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Spatial and temporal characteristics of the spine muscles activation during walking in patients with lumbar instability due to degenerative lumbar disk disease: Evaluation in pre-surgical setting

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ABSTRACT

Our purpose was to investigate the spatial and temporal profile of the paraspinal muscle activation during gait in a group of 13 patients with lumbar instability (LI) in a pre-surgical setting compared to the results with those from both 13 healthy controls (HC) and a sample of 7 patients with failed back surgery syndrome (FBSS), which represents a chronic untreatable condition, in which the spine muscles function is expected to be widely impaired.

Spatiotemporal gait parameters, trunk kinematics, and muscle activation were measured through a motion analysis system integrated with a surface EMG device. The bilateral paraspinal muscles (longissimus) at L3-L4, L4-L5, and L5-S1 levels and lumbar iliocostalis muscles were evaluated.

Statistical analysis revealed significant differences between groups in the step length, step width, and trunk bending and rotation. As regard the EMG analysis, significant differences were found in the cross-correlation, full-width percentage and center of activation values between groups, for all muscles investigated.

Patients with LI, showed preserved trunk movements compared to HC but a series of EMG abnormalities of the spinal muscles, in terms of left-right symmetry, top-down synchronization, and spatiotemporal activation and modulation compared to the HC group. In patients with LI some of such EMG abnormalities regarded mainly the segment involved by the instability and were strictly correlated to the pain perception. Conversely, in patients with FBSS the EMG abnormalities regarded all the spinal muscles, irrespective to the segment involved, and were correlated to the disease's severity. Furthermore, patients with FBSS showed reduced lateral bending and rotation of the trunk and a reduced gait performance and balance.

Our methodological approach to analyze the functional status of patients with LI due to spine disease with surgical indications, even in more complex conditions such as deformities, could allow to evaluate the biomechanics of the spine in the preoperative conditions and, in the future,

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to verify whether and which surgical procedure may either preserve or improve the spine muscle function during gait.

1. Introduction

A high percentage (more than 80%) of the working-age adult population in the world complains of low back pain (LBP) (Rubin, 2007). Most cases of LBP are associated with degenerative disk disease (DDD) (Luoma et al., 2000, Cheung et al., 2009, Yang, Liao, Shen, & Mei, 2018), including segmental spine instability, which is present in more than half of the patients (Resnick, Haid, & Wang, 2009). Typically, patients with segmental spinal instability due to DDD present with a chronic debilitating axial pain that does not recede after conservative treatments thus even requiring surgery (Madera et al., 2017). However, it has been shown that open surgery can produce iatrogenic deafferentation and denervation of the paraspinal muscles resulting in a reduction in both their geometrical cross-sectional area (CSA) and contractile density (Ghiasi et al., 2016), which can occur in 15% of those with Failed Back Surgery Syndrome (FBSS) (North et al., 1991). Preserving trunk function, by preserving the anatomical and functional integrity of paraspinal muscles, must be a major aim of spine surgery in patients with DDD who have been shown to benefit from even conservative behaviors (Carreon, Glassman, & Howard, 2008; Carreon, Puno, Dimar, Glassman, & Johnson, 2003; Glassman, Berven, Bridwell, Horton, & Dimar, 2005). All the more so because the paraspinal muscles activity greatly contributes to maintain the biomechanical function of the trunk in both static and dynamic conditions. It is known that the trunk has a great functional importance to minimize the magnitude of linear and angular displacement of the head, ensure clear vision (Grossman, Leigh, Abel, Lanska, & Thurston, 1988; Hirasaki, Moore, Raphan, & Cohen, 1999), facilitate the integration of vestibular information (Pozzo, Berthoz, & Lefort, 1990), contributes to the maintenance of balance (Caliandro et al., 2017; Chini et al., 2017; Conte et al., 2014; Prince, Winter, Stergiou, & Walt, 1994; Winter, Mcfadyen, & Dickey, 1991), is a driving force for movement (Gracovetsky, 1985), and creates a more energy-efficient gait pattern (Saunders, Inman, & Eberhart, 1953). Consequently, a biomechanical impairment of the spine muscles might result in ineffective and energy-consuming locomotion.

Therefore, in patients with segmental spinal instability due to DDD, it is essential to objectively evaluate the biomechanical function of the spine muscles during walking, even before the surgery, in order to fully characterize the spine muscle abnormalities in these patients. This would help us in the future to categorize patients for a better evaluation of efficacy of different surgical techniques.

Although few studies have analyzed the electromyographic (EMG) activation of the paraspinal muscles in patients with chronic LBP during walking (Lamoth, Meijer, Daffertshofer, Wuisman, & Beek, 2006; Mueller et al., 2017; Toosizadeh et al., 2015), no studies specifically focused on the DDD and its associated segmental instability.

In the present study, we investigated the trunk kinematics and the spatial and temporal profile of paraspinal muscle activation across the gait cycle in a sample of patients with LI due to DDD in a pre-surgical setting and compared the results to those from both healthy subjects and a sample of patients with FBSS, which represents a chronic untreatable condition, in which the spine muscles function is expected to be widely impaired.

Particularly, we focused on three important aspects of spinal muscle activation during gait: i) left–right symmetry and up-down synchronization; ii) the time–amplitude EMG activation pattern of each paraspinal muscle at different metameric levels; iii) the muscle activation modulation in different gait subphases. Our hypothesis herein was that patients with LI may show abnormalities in some or all of these aspects of muscle activation (when compared to healthy controls), and that such abnormalities may be limited to the spine segment involved (when compared to the patients with FBSS).

2. Methods

2.1. Patients

Thirteen patients (5 men, 8 women; mean age, 60.5 years; range, 25–74 years) with lumbar spine instability (LI) due to DDD were included in the study. Patients were consecutively referred to the Orthopedic and Neurosurgical Unit of the Department of Medical and Surgical Sciences and Biotechnologies of the University of Rome, Sapienza, Latina, from July 2013 to January 2016.

All patients presented axial low-back pain exacerbated by trunk movement. Radicular pain could be present but was not prominent in any case. All patients complained of lumbar pain that persisted for 4–8 weeks after conservative treatment, including rest, anti-inflammatory non-steroidal cycles, and physical therapy for at least 6 months.

Radiological diagnosis was based on MRI and dynamic radiographs, which confirmed mono segmental instability due to DDD: degeneration of the disc was graded using the Pfirrmann classification for all subjects (Urrutia et al., 2016). The affected spinal levels were L3-L4 in 3/13 patients (23.1%), L4-L5 in 8/13 patients (61.5%), and L5-S1 in 2/13 patients 15.4%). Exclusion criteria consisted of an age older than 80 years, previous spinal surgery, severe lumbar stenosis or disk herniation with mono o poli-radicular impairment, spondylolysis, patients receiving worker's compensation, and patients with pluri-segmental DDD and global sagittal unbalance.

We also enrolled a group of 7 patients with FBSS (3 men, 4 women; mean age, 55.7 years; range, 45–63 years). All patients with FBSS had a history of open standard surgery with posterolateral arthrodesis for segmental instability due to DDD L3-L4 in 2/7

patients (28.6%), L4-L5 in 4/7 patients (57.1%), and L5-S1 in 1/7 patients (14.3%).

All patients presented chronic longstanding back pain, with or without referred or radicular symptoms and had one or more surgical interventions that failed to treat the pain according to the criteria previously reported (mean time from last surgery was 54 (7) months) (Baron et al., 2016; Chan & Peng, 2011; Lee et al., 2016; Thomson, 2013).

The research was approved by the local ethics committee (ICOT-ASL2017 Latina, University of Rome, Polo Pontino) and conformed to the Helsinki Declaration. All participants gave their informed written consent. The patients' demographic and clinical data are summarized in Tables 1a and b.

All patients used the visual analogue scale (VAS) and Oswestry Disability Index (ODI; 0–100%, where 0–20% indicate minimal disability; 81–100% complete disability) to determine their functional outcomes (Fairbank & Pynsent, 2000; Fairbank, 2014).

Thirteen healthy subjects were included in the study as a control group (4 men, 9 women; mean age 49.3; range, 27–69 years).

2.2. Instrumental evaluation

2.2.1. Kinematic recordings

Recordings were performed using the optoelectronic SMART-DX 500 motion analysis system (BTS, Milan, Italy). The system detected the motion of 22 passive spherical markers (15 mm in diameter) placed over anatomical landmarks according to Davis et al. (Davis, Õunpuu, Tyburski, & Gage, 1991; Wu et al., 2002).

2.2.2. sEMG recordings

The sEMG signals were recorded with a sampling rate of 1,000 Hz using a 16-channel Wi-Fi transmission surface electromyography (FreeEMG System, BTS, Milan, Italy). After skin preparation, bipolar circular surface electrodes Ag/AgCl (FIAB SpA, Florence, Italy), prepared with electroconductive gel (1 cm diameter, 2 cm distance between electrodes) were placed over the right and left sides of the paraspinal muscles (longissimus) at the L3-L4, L4-L5, and L5-S1 levels and over the right and left sides of the lumbar iliocostalis. Electrodes were placed on the center of the muscle belly, in the direction of the muscle fibers, according to the European Recommendations for Surface Electromyography (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000).

2.3. Procedure

Before the formal measurements began, the participants had a practice session to familiarize themselves with the experimental procedure. Patients were required to walk normally while barefoot at a self-selected speed along a walkway approximately 10 m long.

Assuming that speed was slower in patients, in order to avoid the potential velocity bias, the gait speed was matched between groups as follows: for each control group subject, we considered only those trials in which the gait speed value fell within the range identified by the patients' mean gait speed ± SD (Conte et al., 2012; Mari et al., 2012; Serrao et al., 2013).

Six walking trials per subject were acquired. We rejected the first walking trial and considered the subsequent 5 trials. Each trial was composed by eight strides. However, we took into consideration only the central strides (4 strides for each trial) in order to capture the gait variables during steady state walking. Hence, a total of 20 strides were collected for the final analyses.

To prevent fatigue, trials were separated by a 1-min rest.

2.4. Data analysis

Three-dimensional marker trajectories were acquired using three-dimensional (3-D) acquisition software (Smart Capture, BTS, Milan, Italy) and were labeled using a frame-by-frame tracking system (Tracklab, BTS, Milan, Italy). All data was processed using 3-D

Table 1a
Patients' demographic and clinical data (Lumbar Instability).

Patients	Gender	Age	Height (m)	Weight (kg)	VAS	ODI	Level of lumbar instability
1	M	58	1.77	96	7	49	L4-L5
2	F	74	1.55	59	8	68	L4-L5
3	M	63	1.71	78	9	60	L3-L4
4	F	53	1.55	72	9	74	L4-L5
5	F	25	1.63	55	8	39	L4-L5
6	F	60	1.53	66	7	44	L4-L5
7	M	74	1.63	55	8	56	L5-S1
8	F	72	1.51	58	8	64	L4-L5
9	F	43	1.64	67	7	74	L4-L5
10	M	71	1.57	76	9	60	L3-L4
11	F	58	1.67	75	10	72	L3-L4
12	M	68	1.64	74	9	72	L5-S1
13	F	68	1.49	62	8	70	L4-L5
Means		60.5	1.6	68.7	8.2	61.7	
SD		14	0.1	11.6	0.9	118	

Table 1b
Patients' demographic and clinical data (Fail Back Surgery Syndrome).

Patients	Gender	Age	Height (m)	Weight (kg)	VAS	ODI	Level of lumbar instability
1	M	56	1.59	69	7	75	L4-L5
2	F	59	1.55	79	9	80	L3-L4
3	F	62	1.69	83	10	85	L3-L4
4	M	45	1.84	84	7	65	L4-L5
5	F	63	1.57	75	9	70	L4-L5
6	M	58	1.7	81	9	56	L4-L5
7	F	47	1.53	74	10	65	L5-S1
Means		55.7	1.6	77.9	8.7	70.9	
SD		7.1	0.1	5.4	1.3	9.9	

Table 1c
Healthy controls' demographic data.

Subjects	Gender	Age	Height (m)	Weight (kg)
1	M	27	1.86	75
2	M	63	1.72	82
3	F	45	1.65	49
4	F	55	1.66	54
5	F	50	1.58	52
6	F	40	1.56	63
7	F	36	1.53	50
8	M	46	1.82	80
9	M	39	1.71	69
10	F	45	1.68	61
11	F	69	1.49	51
12	F	60	1.60	49
13	F	66	1.51	62
Means		49.3	1.7	61.3
SD		12.6	0.1	11.9

elaboration software (SMART Analyzer, BTS, Milan, Italy) and MATLAB software (Matlab R2014a, version 8.3, MathWorks, Natick, MA, USA).

2.4.1. Gait parameters

Kinematic data were normalized between the two consecutive heel strikes when reduced to 100 samples in the gait cycle using a polynomial procedure. The following time-distance parameters were considered for the statistical analysis: step length (cm) and width (cm), stance phase duration (%), swing phase duration (%), double support phase duration (%), cadence (step/min), and speed (m/*sec*).

2.4.2. Trunk kinematics

To assess trunk kinematics, we determined the trunk and pelvis joint centers of rotation and calculated them the trunk range of motion (RoM) in the sagittal (flexion–extension), frontal (lateral bending), and transverse planes (rotation) during the gait cycle.

2.4.3. EMG processing

The EMG data were digitally filtered: the lower and upper cut-off frequencies of the Hamming filter were 10 and 400 Hz, respectively.

The acquired EMG signals were processed by subtracting their average value; subsequently, the EMG signals were full-wave rectified and filtered with a zero-lag fourth-order Butterworth with a low pass filter cut-off of 3 Hz (Winter, MacKinnon, Ruder, & Wieman, 1993).

2.4.3.1. Cross-Correlation analysis. To obtain information on the left–right activation symmetry and up-down synchronization, we evaluated the similarity of timing and shape of the EMG signals by using the cross-correlation analysis (Wren, Do, Rethlefsen, & Healy, 2006).

The cross-correlation allows for a stationary first signal, x, while the second signal, y, is time-shifted incrementally forwards for a range of time. The signal x and y are the EMG envelope of two pairs of trunk muscles. A normalized cross-correlation function R_{xy} at each shift of time was calculated using the Nelson-Wong et al. formula (Nelson-Wong, Howarth, Winter, & Callagan, 2009):

$$R_{xy}(\tau) = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})\cdot(y_{i+\tau \cdot f_s} - \bar{y})}{\frac{1}{N}\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{N}(y_i - \bar{y})^2}}$$

where N is the number of data points in the input signal records, τ is the discrete temporal phase shift, and f_s is the frequency at which the original signals were sampled.

R_{xy} revealed the shape similarity between the two signals as a scalar between 0 and 1.

Specifically, to compare the shape of the right and left muscle signals, the R_{xy} curves were calculated between the right and left sides of the iliocostalis and the L3-L4, L4-L5, and L5-S1 paraspinal muscles (longissimus).

The mean of the R_{xy} curves, for each comparison, was used as an index of muscle synchronization.

Using the R_{xy} curves, the synchronization of the trunk muscles was calculated between the following two pairs of trunk muscles for each side:

Erector spinae iliocostalis vs L5-S1;
L3-L4 vs L5-S1;
L4-L5 vs L5-S1;
Erector spinae iliocostalis vs L4-L5;
L3-L4 vs L4-L5;
Erector spinae iliocostalis vs L3-L4.

2.4.3.2. Full-Width percentages. To obtain information on the time–amplitude features of the EMG signals across the gait cycle, we used the full-width (FW) maximum method (Martino et al., 2015). We calculated the FW as the sum of the durations of the intervals in which the EMG activity exceeded 50% (FW50%), 40% (FW40%), 30% (FW30%), 20% (FW20%), and 10% (FW10%) of its maximum.

2.4.3.3. Center of activity. To obtain information on the spatial localization of the EMG signals according to the gait cycle subphases, we used the CoA calculated using circular statistics (Batschelet, 1981; Mari et al., 2014; Martino et al., 2014) and plotting in polar coordinates (with angle ϑ that varies from 0 to 360°). The CoA of the EMG waveform was calculated using the following formula:

$$CoA = \tan^{-1}\left(\frac{\sum_{i=1}^{101} EMG_i \sin \vartheta_i}{\sum_{i=1}^{101} EMG_i \cos \vartheta_i}\right)$$

where i is the i-time point within the gait cycle.

2.5. Statistical analysis

Statistical analyses were performed using SPSS software ver. 20.0 (IBM, Armonk, NY, USA).

Given the small sample, we used non-parametric statistical methods (Dwivedi, Mallawaarachchi, & Alvarado, 2017).

We used the Kruskal-Wallis test to evaluate the differences between groups of the spatiotemporal parameters, trunk kinematics, cross-correlation curve, and FW (50–10%) values.

The Watson–Williams test (Berens, 2009; Fisher, 1995) for circular data was used to investigate between-group differences in EMG CoA activation parameters.

The Spearman coefficient correlation was used to determine the correlation between clinical scales (VAS and ODI) and EMG data, trunk kinematics, and spatiotemporal parameters.

A p-value of < 0.05 was considered as statistically significant.

The power analysis for the relevant variables were measured and reported in Table 3 (Supplementary Materials).

Table 2
Spatio-temporal parameters and trunk kinematics results.

Spatio-temporal parameters	HC		LI		FBSS		Kruskal-Wallis Test	LI vs HC Mann-Whitney	FBSS vs HC Mann-Whitney	FBSS vs LI Mann-Whitney
Variables	Mean	SD	Mean	SD	Mean	SD	p-value	p-value	p-value	p-value
Stance phase (%)	62.1	0.8	62.7	2.7	63.3	2.1	ns	ns	ns	ns
Swing phase (%)	37.9	0.7	37.3	2.7	36.7	2.1	ns	ns	ns	ns
Double support phase (%)	12	1.3	12.6	2.6	13.5	3.6	ns	ns	ns	ns
Cadence (step/min)	100.6	9.7	102.4	13.2	103.8	7.6	ns	ns	ns	ns
Step length (cm)	56.3	6.1	48.2	7.2	47.6	10	**0.020**	**0.010**	**0.031**	ns
Step width (cm)	17.1	2.7	15.0	1.0	18.4	2.3	**0.004**	ns	ns	**0.005**
Speed (m/s)	1.0	0.16	0.9	0.2	0.9	0.2	ns	ns	ns	ns
Trunk kinematics										
ROMs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	p-value	p-value	p-value	p-value
Flexion-extension (°)	4.59	3.91	4.39	1.33	5.08	3.55	ns	ns	ns	ns
Lateral bending (°)	8.54	2.30	7.01	3.42	4.80	2.39	**0.016**	ns	**0.003**	ns
Rotation (°)	14.43	3.28	11.37	4.58	8.48	1.33	**0.001**	ns	**0.001**	**0.045**

3. Results

3.1. Gait parameters and trunk kinematics

The spatiotemporal parameters and trunk kinematic results are reported in Table 2.

At no-matched speed, the values of gait speed were 1.13 (0.15) m/s for the HC group, 0.90 (0.22) m/s for the LI group, and 0.89 (0.22) m/s for the FBSS group. A reduced speed was significant between the HC subjects compared to the LI patients ($p = 0.021$) and between the FBSS patients compared to the HC group ($p = 0.041$), thus confirming the initial assumption that the gait of patients was slower than that of healthy subjects.

At a matched speed, a significant effect of group was found regarding step length, step width, and trunk bending and rotation. Post-hoc analysis revealed a significantly reduced step length in the LI patients compared to the HC group, an increase of step width in the FBSS group compared to the LI group, a reduced step length and trunk bending and rotation in the FBSS patients compared to the HC group, and reduced trunk rotation in the FBSS group compared to the LI group (Table 2).

3.2. Cross-Correlation analysis findings

A significant effect of group was found on both left–right and up-down cross-correlation curve mean values for all muscles. Post-hoc analysis revealed significantly higher mean values of the left/right cross-correlation curves for the L4-L5 paraspinal muscles, in both the LI and/or FBSS patients compared to the HC subjects, as well as higher mean values of the upper-down cross-correlation curves for all paraspinal muscles in the FBSS and/or LI patients compared to the HC subjects (Fig. 1).

Fig. 2 shows the left–right and up-down cross-correlation curves in the three representative subjects for the HC, LI and FBSS groups, respectively. A gradual loss of sinusoidal from of the curve can be noticed, indicating the loss of left–right symmetry and up-down synchronization from the HC subjects to the FBSS patients.

3.3. Full-width percentages findings

A significant group effect was found on FW50%, FW40%, FW30%, and FW20%, while no effect was found on FW10%.

Post-hoc analysis revealed significantly higher values in the FBSS group than in the HC at all FW percentages (50–20%) and for all muscles bilaterally, as well as significantly higher values in the LI than in the HC at FW50%, FW40%, and FW30%, for L4-L5 and L5-S1 paraspinal muscles, predominantly in the right side (Fig. 3).

3.4. CoA findings

Fig. 4 shows the circular and linear envelop curves of the EMG signal as well as the CoA values on the polar plot in HC, LI, and FBSS groups. In HC group, both the circular (first columns) and linear envelop (second columns) curves display an 8-shape and a double-hump behavior, respectively, indicating the highest muscle activation during both the initial stance (loading response sub-phase, about 0–10% of the gait cycle) and swing (early swing sub-phase, about 60–70% of the gait cycle). In the polar plot, the CoA is located in the third quadrant for the iliocostalis and L3-L4 paraspinal muscles, indicating the highest activation of these muscles

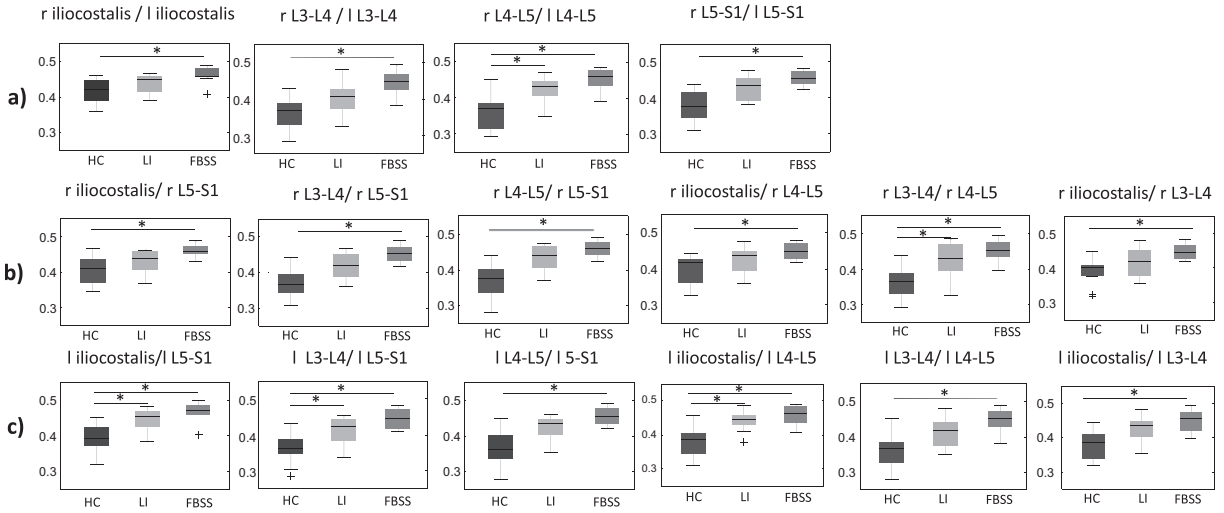

Fig. 1. Box plot of mean values of the cross correlation's curves. The box plots reported in the upper panel (a) show the mean values of the left/right cross-correlation comparisons. The box plots in the middle panel (b) show the mean values of the right top-down cross-correlation comparisons. The box plots in the lower panel (c) show the mean values of the left top-down cross-correlation comparisons.

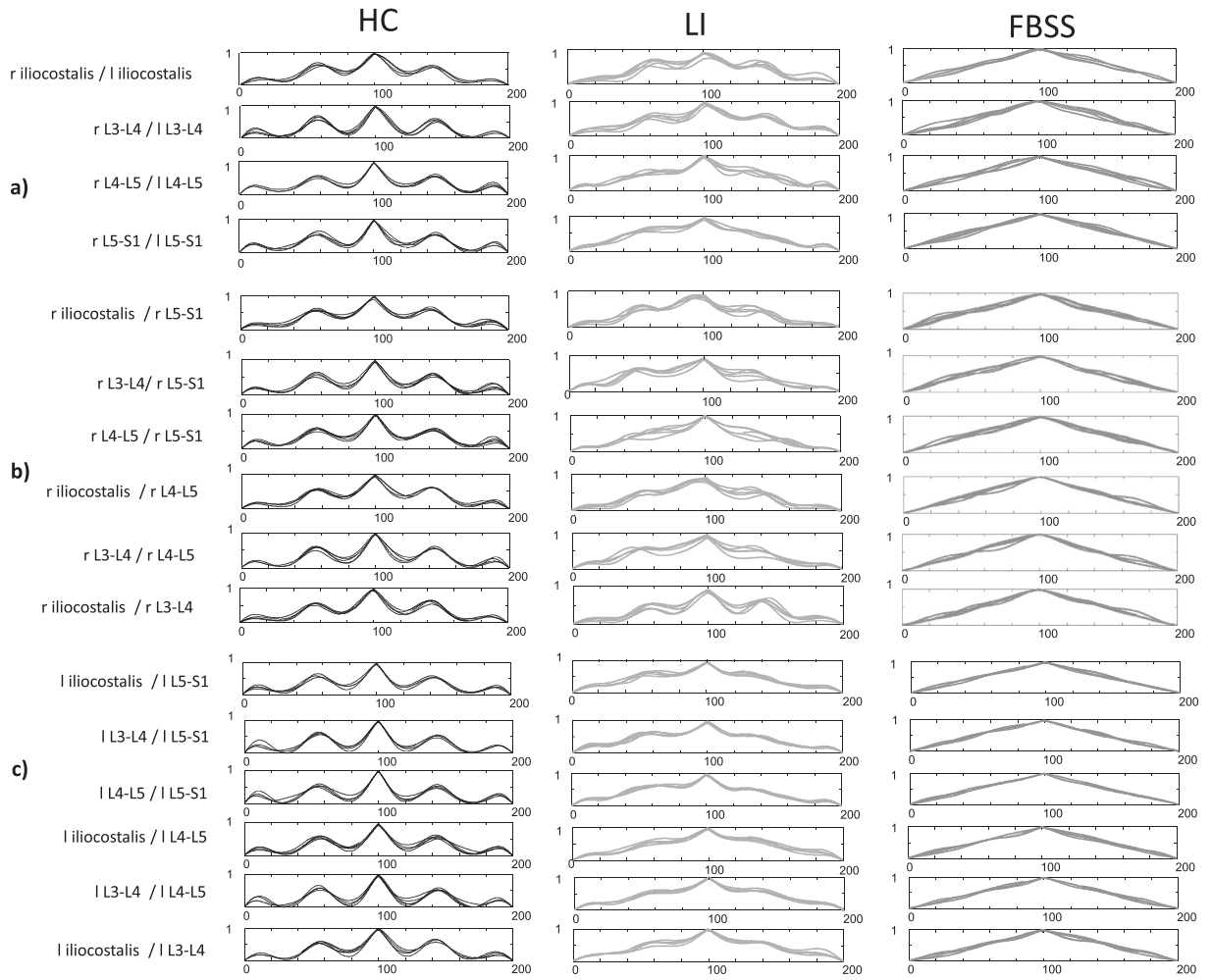

Fig. 2. Cross-correlation curves in a representative healthy subject (dark line), in a patient with LI (light gray line) and in a patient with FBSS (dark gray line). The graphs reported in the upper panel (a) show the corss-correlation curves between the left and right muscles. The graphs reported in the middle panel show the up-down cross-correlation curves between pairs of muscles of the right (b) and left (c) sides.

during the early swing, and in the first quadrant for the L4-L5 and L5-S1 paraspinal muscles, indicating the highest activation of these muscles during the loading response. In the LI group, and with more evidence in the FBSS group, this rostro-caudal CoA behavior is lost, with muscle activation being markedly enlarged (as noticeable in the circular envelops) and more tonically active (as noticeable in the linear envelops).

Using the Watson–Williams test, we found significant differences in CoA location between the HC and LI groups for the bilateral iliocostalis muscles and right L5-S1 paraspinal muscles, between the HC and FBSS groups for the left L5-S1 paraspinal muscles, and between the LI and FBSS groups for the right iliocostalis, and L4-L5 and L5-S1 paraspinal muscles.

3.5. Correlation findings

In the LI group, a significant positive correlation was found between VAS scores and CoA activation of the L4-L5 muscles ($r = 0.692$, $p = 0.013$) and between VAS scores and FW at 30% ($r = 0.582$, $p = 0.047$) and 40% ($r = 0.683$, $p = 0.014$) in the iliocostalis muscle.

In the FBSS group, a significant positive correlation was found between the ODI scores and mean cross-correlation curve of L3-L4/ L5-S1 muscles ($r = 0.800$, $p = 0.031$) and between the ODI scores and FW at 10% ($r = 0.825$, $p = 0.022$), at 30% ($r = 0.782$, $p = 0.038$), and at 50% ($r = 0.757$, $p = 0.049$) of the L5-S1 muscles in the FBSS group, whereas no significant correlation was found in patients with LI. Conversely, a significant negative correlation was found between the ODI scores and both trunk rotation ($r = -0.901$, $p = 0.006$) and gait speed ($r = -0.775$, $p = 0.04$).

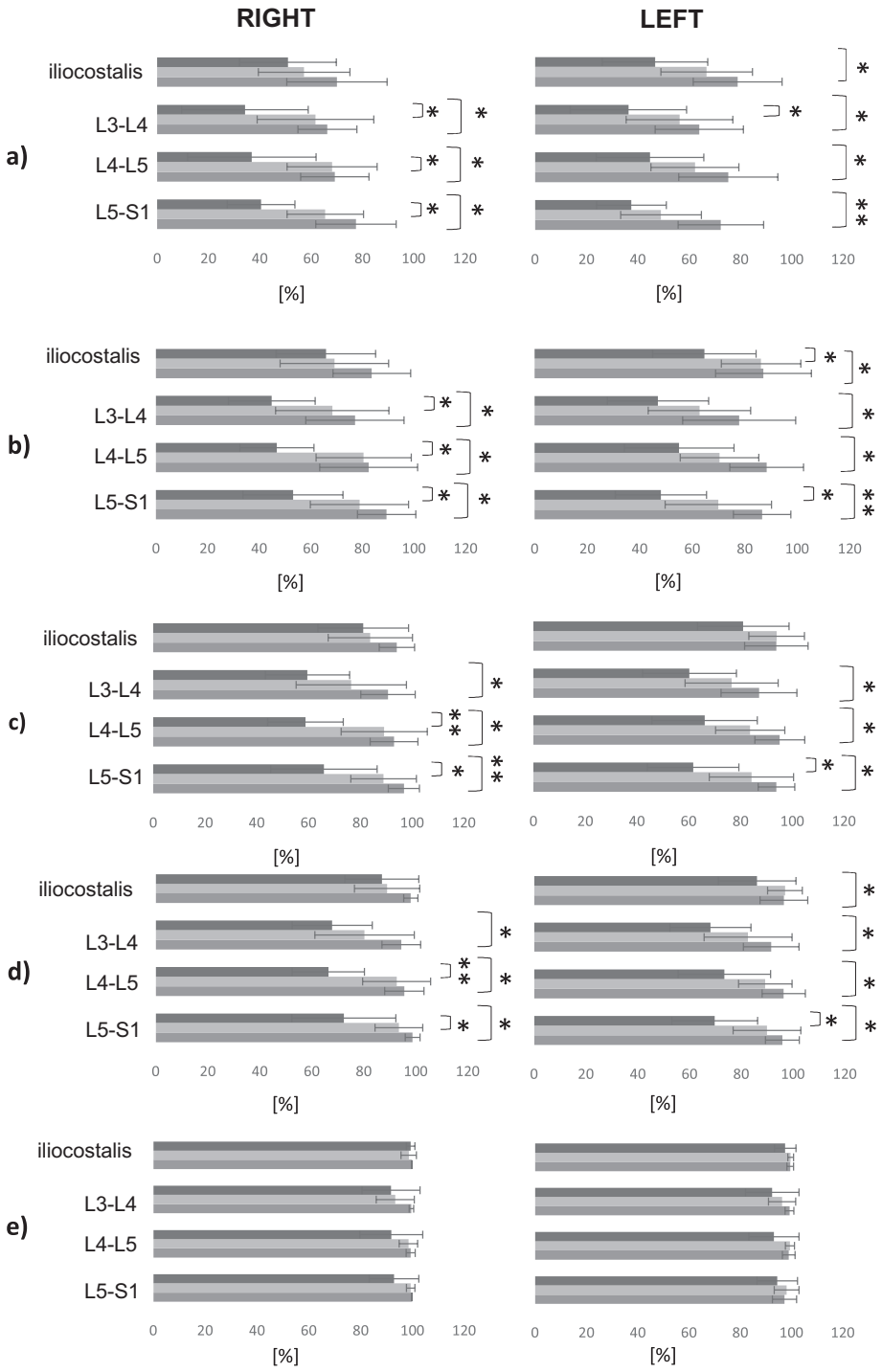

Fig. 3. Mean values and standard deviations of the FW at 50% (a), 40% (b), 30% (c), 20% (d) and 10% (e) of all muscles in HC (black bars), LI (light gray bars) and FBSS (dark gray bars) groups, respectively.

4. Discussion

In the present study, we fully characterized the EMG spatiotemporal activation of the spinal muscles during walking in a group of patients with LBP due to DDD and segmental LI in a presurgical setting. Our assumption, herein, was that by comparing the data of LI with those in the HC group, we could understand the impact of LBP on the function of trunk muscles during walking in a group of patients who could benefit from surgery.

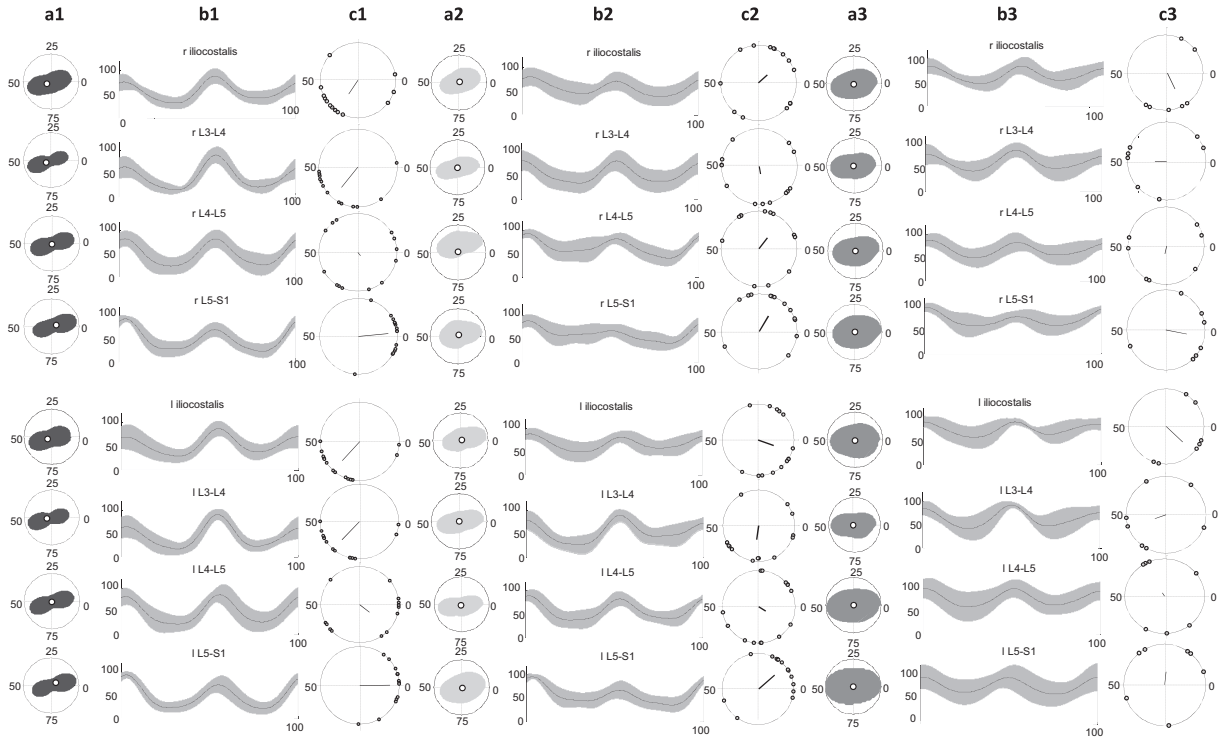

Fig. 4. Circular envelop and CoA (a), linear envelop (b) and mean circular plots of the CoA (**c**) of the paraspinal muscles of both sides, in HC (1), LI (2) and FBSS (3), respectively. The circular plot from 0 to 2 π represents the 0–100% of the gait cycle.

Furthermore, by comparing the data between patients with LI and FBSS, we could understand the potential impact of surgical complications on trunk kinematics and gait, and then define possible targets of surgical procedures and post-surgical rehabilitation for a good clinical outcome.

In our study, although a trend for a reduction in trunk bending and rotation with a HC > LI > FBSS gradient (Table 2 and figure in Supplementary Materials), patients with LI did not show significant changes in trunk kinematics compared to the HC group. This result is in line with previous evidences (Mueller et al., 2017), which failed to find significant differences in the 3-D trunk motion on a sample of 14 back pain symptomatic subjects. Conversely, patients with FBSS showed markedly reduced trunk bending and rotation compared to the HC group, and a marked reduced trunk rotation compared to LI (Table 2 and figure in Supplementary Materials). Thus, although both lumbar pain and instability are present, trunk motion seems to be relatively spared in patients with LI before surgery.

Regarding the spatiotemporal gait parameters, previous studies showed several differences in gait parameters between patients with low back disorders, due to several spine pathologies, before surgical intervention, and healthy subjects (Toosizadeh et al., 2015) (see for review). Some of such differences (e.g. gait speed) were related to the level of subjective rated pain (Al-Obaidi, Beattie, Al-Zoabi, & Al-Wekeel, 2005). In our study, we found a decreased gait speed and a shorter step length (at matched speed) in the LI group compared to the HC group. Although our findings are partially in line with previous studies, differences in patients' selection (Engsberg et al., 2003; Gottipati, Fatone, Koski, Sugrue, & Ganju, 2014) could make the comparisons poorly reliable. Moreover, most previous studies did not match the gait speed between groups. Since many spatiotemporal and joint kinematic parameters are speed-dependent (Chung & Wang, 2010; Kirtley, Whittle, & Jefferson, 1985), the comparisons between patients and healthy controls (Khodadadeh & Eisenstein, 1993; Suda et al., 2002), as well as before and after surgery (Gottipati et al., 2014; Hasday, Passoff, & Perry, 1983; Khodadadeh & Eisenstein, 1993; Lenke et al., 2001; Suda et al., 2002), may be biased by the gait speed.

The decreased gait speed and step length reflect the reduced gait performance in patients with LI, likely induced by both or either lumbar pain and instability. Interestingly, patients with FBSS showed, other than a reduced gait speed and step length, also an increased step width, compared to both the HC and LI groups. It has been demonstrated that an enlarged base of support is a common compensation adopted by patients with balance disorders or by healthy subject during unstable conditions, to improve dynamic stability, reduce the need of adopting other compensatory mechanisms (e.g. increased double support duration, increased muscle co-activation), and to preserve energy expenditure (Caliandro et al., 2017; Chini et al., 2017; Conte et al., 2017; Martino et al., 2015; Serrao et al., 2012). Thus, the impaired trunk function in patients with FBSS impairs both gait performance and balance maintenance.

An interesting aspect to take into consideration is that the high values of VAS reported by patients are not reflected on the all gait parameters at matched speed.

The most important result we found was the impaired spinal muscle activity (iliocostalis and longissimus) in both the LI and FBSS groups compared to the HC group.

First, we found a decreased left–right symmetry in the cross-correlation values according to the HC > LI > FBSS gradient (Fig. 1). Specifically, LI patients showed significantly higher asymmetry between L4-L5 longissimus muscles compared to the HC group. This result fits well with the localization of the LI instability in our patients, which involved the L4-L5 level in about 70% of cases and suggests that the abnormalities in muscle symmetry mainly regard the affected segments, in terms of mechanical instability. Conversely, in patients with FBSS, the asymmetry in the cross-correlation values regards all the spinal muscles irrespective to the segment involved.

Second, we found a reduced synchronization in the cross-correlation values according to the HC > LI > FBSS gradient (Fig. 1). Specifically, LI patients showed a significantly higher desynchronization of spinal muscles between all levels, except for L4-L5 and L5-S1, compared to the HC group. This finding suggests similar abnormalities in the lower segments (L4-S1) compared to the higher segments (L2-L4). In FBSS patients, all the spinal muscles were desynchronized (Fig. 1), losing the typical sinusoidal cross-correlation of the HC subjects (Fig. 2).

Third, we found a significantly higher degree of muscle activation of all spinal muscles during the gait cycle in both the LI and FBSS groups compared to the HC, according to the FBSS > LI > HC gradient (Fig. 3). Specifically, the higher degree in the spinal muscle activation, from 20% to 50% of FWM (Fig. 3), simply indicates that the spinal muscles in patients with LI, and even more in patients with FBSS, are always active during the whole gait cycle, whereas the spinal muscles in HC subjects are not, due to the presence of alternating active and inactive periods (Ceccato, de Sèze, Azevedo, & Cazalets, 2009; de Sèze, Falgairolle, Viel, Assaiante, & Cazalets, 2008; Saunders et al., 1953).

Fourth, we found that the gait sub-phase modulation of spinal muscle activation is lost in LI patients, and even more in FBSS patients, compared to HC subjects (Fig. 4). Interestingly, HC subjects show a main activation of the spinal muscles, as measured by CoA, in the ranges of 0–10% and 60–70% of the gait cycle, corresponding to the loading response and early swing subphases, respectively. Such a modulation is well-represented in Fig. 4 by the eight-shape of the polar envelop. Furthermore, muscle activation prevails during the early swing, in the higher segments (L2-L3-L4), and during the loading response in the lower segments (L4-L5-S1); thus, in a top-down way as well-represented in Fig. 4 by the bar direction on either the left or right in the circular plot, respectively.

These findings, to our knowledge, are novel in healthy subjects, and further suggest that the spinal muscles actively participate to lift the pelvis of the swinging limb and to stabilize the trunk during weight acceptance (Anders et al., 2007; Olson, 2010). Conversely, patients with LI, and even more patients with FBSS, lose the specific gait sub-phase modulation because of an increased muscle activation, extending to all the gait sub-phases. This is represented in Fig. 4, as ellipsoid-like shapes in LI patients and as circle-like shapes in FBSS patients, instead of the eight-shape of the HC subjects. The LI and FBSS patients also lose the top-down differential modulation, without showing a regular left (higher-level muscles) and right (lower-level muscles) bar direction in the circular plot of Fig. 4.

In conclusion, low back pain and mechanical instability in patients with LBP are due to DDD and segmental LI, which induces a series of EMG abnormalities of the spinal muscles, in terms of left–right symmetry, top-down synchronization, spatiotemporal activation, and activity modulation according to the gait sub-phases. Such abnormalities affect trunk function during gait, leading to a reduction in gait performance, i.e. reduced gait speed and short steps. In patients with FBSS, who are considered patients with irreversible or chronic LBP, spinal muscle abnormalities worsen, which further affects trunk function (reduced trunk rotation and bending) and reduces both gait performance (slow speed and short step) and balance maintenance (wide step).

Analysis of muscle spine activity during gait in patients with LBP due to surgical disease may yield important information on the progressive impairment of the muscle physiology of the spine, and thus, its function during dynamic conditions. It should be noted that FBSS represents the extreme negative condition of patients with LBP due to surgical disease, which must be prevented with a correct diagnostic assessment and a well-indicated and well-executed surgery. The correlation between the ODI scores and the EMG abnormalities in patients with FBSS further reinforces this notion indicating that the impairment of spine muscle functions is associated with the severity of the disability. Conversely, the correlation between the VAS scores and EMG abnormalities may indicate that both lumbar spine muscle dysfunction and LBP are consequences of LI. Furthermore, since no correlation was found between VAS scores and gait spatio-temporal parameters, the high VAS scores referred by patients seem to be indirectly reflected on the gait parameters (e.g. slow speed, reduced step length, increased step width). Thus, beyond the pain assessment, spine muscle activation may represent a biomarker that needs to be considered before and after surgical intervention.

The main limitation of our study is the small sample size which, even though is partly offset by the adoption of sensitive quantitative measures of motion, leads to interpret the results with caution.

Another limit of the study is that the range age of both healthy (27–69 years) and LI (25–74 years) groups was wider than that of FBSS group (45–63 years).

In our study, we chose to measure the mean cross-correlation analysis. Previous studies (Prince et al., 1994; Nelson-Wong, Howarth, Winter, & Callagan, 2009) demonstrated a clear difference in time delay of the maximal value of the cross-correlation curve (coefficient of cross-correlation) between muscles of distant segments (e.g. between C7 and L4). However, they revealed a trend toward zero of the shift between muscles of close segments (i.e. between lumbar segments). This indicates that maximal values of the cross-correlation curves are very similar between muscles which are too close each other as also revealed in our study (see additional material). In the opposite, the mean values of the cross-correlation curves may represent an adequate method to detect differences between close segments.

Further studies, investigating a larger sample of patients before and after surgery and comparing patients with LBP of different etiologies are needed. Our methodological approach to analyze the functional status of patients with LI due to spine disease with surgical indications, even in more complex conditions such as deformities, could allow to evaluate the biomechanics of the spine in the preoperative conditions and, in the future, to verify whether and which surgical procedure may either preserve or improve the

spine muscle function during gait.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.05.013.

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