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Multi-segment analysis of spinal kinematics during sit-to-stand in patients with chronic low back pain

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While alterations in spinal kinematics have been frequently reported in patients with chronic low back pain (CLBP), a better characterization of the kinematics during functional activities is needed to improve our understanding and therapeutic solutions for this condition. Recent studies on healthy subjects showed the value of analyzing the spine during sit-to-stand transition (STST) using multi-segment models, suggesting that additional knowledge could be gained by conducting similar assessments in CLBP patients. The objectives of this study were to characterize three dimensional kinematics at the lower lumbar (LLS), upper lumbar (ULS), lower thoracic (LTS) and upper thoracic (UTS) joints during STST, and to test the hypothesis that CLBP patients perform this movement with smaller angle and angular velocity compared to asymptomatic controls. Ten CLBP patients (with minimal to moderate disability) and 11 asymptomatic controls with comparable demographics (52% male, 37.4 ± 5.6 years old, 22.5 ± 2.8 kg/m^2) were tested using a three-dimensional camera-based system following previously proposed protocols. Characteristic patterns of movement were identified at the LLS, ULS and UTS joints in the sagittal plane only. Significant differences in the form of smaller sagittal-plane angle and smaller angular velocity in the patient group compared to the control group were observed at these three joints. This indicated a more rigid spine in the patient group and suggested that CLBP rehabilitation could potentially be enhanced by targeting movement deficits in functional activities. The results further recommended the analysis of STST kinematics using a pelvis-lumbar-thoracic model including lower and upper lumbar and thoracic segments.

1. Introduction

Chronic low back pain (CLBP) is one of the most frequent causes for limitations in daily, leisure and work related activities. Although CLBP is associated with significant decreases in quality of life and induces severe economic burden in most western countries, responses to treatments are still fairly limited (Hoy et al., 2010; Mansell et al., 2014). Better understanding kinematic alterations is critical to improve therapeutic solutions, as altered spinal kinematics is considered a possible major cause of persistence of symptoms and disability in CLBP (Dubois et al., 2014; O'Sullivan, 2005).

Several studies reported reduced range of motion and angular velocity at the lumbar spine in CLBP patients compared to asymptomatic individuals (Laird et al., 2014; Lehman, 2004). However, these studies used biomechanical models considering the lumbar spine as a single segment, whereas recent research with healthy subjects showed that the upper and lower regions of the lumbar spine move differently (Leardini et al., 2011; Mitchell et al., 2008). Specifically, rotation between the upper and lower lumbar segments were reported in the sagittal-plane during sit-to-stand transitions (Parkinson et al., 2013). Furthermore, in the study by Parkinson et al. (2013), significant differences between male and female lumbar kinematics were noticed with a multi-segment lumbar spine model, but not with a single-segment model. These observations suggest that single-segment models could hide

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important kinematic information and additional CLBP knowledge could be gained with multi-segment lumbar models. Prior research also suggests that kinematic analyses of CLBP patients should include the thoracic region. While pain in CLBP patients is mainly present in the lumbar region, alterations in thoracic kinematics were shown in this population (Crosbie et al., 2013). Therefore, there is a need to characterize the spinal kinematics of CLBP patients using a pelvis-lumbar-thoracic multi-segment model and to compare CLBP and asymptomatic subjects.

The sit-to-stand transition (STST) is a particularly relevant movement to improve our understanding of spinal kinematics in CLBP because it is a frequent daily activity (on average 60 times per day) requiring around 60% of total sagittal-plane lumbar mobility (Dall and Kerr, 2010; Hsieh and Pringle, 1994). Small, but possibly clinically relevant, rotations were also reported in the frontal and transverse planes during this movement (Baer and Ashburn, 1995; Gilleard et al., 2008; Leardini, 2011). Studying STST is further motivated by the fact that this movement is frequently described as painful by CLBP patients and is often addressed in rehabilitation (Andersson et al., 2010). Additionally, Shum and Colleagues (2005) compared this movement between patients with subacute low back pain and pain-free controls, and reported significant differences in sagittal-plane range of motion and angular velocity. Nevertheless, these results were obtained with a single-segment lumbar model. Because recent research on healthy subjects recommended differentiating the lower and upper lumbar spine regions and testing thoracic kinematics (Crosbie et al., 2013; Leardini et al., 2011; Parkinson et al., 2013), there is a strong interest to analyze CLBP patients STST using a multi-segment model.

This study aimed at comparing spinal kinematics (angle and angular velocity) between CLBP patients and asymptomatic controls during STST using a pelvis-lumbar-thoracic model with lower and upper lumbar segments. The first objectives of this work were to characterize the patterns of movement at the lower lumbar, upper lumbar, lower thoracic and upper thoracic joints to identify characteristic features that can be used to compare patient and control movements. This study then tested the hypothesis that CLBP patients perform STST with smaller angle and angular velocity than asymptomatic controls.

2. Methods

2.1. Participants

This study prospectively enrolled patients with non-specific CLBP for more than three months (Balagué et al., 2011) and with an age and body mass index (BMI) comprised between 30 and 50 years old and 18 and 27 kg/m^2, respectively. Exclusion criteria for this group were the presence of infection, rheumatological or neurological diseases, spinal fractures, any known spinal deformities, back surgery, tumors or radicular symptoms.

Healthy subjects without history of low back pain requiring medical attention during the last two years were enrolled as asymptomatic controls. Controls were selected to match the age, sex and BMI of the patient group, as these factors were shown to influence lumbar kinematics (Marras et al., 1994; Parkinson et al., 2013). General exclusion criteria for both groups were pregnancy and pain or injury in any other body parts that could compromise the evaluation of lumbar kinematics. The research was approved by the local Research Ethics Committee (protocol VD-340/14) and all participants signed an informed consent form before enrollment in the study.

2.2. Experimental procedures

Spinal kinematics was measured using a camera-based motion capture system recording marker positions at 120 Hz (VICON, Oxford Metrics, UK). Nineteen reflective markers were attached to the pelvis, lumbar spine and thoracic spine, following previously described protocols (Ebert et al., 2014; Seay et al., 2008; Wade et al., 2012). Five central markers were placed on the spinous processes of T1, T6, L1, L3 and L5 (Fig. 1). In addition, 8 lateral markers were placed between central markers on each side of the spine, at a distance of 5 cm. The 6 remaining markers were placed on the pelvis, at the posterior superior iliac spines, anterior superior iliac spines and tip of each iliac crest. The same experienced physiotherapist identified the anatomical landmarks for every participant following the same procedure.

Data collection started with the capture of a reference standing posture. Then, participants were asked to sit on a stool and STST were recorded. Participants were asked to place their feet shoulder width apart, to start the STST in their normal upright sitting posture with their arms relaxed, to stand up at their self-selected normal speed and to finish the STST in their normal upright standing posture (Parkinson et al., 2013). The height of the stool was adjusted individually in order to have participant thighs horizontal while sitting. Three STST were recorded after participants had practiced the movement. After the recording, patients were asked to evaluate the pain associated with the STST they just did using a numeric pain rating scale (NPRS) (Dworkin et al., 2005; Mannion et al., 2007). In addition to the kinematic test described above, pain during the last 24 h, disability and kinesiophobia were assessed for the CLBP patients using the Oswestry Disability Index (ODI), the NPRS and the Tampa Scale of Kinesiophobia (TSK) (Chapman et al., 2011; Fairbank and Pynsent, 2000; Vlaeyen et al.,1995).

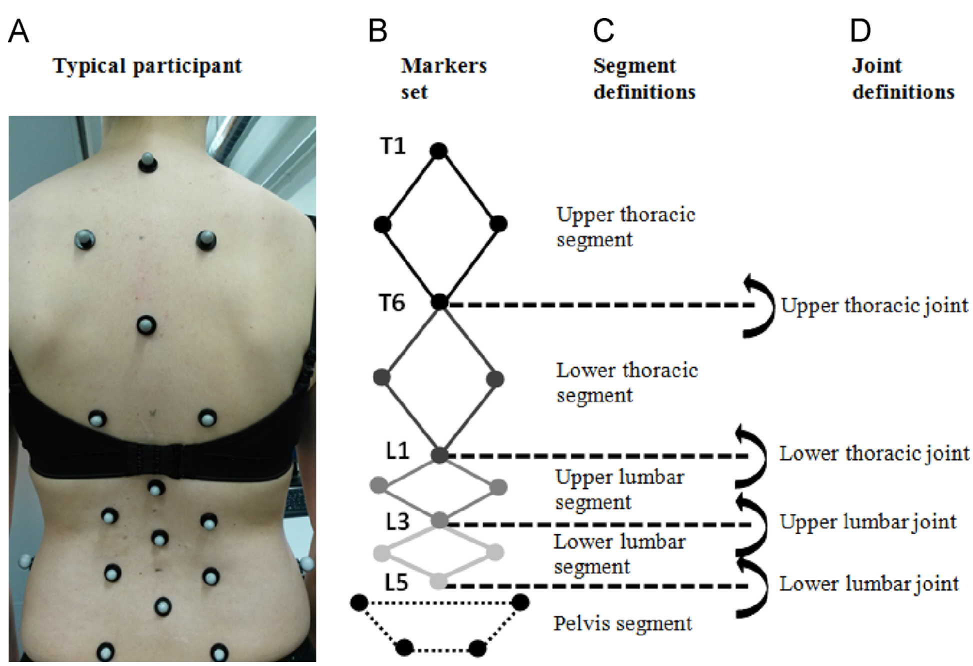

Fig. 1. Model description. (A) Picture of a typical participant with the markers, (B) markers set, (C) segment definitions, (D) joint definitions.

2.3. Data processing

Spinal kinematics were calculated based on previously described models (Ebert et al., 2014; Seay et al., 2008; Wade et al., 2012). Briefly, markers trajectories were used to calculate the position and orientation of the anatomical frames of the five segments (pelvis and lower lumbar, upper lumbar, lower thoracic and upper thoracic spine). The joint coordinate system (Grood and Suntay, 1983) was used to calculate three-dimensional joint angles (i.e., flexion, lateral bending and rotation): the lower lumbar joint angles (LLSa) were defined as the angles between the lower lumbar and pelvis segments, the upper lumbar joint angles (ULSa) as the angles between the upper lumbar and lower lumbar segments, the lower thoracic joint angles (LTSa) as the angles between the lower thoracic and upper lumbar segments and the upper thoracic joint angles (UTSa) as the angles between the upper thoracic and lower thoracic segments (Fig. 1). The natural inter-individual variations in morphology, which could offset the angle curves, were limited by subtracting the angles measured during the reference standing posture from the STST angle curves. The angular velocity curves (LLSv, ULSv, LTSv and UTSv) were obtained by numerical differentiation of the angle curves. Each STST was screened to determine visually the beginning and the end of the movement; a single investigator followed the same rules (start of C7 anterior displacement and stop of L5 displacement) for every subject. Finally, the angle and angular velocity curves were time-normalized to 0–100% during this interval. All calculations were performed with Matlab (R2013b, MathWorks, Inc, Natick, MA).

2.4. Statistical analysis

The consistency of the angle and angular velocity patterns among individuals was assessed using the coefficient of multiple correlation (CMC) (Kadaba et al., 1989). This coefficient results in a value varying between 0 (patterns highly different among individuals) and 1 (patterns highly similar among individuals). For each angle (LLSa, ULSa, LTSa and UTSa in the sagittal, frontal and transverse planes) and angular velocity (LLSv, ULSv, LTSv and UTSv in the sagittal, frontal and transverse planes) of each participant, the three curves corresponding to the three repetitions were averaged and the average curve was standardized by setting its mean value to zero and its standard deviation to 1. Next, the CMC was calculated, for each angle and angular velocity, first based on the standardized curves of all CLBP patients and then based on the standardized curves of all control subjects.

The curves reporting a consistent pattern among controls (CMC >0.5) were further analyzed to compare patients and controls STST kinematics. This was done by screening the curves to identify characteristic minimum or maximum peaks and then by extracting the amplitude and time of occurrence of the characteristic peaks in each curve. Reliability of these measurements for the three STST repetitions was assessed using the intraclass correlation coefficient of variation (ICC 2,1) and the standard error of measurement (SEM). Finally, to compare kinematics between CLBP and asymptomatic individuals, the three measurements obtained for each participant and each characteristic peak were averaged to have only one data point per participant and variable of interest. Because these data did not met the assumptions of normal distribution and homogeneity, nonparametric Mann–Whitney *U* tests were used to compare the amplitude and time of occurrence of the characteristic peaks between groups (Portney and Watkins, 2000). All data analyses were performed with SPSS (Version 21, IBM, NY, USA) and significance set *a priori* at alpha <0.05.

3. Results

This study analyzed 10 CLBP patients and 11 asymptomatic controls (Table 1). There were no significant differences in age, weight, height and BMI between patient and control groups ($p>0.4$). Similarly, there were no significant differences between patients and controls in the spinal angles (LLSa, ULSa, LTSa and UTSa) measured during the standing posture ($p>0.4$). Clinical scores indicated minimal disability in half of the patients and moderate disability in the other half. Moreover, 60% of patient had a TSK score indicating high kinesiophobia.

The sagittal-plane angle curves (i.e., flexion-extension) during STST at the lower lumbar (LLSa), upper lumbar (ULSa) and upper thoracic (UTSa) joints had consistent pattern among asymptomatic controls and among CLBP patients, with CMC between 0.66 and 0.87 (Fig. 2). Furthermore, these three angle patterns were similar for patients and controls. Conversely, no characteristic pattern was observed in the sagittal-plane at the lower thoracic joint (LTSa), with CMC equal to 0.35 and 0.05 for the control and patient groups, respectively. The three joints with consistent sagittal-plane angle pattern also reported consistent pattern for the sagittal-plane angular velocity (LLSv, ULSv and UTSv) among controls, with CMC between 0.52 and 0.71 (Fig. 3). CMC for the patient group indicated consistent sagittal-plane angular velocity pattern at the lower lumbar joint (LLSv CMC$=$0.6) and the upper thoracic joint (UTSv CMC$=$0.53), but not at the upper lumbar joint (ULSv CMC$=$0.23). LLSv and UTSv had similar patterns in the sagittal plane for patients and controls. On the contrary, none of the angle and angular velocity curves in the frontal and transverse planes reported consistent pattern among the control or CLBP groups (CMC <0.3). Based on this pattern analysis, only sagittal-plane kinematics was further analyzed. Specifically, 7 characteristic peaks were identified in the flexion-extension angle curves and 5 in the flexion-extension angular velocity curves. These 12 features are listed in Tables 2 and 3 and illustrated in Fig. 4.

Table 1
Participant characteristics. Values are reported as mean ± standard deviation (SD). The *p*-values correspond to un-paired *t*-tests done to compare the two groups. BMI: Body Mass Index; NPRS: Numeric Pain Rating Scale; ODI: Oswestry Disability Index; TSK: Tampa scale of kinesophobia.

	CLBP patients Mean (SD)	**Asymptomatic controls** Mean (SD)	*p*-value
Sex (n)	5M, 5F	6M, 5F	
Age (years)	38.2 (6.7)	36.7 (5.4)	0.56
Weight (kg)	65.6 (9.0)	69.5 (9.8)	0.39
Height (m)	1.72 (0.07)	1.74 (0.05)	0.56
BMI (kg/m^2)	21.9 (1.7)	22.9 (3.8)	0.46
Duration of LBP (months)	133 (96)	–	
Mean NPRS-24 h	4.0 (2.1)	–	
Max NPRS-24 h	5.4 (2.5)	–	
ODI	23.4 (10)	–	
TSK	40.3 (8.9)	–	

Sagittal-plane spinal kinematics during STST differed between CLBP patients and controls, with patients reporting smaller angle and angular velocity amplitudes (Table 2, Fig. 4). Specifically, the peak extension angle at the lower lumbar joint ($LLSa_{extension}$) was significantly smaller, on median by 4.3°, in the patient compared to the control groups ($p=0.007$). Additionally, the peak flexion angle ($ULSa_{flexion}$) and the total range of motion ($ULSa_{extenion}$–$ULSa_{flexion}$) at the upper lumbar joint were smaller for the patients compared to the controls, with median differences between groups of 14.2° ($p=0.02$) and 11.5° ($p=0.005$), respectively. Patients also had a smaller range of motion between the extension peak and the terminal flexion peak at the upper thoracic joint ($UTSa_{extension}$ – $UTSa_{terminal\text{-}flexion}$), on median of 2.4°, compared to the controls ($p=0.04$). Furthermore, the angular velocity was smaller in the patient compared to the control groups for the peak extension velocity ($LLSv_{extension}$; median differences of 5.0°/s; $p=0.008$) and range between flexion and extension peak velocities at the lower lumbar joint ($LLSv_{extension}$–$LLSv_{flexion}$; median differences of 8.2°/s; $p=0.04$). The amplitude of the peak extension velocity at the upper lumbar joint ($ULSv_{extension}$; median differences of 11.8°/s; $p=0.01$) and the peak flexion velocity at the upper thoracic joint ($UTSv_{flexion}$; median differences of 3.0°/s; $p=0.02$) were also significantly smaller in the patient group compared to the control group. Conversely to the amplitude, the time occurrence of none of the angle and angular velocity peaks significantly differed between groups (Table 3).

According to the NPRS, STST was pain-free for 60% of patients. Reliability assessment indicated median [interquartile range (IQR)] ICC and SEM of 0.84 [0.80–0.91] and 1.9° [1.3–2.2] for the amplitude of the angle peaks, respectively. The amplitude of the angular velocity peaks reported a median ICC of 0.72 [0.48–0.8] and a median SEM of 3.2°/s [2.6–4.9].

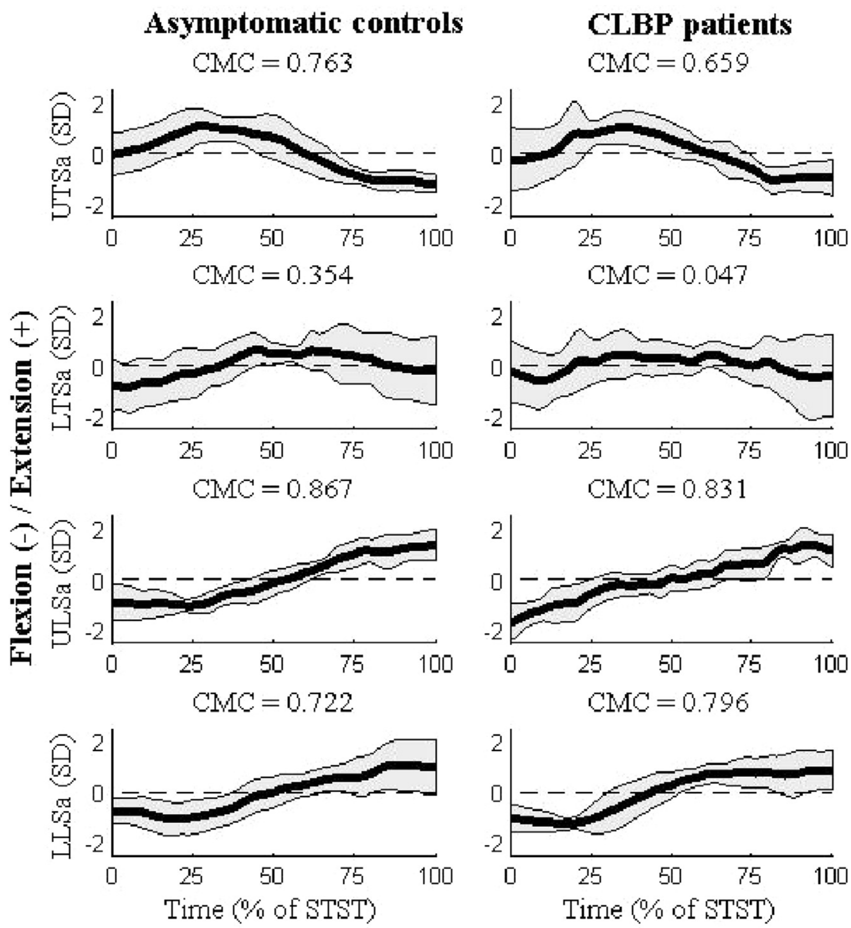

Fig. 2. Standardized sagittal-plane angle curves for the asymptomatic control group (left column) and the CLBP patient group (right column). In each graph, the black line presents the average curve and the gray shaded area the standard deviation of the group. The CMC values at the top of the graphs indicate the coefficients of multiple correlation. The vertical axes are in standard deviation unit (SD). Horizontal axes correspond to the normalized duration of the STST, with 0% and 100% corresponding to the beginning and the end of the transition, respectively. UTSa: upper thoracic joint angle; LTSa: lower thoracic joint angle; ULSa: upper lumbar joint angle; LLSa: lower lumbar joint angle.

4. Discussion

The sagittal-plane movement at the upper lumbar joint observed in this study supported the analysis of spinal kinematics during STST using a biomechanical model considering the lumbar spine region as two segments. Indeed, consistent angle patterns existed in the sagittal plane between the lower and upper lumbar segments (ULSa) in the asymptomatic controls and CLBP patients, and consistent angular velocity pattern was noticed between these segments (ULSv) in the controls. In addition to confirming the importance of modeling this spinal region as two segments to accurately describe lumbar kinematics, the CMC results also stressed the importance of separating the lower and upper sections of the lumbar spine to understand kinematic alterations with CLBP. In fact, the lower consistency for the angular velocity (ULSv) in the patient group was a first indication of altered kinematics with CLBP. Specifically, this lower consistency indicated that the movement between the lower and upper lumbar segments in the sagittal plane varied more among CLBP patients than among controls, thus suggesting an individual adaptation in the patient population. The large peak amplitudes observed in the angle and angular velocity curves at the upper lumbar joint (ULSa and ULSv) compared to those obtained at the other spinal joints further supported the modeling of the lumbar region as two segments in healthy subjects and in CLBP patients. While previous research already recommended two-segment lumbar models based on the range of motion measured between the lower and upper regions during STST in asymptomatic individuals (Mitchell et al., 2008; Parkinson et al., 2013), the present results highlighted the value of two-segment lumbar models to study clinical population as well. In fact, this study suggested that the movement between the lower and upper lumbar segments is particularly affected by CLBP.

The hypothesis was supported as CLBP patients showed reduced sagittal-plane angle and angular velocity compared to asymptomatic controls during STST. The results indicated that the lower and upper lumbar joints move similarly during STST, following a flexion-extension-flexion sequence. Interestingly, while both the amplitude of the peak flexion angle during the first half of STST and the amplitude of the extension peak during the second half of STST were smaller in the patient group, the differences among groups were observed at different joints. Patients had smaller flexion angle at the upper lumbar joint (ULSa) and smaller extension angle at the lower lumbar joint (LLSa). These differences between groups were large (more than 60%) and can thus be considered as clinically important for a daily activity like STST. Previous research using single-segment lumbar models already identified a flexion-extension-flexion sequence between the pelvis and lumbar spine segments during STST and reported limited flexion angle in CLBP patients (Janssen et al., 2002; Shum et al., 2005). The present study improved our understanding of CLBP by showing that flexion reduction occurred principally at the upper

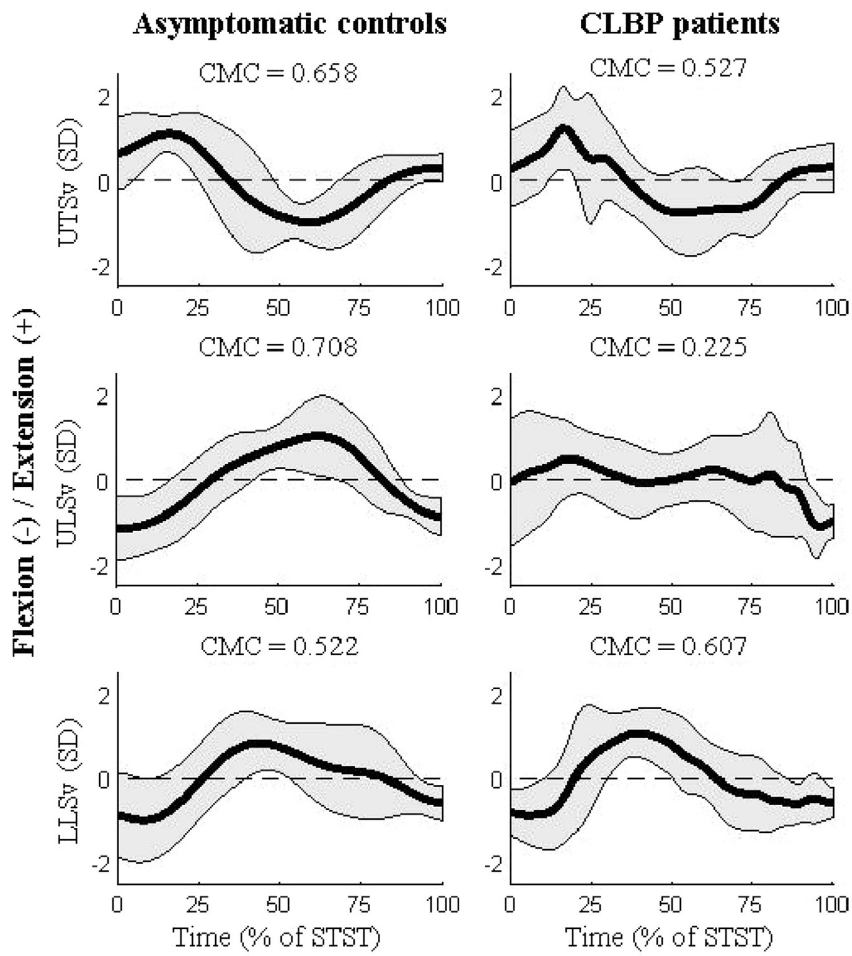

Fig. 3. Standardized sagittal-plane angular velocity curves for the asymptomatic control group (left column) and the CLBP patient group (right column). In each graph, the black line presents the average curve and the gray shaded area the standard deviation of the group. The CMC values at the top of the graphs indicate the coefficients of multiple correlation. The vertical axes are in standard deviation unit (SD). Horizontal axes correspond to the normalized duration of the STST, with 0% and 100% corresponding to the beginning and the end of the transition, respectively. UTSv: upper thoracic joint angular velocity; LTSv: lower thoracic joint angular velocity; ULSv: upper lumbar joint angular velocity; LLSv: lower lumbar joint angular velocity.

lumbar joint (ULSa) and by detecting reductions in extension. It is highly probable that the alterations in extension were not detected in prior studies due to the use of single-segment lumbar models. As STST is often described as a painful movement by CLBP patients (Claeys et al., 2012; Shum et al., 2005), it is possible that pain is related to the rapid changes from a flexion to an extension posture required by this movement. This interpretation is further supported by the smaller extension angular velocity observed at the lower and upper lumbar joints (LLSv and ULSv) in patients compared to controls.

Limited sagittal-plane spinal kinematics in CLBP patients was also noticed in the thoracic region. The consistent angle and angular velocity patterns in the sagittal plane among patients and controls at the upper thoracic joint (UTSa and UTSv) indicated that this joint has a characteristic function during STST. When comparing this joint between groups, a smaller range of motion and a smaller angular velocity peak towards flexion were observed during the second half of STST in the CLBP patients. This finding of less movement suggested that the lack of movement at the lumbar spine in CLBP patients is not compensated at the thoracic spine. This observation further suggested that CLBP effects on sagittal-plane kinematics are not limited to the lumbar region and thus confirmed the value of studying CLBP with a pelvis-lumbar-thoracic biomechanical model.

The reduced sagittal-plane mobility with CLBP consistently observed in this study suggested that CLBP patients perform the STST with a more rigid spine. This observation could be related to previous studies showing muscle hyperactivity in this clinical population (Dankaerts et al., 2009; Hodges et al., 2009; Shum et al., 2007). This increased spinal stiffness could modify movement patterns in a harmful way and possibly induce sensitization of spinal and peripheral structures, which could adversely contribute to the chronicity of pain (Hodges and Smeets, 2015; O'Sullivan, 2012). Consequently, there could be opportunities to improve CLBP rehabilitation by focusing on exercises that target this increase in spinal stiffness, including rapid postural changes during functional activities.

Although patients in this study had chronic pain, most of them did not feel pain during STST, suggesting that the kinematics differences compared to the asymptomatic controls were not due to painful stimuli at the time of data collection. Crosbie et al. (2013) also demonstrated altered kinematics in patients with recurrent LBP who were in a pain-free period at the time of experiment. Together these results suggested that spinal motor behavior is generally altered in CLBP patients, even during painless activities. This interpretation is supported by other research reporting disruption in the sensorimotor system in CLBP patients, implying a reorganization of motor tasks planning (Pijnenburg et al., 2015; Tsao et al., 2008; Wand et al., 2011).

This study should be interpreted in regards of its limitations. Firstly, although consistent differences between groups were detected and although the results agreed with previous research,

Table 2
Amplitude of the characteristic angle and angular velocity peaks. p-values in bold indicate significant differences between patients and controls ($p < 0.05$). The UTS, ULS and LLS abbreviations correspond to the upper thoracic, upper lumbar and lower lumbar joints, respectively. The "a" and "v" subscript letters refer to angle and angular velocity curves, respectively. For an illustration of the various characteristic peaks ("initial-flexion", "extension", "terminal-flexion", ...) please refer to Fig. 4. IQR: interquartile range.

Variables		**CLBP patients**		**Asymptomatic controls**		p-value
Angles		Median	IQR	Median	IQR	
Upper thoracic joint	$UTSa_{initial\text{-}flexion}$ (°)	0.8	[−1.5 to 2.8]	0.9	[−2 to 1.7]	0.5
	$UTSa_{extension}$ (°)	5.3	[2.3 to 6.5]	4.3	[2.7 to 6.4]	0.86
	$UTSa_{terminal\text{-}flexion}$ (°)	−0.3	[−1.9 to 2.6]	−1.9	[−4 to −1.1]	0.06
	$UTSa_{extension} - UTSa_{initial\text{-}flexion}$ (°)	3.2	[1.7 to 6.2]	3.3	[3.1 to 5.1]	0.55
	$UTSa_{extension} - UTSa_{terminal\text{-}flexion}$ (°)	3.3	[2.7 to 5.4]	5.7	[5 to 6.9]	**0.04**
Upper lumbar joint	$ULSa_{flexion}$ (°)	−7.7	[−19 to −3.5]	−21.9	[−26.3 to −18.7]	**0.02**
	$ULSa_{extension}$ (°)	0.1	[−0.7 to 6.1]	−1	[−3.9 to 3.8]	0.65
	$ULSa_{extension} - ULSa_{flexion}$ (°)	10.3	[6.5 to 18]	21.8	[19.8 to 25.6]	**0.005**
Lower lumbar joint	$LLSa_{flexion}$ (°)	−13	[−16 to −6.2]	-9.9	[-14 to -8]	0.7
	$LLSa_{extension}$ (°)	−1	[−3.6 to 0.2]	3.3	[1.3 to 8.1]	**0.007**
	$LLSa_{extension} - LLSa_{flexion}$ (°)	11.4	[6.8 to 15]	14.8	[11.7 to 19.9]	0.11
Angular velocity						
Upper thoracic joint	$UTSv_{extension}$ (°/s)	5.8	[2.3 to 11]	4.9	[3.8 to 7.6]	0.92
	$UTSv_{flexion}$ (°/s)	−5.3	[−6.2 to −2.9]	−8.3	[−8.9 to −6.6]	**0.02**
	$UTSv_{extension} - UTSv_{flexion}$ (°/s)	10.7	[5.1 to 16]	12.8	[11.3 to 16.9]	0.25
Upper lumbar joint	$ULSv_{extension}$ (°/s)	10.7	[4 to 14]	22.5	[16.5 to 26.9]	**0.01**
Lower lumbar joint	$LLSv_{flexion}$ (°/s)	−4.5	[−7.1 to −0.8]	−6.1	[−9.6 to −3.9]	0.17
	$LLSv_{extension}$ (°/s)	10.5	[7.2 to 14]	15.5	[13.7 to 17.1]	**0.008**
	$LLSv_{extension} - LLSv_{flexion}$ (°/s)	13.4	[9.8 to 20]	21.6	[17.1 to 26.5]	**0.04**

Table 3
Time occurrence of the characteristic angle and angular velocity peaks. Data are in % of the STST duration. The UTS, ULS and LLS abbreviations correspond to the upper thoracic, upper lumbar and lower lumbar joints, respectively. The "a" and "v" subscript letters refer to angle and angular velocity curves, respectively. For an illustration of the various characteristic peaks ('initial-flexion', "extension", "terminal-flexion", ...) please refer to Fig. 4. IQR: interquartile range.

Variables		**CLBP patients**		**Asymptomatic controls**		p-value
Angle		Median	IQR	Median	IQR	
Upper thoracic joint	$UTSa_{initial\text{-}flexion}$ (%)	10.3	[7.7 to 18]	9	[2.1 to 17.8]	0.62
	$UTSa_{extension}$ (%)	31.2	[27 to 32]	32	[25.3 to 45.5]	0.55
	$UTSa_{terminal\text{-}flexion}$ (%)	82.7	[79 to 88]	82.7	[77.8 to 87.3]	0.81
Upper lumbar joint	$ULSa_{flexion}$ (%)	11.9	[7.3 to 21]	19	[8.5 to 23.3]	0.67
	$ULSa_{extension}$ (%)	86	[82 to 89]	88	[77.4 to 96.3]	0.83
Lower lumbar joint	$LLSa_{flexion}$ (%)	18.5	[12 to 26]	20.3	[12.5 to 28.4]	0.55
	$LLSa_{extension}$ (%)	78.7	[66 to 88]	85.7	[67.3 to 89]	0.72
Angular velocity						
Upper thoracic joint	$UTSv_{extension}$ (%)	19.9	[14 to 26]	18.7	[11.3 to 30.8]	0.81
	$UTSv_{flexion}$ (%)	53.2	[38 to 59]	47.3	[44.5 to 65.5]	0.6
Upper lumbar joint	$ULSv_{extension}$ (%)	46.2	[44 to 67]	58.3	[54.9 to 63.9]	0.75
Lower lumbar joint	$LLSv_{flexion}$ (%)	11.8	[7.5 to 13]	9	[5.1 to 12.4]	0.6
	$LLSv_{extension}$ (%)	42.5	[30 to 52]	50.7	[35.9 to 64]	0.19

other studies with larger cohorts will be necessary to derive definite clinical conclusions. Secondly, the cross-sectional design of this study precluded the investigation of any causal relationship between CLBP and spinal kinematics. Further longitudinal studies will be needed to understand the relationship between movement disorders and clinical outcomes (Mansell et al., 2014). No consistent pattern was observed for the angles and angular velocities in the frontal and transverse planes. Although these results agree with the fact that STST is a movement mainly occurring in the sagittal plane, they also suggest that in the future it could be interesting analyzing additional functional movements involving lateral bending and rotation of the spine. Finally, while the ICC and

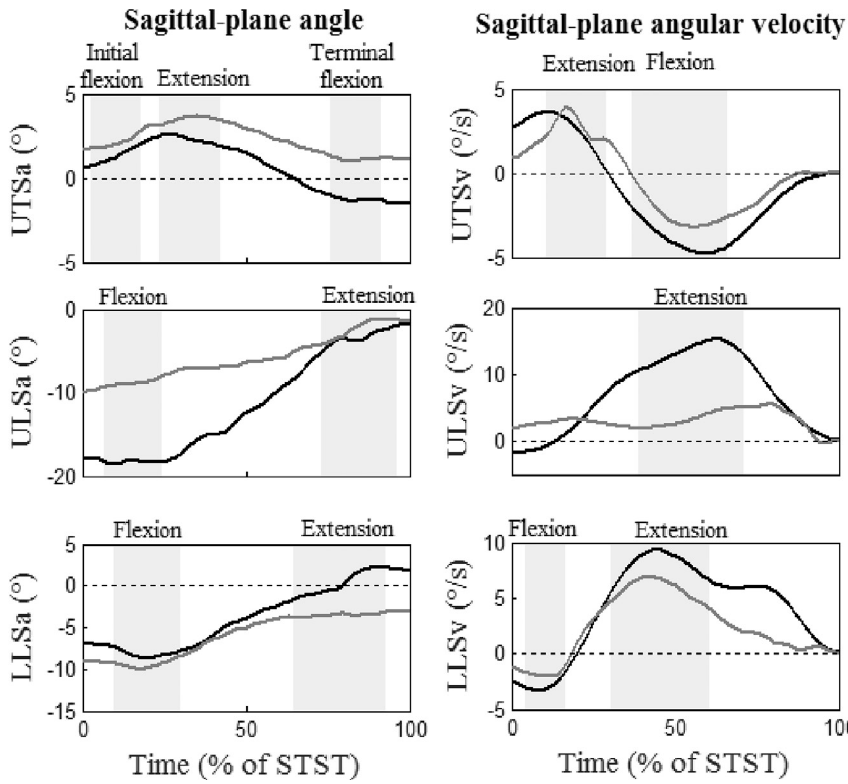

Fig. 4. Average sagittal-plane angle (left column) and angular velocity (right column) curves for the CLBP patient group (in dark gray) and the asymptomatic control group (in black). Plots are presented as flexion (negative direction) and extension (positive direction). The light gray areas correspond to the time occurrence (mean ± standard deviation) of the characteristic peak used to describe spinal kinematics during STST. Please refer to Table 2 for a comparison of the peak amplitude between patients and controls and Table 3 for a comparison of peak occurrence time. Vertical axes are in degrees (°) or in degrees per second (°/s). Horizontal axes correspond to the normalized duration of the STST, with 0% and 100% corresponding to the beginning and the end of the transition, respectively. UTS: upper thoracic joint; LTS: lower thoracic joint; ULS: upper lumbar joint; LLS: lower lumbar joint.

SEM values were good, it should be acknowledged that limited information exists in the literature regarding the validity and reliability of the spinal model used in this study. Nevertheless, both groups were equally exposed to soft tissue artefacts and other measurement errors and thus it is unlikely that the differences between groups were due to such errors. However, one cannot exclude that experimental errors obscured additional differences between groups.

In conclusion, this study showed that the lower lumbar, upper lumbar and upper thoracic joints have characteristic sagittal-plane movement during STST both among asymptomatic individuals and CLBP patients. Moreover, the results indicated that patients performed STST with less spinal movement in the lumbar, but also in the thoracic, regions. This denoted a more rigid spine in the patient group and suggested that CLBP rehabilitation could potentially be enhanced by targeting these movement deficits in functional activities. Finally, the results in this study recommend analyzing STST spinal kinematics in CLBP using a pelvis-lumbar-thoracic model including lower and upper lumbar and thoracic segments.

Conflict of interest statement

The authors have no conflict of interest with this work.

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