau et al., 2011) with the arms parallel to the trunk. Three trials were performed at a sampling frequency of 64 Hz for a duration of 64 s (Nault et al., 2002).

From the forces and moments measured by the force plate, the anterio-posterior (AP) and medio-lateral (ML) center of pressure (CoP) positions were calculated with respect to the center of the force plate at each instant of a trial. The free moment (Tz) is the moment acting at the CoP along the vertical axis. It is calculated from the vertical moment and the moments resulting from the antero-posterior and medio-lateral forces acting at the origin of the force plate (Dalleau et al., 2007) The mean anterio-posterior (CoP_{AP}) and medio-lateral (CoP_{ML}) center of pressure positions were calculated for each subject from their respective trials.

The CoP excursion in the AP and ML directions and the corresponding free moments were processed as individual signals as shown in Fig 1 and 2. Each $\mathrm{CoP_{AP}}$, $\mathrm{CoP_{ML}}$ and $\mathrm{T_Z}$ signals were filtered with a zero-lag 4th order Butterworth low-pass filter having a 20 Hz cut-off frequency (Fig. 1 A to C). Then each signal was divided into six 10s epochs. This was performed for the three trials totaling in 18 epochs per subject per signal type ($\mathrm{CoP_{AP}}$, $\mathrm{CoP_{ML}}$ and $\mathrm{T_Z}$). Afterwards, the mean epoched signal was calculated and removed from each signal to obtain a zero-centered epoched $\mathrm{CoP_{AP}}$, $\mathrm{CoP_{ML}}$ and $\mathrm{T_Z}$ signals (Fig. 1 D to F).

PLEASE INSERT FIG 1 ABOUT HERE

The wavelet auto-spectrum of each zero-centered epoched signal (Fig. 2A to C) and the wavelet cross-spectrum between each zero-centered epoched signal (Fig. 2 D to F) were obtained with a Morlet wavelet transform (Gasq et al., 2015) yielding a 0.16 Hz to 8.00 Hz frequency band in 0.05 Hz steps. This frequency bandwidth corresponds to the overall frequency range of the whole signal. The wavelet magnitude-squared coherences, $R^2_{X,Y}(\omega, u)$, are shown in Fig. 2 G to I. The wavelet cross-spectrum normalized by the wavelet auto-spectrum of each signal, was obtained by

$$R^2_{X,Y}(\omega, u) = \frac{\left|S_{X,Y}(\omega,u)\right|^2}{S_X(\omega,u)S_Y(\omega,u)},$$

where $S_{X,Y}(\omega, u)$ is the wavelet cross-spectrum between *X* and *Y* signals ($\mathrm{COP_{AP}}$, $\mathrm{COP_{ML}}$ and $\mathrm{T_Z}$ signals) and $S_X(\omega, u)$ and $S_Y(\omega, u)$ are the wavelet auto-spectrum of each *X* and *Y* signals at frequency ω and time u.

PLEASE INSERT FIG 2 ABOUT HERE

To properly quantify the magnitude of the CoP_{AP}-CoP_{ML}, CoP_{AP}-T_Z and CoP_{ML}-T_Z coherences, values were averaged only where significant correlations between two signals were detected as significant on the wavelet cross-spectrum (Bigot et al., 2011). For each signal pairs, the magnitude of the coherence was averaged over the entire time period for three frequency bands: overall frequency band (0.16-8.00 Hz), low frequency band (0.16-0.50 Hz) and high frequency band (0.50-8.00 Hz) respectively. The 0.5 Hz demarcation frequency was based on the results reported by Hay and Wachowiak (Hay and Wachowiak, 2017).

Independent one-way ANOVA was performed on the mean CoP positions and the 9 coherence values (3 pairs and 3 frequencies) to compare the able-bodied and the scoliotic groups. Another one-way ANOVA was performed to compare the magnitude of the coherence values between each signal pairs, CoP_{AP}-CoP_{ML}, CoP_{AP}-T_Z and CoP_{ML}-T_Z independently for each frequency band and subject group. A Bonferroni correction procedure was applied to control Type 1 error by adjusting the P values in the analysis (Holland and Copenhaver, 1988) and a P value of 0.05 or smaller was considered statistically significant. Finally, a factor analysis was carried out for each subject to estimate the relative contribution of the coherence relationships. Factors with an eigenvalue greater than 1 and variables with a factor loading of 0.7 or above were considered as statistically significant (Sadeghi, 2000).

Results

Table 1 presents the average values of the mean CoP and those of the coherence values for the three comparisons pairs for each of the three frequency bands. Though the mean medio-lateral CoP of the scoliotic group was more centered than that of the able-bodied subjects, it was not statistically significant. This could be due in part to its large standard deviation. However, the scoliotic girls maintained a more rearward CoP position than the non-scoliotic girls by 11.6 mm. Only the magnitudes of the CoP_{ML}-T_Z coherence were significantly different in the low and high frequency bands. It appears that the scoliotic group displayed a greater dependence on free moment at low frequencies and lesser one at higher frequencies.

PLEASE INSERT TABLE 1 ABOUT HERE

When comparing the magnitude coherence pairs at different frequency bands but within each subject group, only the magnitude of the CoP_{AP}-T_Z coherence was significantly higher than the magnitude of the other two coherence pairs at low frequencies ($P<0.001$), as shown in Fig. 3. The overall frequency and the high frequency bands do not present any statistical difference.

PLEASE INSERT FIG 3 ABOUT HERE

Factor analysis revealed that only three principal components (PC) were necessary to explain 83% and 80% of the variance in the able-bodied and scoliotic girls respectively.

The frequency coherence pairs of the able-bodied group are well distributed among the three PCs as shown in Table 2. It seems that this group favored a mixed standing balance modality of posture and proprioceptive information. However, the first two PCs included coherence pairs in the overall and high frequency bandwidths whereas the coherences calculated in the low band frequency range were in the third PC.

The scoliotic girls adopted an adaptive modality based on the free-moment to maintain their standing balance. Regardless of frequency band, they principally relied (first PC) on the interaction between the free moment and the CoP_{AP} to preserve their standing balance, implying a greater dependence on proprioception information. All the coherence CoP pairs were grouped in the second PC emphasizing a postural balance modality. The medio-lateral CoP dependence on the free moment occurred in the third PC.

PLEASE INSERT TABLE 2 ABOUT HERE

Discussion

Standing imbalance in adolescent idiopathic scoliosis girls has been well documented (Sahlstrand et al., 1978). Both the position of the CoP characterizing standing body posture and its linear displacements have been associated with axial torsion of the spine and trunk (Gauchard et al., 2001) and perturbed proprioception (Simoneau et al., 2006b). These observations reflect an imbalance around the vertical axis characterized by the free moment (Dalleau et al., 2007). The relationships between the CoP linear excursion and the free moment were documented by Hay and Wachowiak (Hay and Wachowiak, 2017) within the range of important frequencies in a mixed group of able-bodied adult women and men but they remain unknown in symptomatic populations.

Though the scoliotic group of this study maintained a centered mean medio-lateral CoP position similar to the non-scoliotic girls, they accomplished it with more difficulty. The CoP_{ML} standard deviation was nearly twice as large as that of the able-bodied group. Concomitantly, the magnitude of their CoP_{ML}-T_Z coherence was greater than that of the able-bodied subjects at low frequencies. This reflects a greater use of their hips or trunk rotations to maintain their center of mass over the body midline position and explains in part the large CoP_{ML} standard deviation. This is in agreement with Gage et al. (Gage et al., 2004) and Shiratoni and Aruin (Shiratori and Aruin, 2004) who reported that postural control in standing can be achieved by the whole body moving in a single block or through individual body segment movements to stabilize the joints. Interestingly, smaller mean coherence values in the high frequency band suggest a greater independence between the CoP excursion and the free moment to maintain quiet standing balance in the scoliotic group. At higher frequencies the proprioceptive modality succeeds the postural one (Beaulieu et al., 2009; Dalleau et al., 2007; Hay and Wachowiak, 2017; Simoneau et al., 2006b).

For each group, the magnitude of the coherence between $CoP_{AP,}$ CoP_{ML}, and T_Z was independently compared in the three different frequency ranges. The hypothesis was to ascertain whether a postural or a proprioception modality dominates at a particular frequency range. In both groups, a significantly higher magnitude of coherence was found between the free moment and the antero-posterior displacements in comparison to the other coherence pairs at low frequencies. This suggests an ankle balance strategy necessitating proprioception control from the free moment to maintain standing balance (Hay and Wachowiak, 2017). A greater free moment range and Root Mean Square as well as statistically moderate correlations between the free moment values and the CoP_{AP} displacements were reported in scoliotic girls by Dalleau et al. (Dalleau et al., 2007). The frequency domain analysis not only confirms a high CoP_{AP}-T_Z coherence in scoliotic girls but also in non-scoliotic individuals. Hay and Wachowiak (Hay and Wachowiak, 2017) have suggested that CoP_{AP} and T_Z were strongly correlated at low frequencies in a mixed adult population. Our study confirms this observation in both scoliotic and non-scoliotic girls though no statistical difference was found among the coherence values in the high frequency range. The latter observation could be an age-related factor.

The main difference between both groups lies in the magnitude of CoP_{ML}-T_Z coherence at low and high frequencies. Medio-lateral imbalance has been well documented in scoliotic girls and relatively absent in able-bodied populations (Bruyneel et al., 2008). The need for rearfoot control at heel-strike during gait confirms of medio-lateral function in prosthetic foot designs (Allard et al., 1992; Allard et al., 1995).

Following a factor analysis, it appears that the non-scoliotic girls displayed a mixed balance modality involving proprioception (CoP_{AP}-T_Z) and posture (CoP_{AP}-CoP_{ML}) information distributed among the first two PC. This is not surprising since such a group has no musculoskeletal ailments or neurologic disorders to exacerbate proprioception regulation. In scoliotic girls, the first PC grouped all the CoP_{AP}-T_Z coherences regardless of the frequency band. Postural modality only appears in the second PC with high eigenvalues for coherence between CoP_{AP}-CoP_{ML}. This is not surprising since scoliotic girls assume a 12 mm mean rearward antero-posterior CoP position than the non-scoliotic group exacerbating their balance. Furthermore, it was reported that scoliosis interferes with the mechanisms responsible for sensory reweighting during balance control (Simoneau et al., 2006a). Proprioception was perturbed at the ankle by a vibratory stimulus that deprives subjects from relevant ankle proprioceptive information produced by body sway. The vibrators were activated (sensory deprivation interval) and deactivated (sensory reintegrated interval) while subjects stood on a force plate. It was concluded that scoliotic adolescents have difficulty in dynamically adjusting the weight of the various sensory inputs to tailor the balance control commands following a brief period of sensory deprivation. Balance control dysfunction in scoliotic girls could be the consequence of the three-dimensional deviation of the spine (Nault et al., 2002) and changes in the orientation of various segments (Zabjek et al., 2005), and neuromuscular disfunction (Farahpour et al., 2014; Dobosiewicz, 1997). These observations support the role and the importance of the free moment relationship with the antero-posterior CoP displacements in scoliotic subjects.

Physical conservative treatments of scoliosis are based on manual therapy techniques (Lotan and Kalichman, 2018; Théroux et al., 2017), exercise-based physical therapy (Kalichman et al., 2016) or physical activity (Green et al., 2009). Generally, physical treatments aimed to improve either posture (Penha et al., 2017) or proprioception

(Pialasse et al., 2016; Hazime et al., 2012). To the best of our knowledge there is no guideline on an integrated postural and proprioceptive method in a reeducation program. Results of the present study suggest a postural reeducation program in scoliotic girls aimed at both improving proprioception while repositioning the mean CoP by postural corrections.

Conclusions

Scoliotic girls appear to make a greater use of their hips or trunk rotations to maintain their center of mass over the midline position evidence by a larger free moment and medio-lateral axis coherence value at low frequencies and smaller coherence values at high frequencies. This explains in part the large standard deviation value in scoliotic girls to maintain a centered body CoP position implying postural control deficit. However, both groups strongly privileged an ankle balance strategy to ensure their CoP antero-posterior displacements over the other coherence relationships. In addition, the scoliotic adolescents displayed a significantly higher mean free moment and CoP positions. This could be related to a nearly 12 mm more rearward mean standing CoP position. Factor analysis revealed that scoliotic girls systematically depend on the interaction between the free moment for antero-posterior displacements of the CoP, emphasizing proprioception control. Postural adaptations through the interactions between the $\mathrm{CoP}_{\mathrm{AP}}$ and $\mathrm{CoP}_{\mathrm{ML}}$ positions regardless of the frequency bands were secondary to maintain standing balance. The non-scoliotic girls controlled first their posture by the CoP positions along both axes with the free moment and little by the CoP position. These results primarily suggest a postural reeducation program aimed at improving proprioception while repositioning the mean CoP in scoliotic girls.

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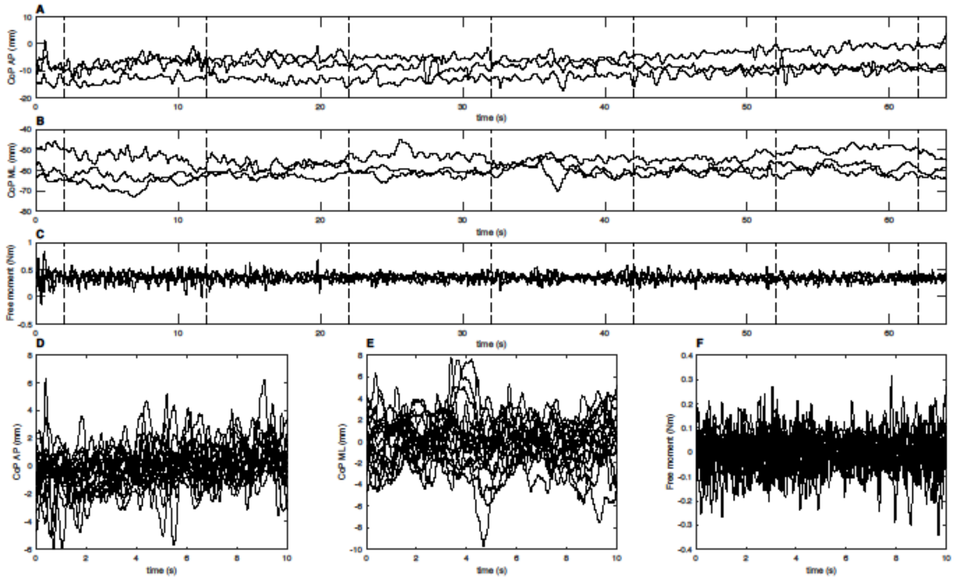


Fig. 1 The displacement of the center of pressure (CoP) in the antero-posterior (A) and mediolateral (B) axes and free moment, T_Z, (C) are shown for three 64 s trial of a non-scoliotic girl. The vertical dashed lines represent six 10s epochs. The signals of 18 10s epochs for the CoP_{AP} (D), CoP_{ML} (E) and T_Z (F) were then combined.

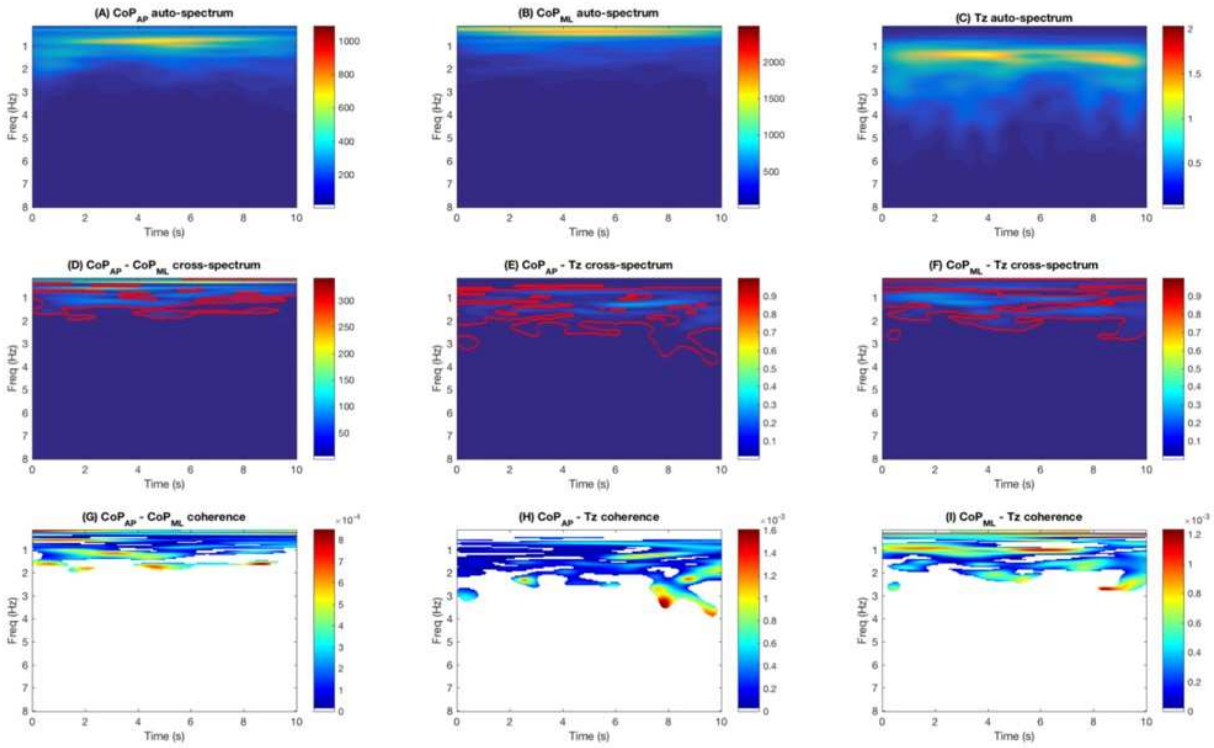
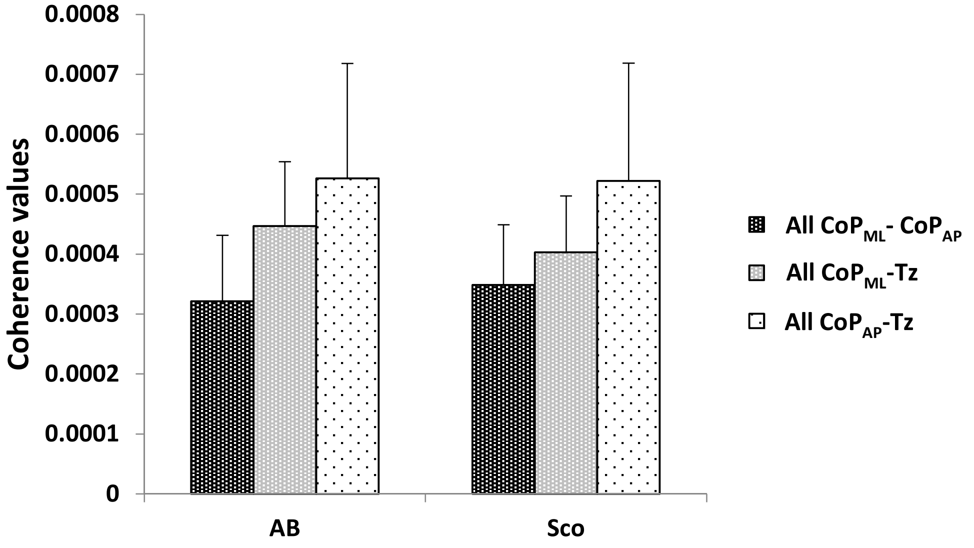
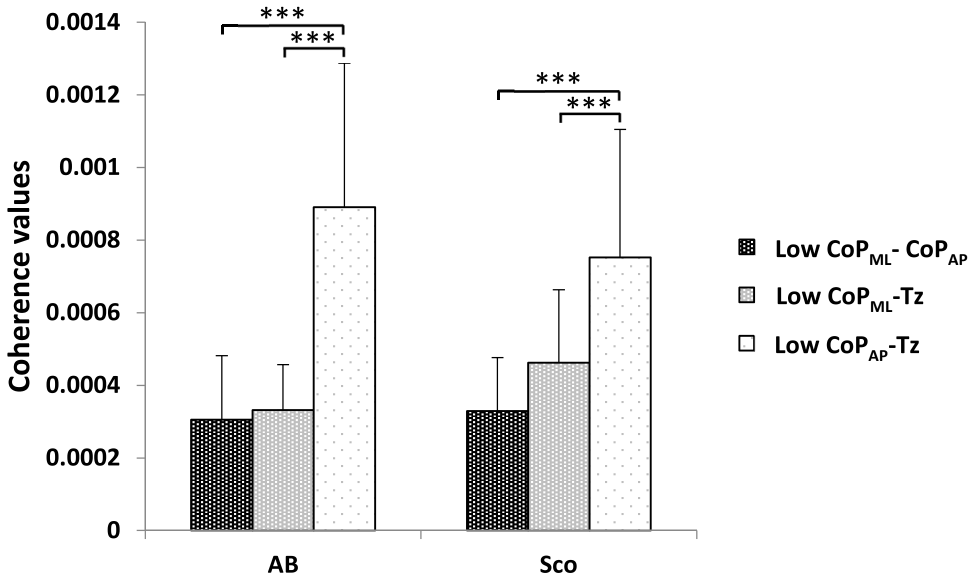


Fig. 2 Typical time-frequency representation of the CoP$_{AP}$, CoP$_{ML}$ and T$_Z$ signals of one scoliotic participant. First row: Wavelet auto-spectra of the CoP$_{AP}$ (A), CoP$_{ML}$ (B) and T$_Z$ (C) signals. Second row: Wavelet cross-spectrum for CoP$_{AP}$-CoP$_{ML}$ (D), CoP$_{AP}$-T$_Z$ (E) CoP$_{ML}$-T$_Z$ (F) signals; the red contours identify the areas in the time-frequency plane where the correlation between the two signals is significant. Third row: Wavelet magnitude-squared coherence for CoP$_{AP}$-CoP$_{ML}$ (G), CoP$_{AP}$-T$_Z$ (H) CoP$_{ML}$-T$_Z$ (I) signals. All non-significant values are whitened. The magnitude of the coherence for each pair was quantified as the mean of significant magnitude-squared coherence over the entire time band in three frequency bands: overall (0.16-8.00 Hz), low (0.16-0.50 Hz) and high bands (0.50-8.00 Hz).

A


Coherence values
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
AB
Sco
All CoP_{ML}- CoP_{AP}
All CoP_{ML}-Tz
All CoP_{AP}-Tz

B


Coherence values
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
***
***
***
***
AB
Sco
Low CoP_{ML}- CoP_{AP}
Low CoP_{ML}-Tz
Low CoP_{AP}-Tz

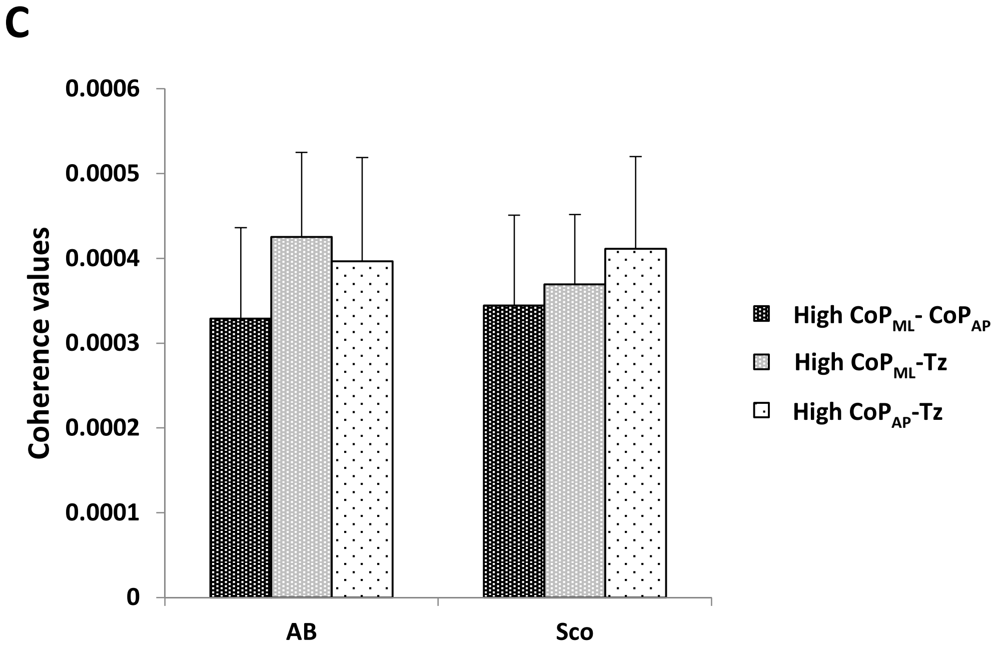


Fig. 3 Coherence values of the able-bodied (AB) and scoliotic (SCO) groups for the overall (A), low (B) and high (C) frequency bands. ***: *P*<0.001.

Table 1 Mean and standard deviation of the CoP positions and coherence pairs for the overall, low and high frequency bands for the able-bodied (AB) and scoliotic (SCO) groups as well as their corresponding *P* values. Note: for display purpose only, all coherence values were multiplied by a 1000 factor. Mean (SD).

	Mean values (mm)		Overall			Low			High		
	CoP_{ML}	CoP_{AP}	CoP_{ML}-CoP_{AP}	CoP_{ML}-T_Z	CoP_{AP}-T_Z	CoP_{ML}-CoP_{AP}	CoP_{ML}-T_Z	CoP_{AP}-T_Z	CoP_{ML}-CoP_{AP}	CoP_{ML}-T_Z	CoP_{AP}-T_Z
AB	-3.1 (8.7)	-61.3 (13.2)	0.32 (0.11)	0.45 (0.11)	0.53 (0.19)	0.31 (0.18)	0.33 (0.12)	0.89 (0.40)	0.33 (0.11)	0.43 (0.10)	0.40 (0.12)
SCO	-2.9 (13.9)	-72.8 (14.7)	0.35 (0.10)	0.40 (0.09)	0.52 (0.20)	0.33 (0.15)	0.46 (0.20)	0.75 (0.35)	0.34 (0.11)	0.37 (0.08)	0.41 (0.11)
P value	0,937	0,005	0,365	0,127	0,941	0,608	0,012	0,197	0,616	0,033	0,665

Table 2 The significant factors and their respective loading values are given for the able-bodied (AB) and scoliotic groups. PC1, PC2, PC3 are the first three principal components of the factor analysis. Values equal or above 0.7 are in bold.

AB	**PC1**	**PC2**	**PC3**
High COP_{AP}-T_Z	**0,918**	-0,074	0,022
All COP_{AP}-T_Z	**0,890**	-0,347	0,122
High COP_{AP}-COP_{ML}	**0,791**	0,345	-0,027
All COP_{ML}- T_Z	-0,057	**0,953**	0,012
High COP_{ML}- T_Z	-0,071	**0,916**	0,040
Low COP_{ML}- T_Z	0,299	0,195	**0,854**
Low COP_{AP}- COP_{ML}	0,425	0,453	-0,642

Scoliotic	**PC1**	**PC2**	**PC3**
All COP_{AP}-T_Z	**0,966**	0,165	0,109
Low COP_{AP}-T_Z	**0,879**	-0,096	0,049
High COP_{AP}-T_Z	**0,790**	0,446	0,144
All COP_{AP}- COP_{ML}	0,050	**0,983**	0,065
High COP_{AP}- COP_{ML}	0,065	**0,833**	0,243
Low COP_{AP}- COP_{ML}	0,141	**0,689**	-0,273
All COP_{ML}- T_Z	0,314	-0,009	**0,910**
High COP_{ML}- T_Z	0,436	0,049	**0,776**
Low COP_{ML}- T_Z	-0,228	0,036	**0,732**