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Trunk Compliance Index During Expected and Unexpected External Perturbations in Individuals with and without Chronic Low Back Pain

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Research Article

Keywords:

Posted Date: April 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8963144/v1

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Additional Declarations: No competing interests reported.

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Abstract

Many studies have documented changes in motor control among individuals with chronic low back pain (CLBP). Some research indicates that pain causes increased co-contraction of trunk muscles, leading to overall stiffening in various directions. Conversely, other studies suggest that CLBP may decrease muscle co-activation and subsequent instability. Methods for assessing trunk stiffness include biomechanical spine modeling, though this approach has limitations due to generalized anatomical features and complexity. The Trunk Compliance Index (TCI) is a biomarker measuring trunk compliance (i.e., 1/stiffness) by evaluating left shoulder displacements relative to normalized force across the frontal, sagittal, and transverse planes through direct trunk measurements. Our goal was to determine whether TCI varies across six directions during unexpected and maximally resisted multi-directional trunk perturbations in participants with CLBP and healthy (H) controls. Additionally, we hypothesized that sex would influence TCIs in unexpected trials. The study involved 40 participants, including 22 with chronic low back pain (CLBP) (average age 34.27 years; 50% female) and 18 healthy controls (average age 29.55 years; 50% female). A total of 30 sudden, multi-directional perturbations were applied to the trunk using a puller motor system, covering six directions across the sagittal, frontal, and horizontal planes. These perturbations were randomized, with each direction repeated five times. Subsequently, a second set of 30 sudden, expected (participants aware of the timing and direction, and instructed to brace their trunk maximally before each impulse. The data were assessed with six separate linear mixed models, followed by ANOVAs, with interactions examined using pairwise comparisons. The study confirmed main effects of perturbation types (expected, unexpected) across all TCIs for both genders and groups, except for LSB. Interestingly, no main effect of group (LBP, H) on TCIs was observed. Sex differences in TCI measurements across six directions were not significant, except for LSB in CLBP, where females showed higher stiffness than males. No significant TCI differences were found between CLBP and H groups at rest or during maximal stiffness in any direction. While previous findings of differing TCIs at rest between CLBP and H were not supported, the study reaffirmed higher stiffness in females with CLBP compared to males in the LSB direction. Overall, results suggest that CLBP does not increase trunk stiffness and provide valuable insights into spinal stiffness, which could enhance interventions for CLBP.

2.1. Introduction

Low back pain (LBP) is a common health issue [1][2], affecting over 80% of people at least once in their lifetime [3] with estimates that 4% to 25% of acute LBP cases progress to a chronic condition [4] Medical expenses for chronic low back pain (LBP)—including both direct costs like healthcare and indirect costs such as lost workdays—are some of the highest among chronic health conditions. This is mainly due to absences from work [5]. There is ongoing debate regarding the extent of trunk stiffness in people with low back pain, with many studies indicating that chronic low back pain (CLBP) is frequently linked to heightened trunk stiffness [6][7][8] often in multiple directions [9]. However, some studies suggest that there is no difference in trunk stiffness between individuals with low back pain and healthy controls [10][11]. The ongoing debate around this issue complicates the process for clinicians and researchers in developing and recommending interventions for individuals with low back pain, as it remains uncertain whether the patient experiences trunk stiffness. This is an important matter that deserves further discussion and investigation.

Multiple methods exist to evaluate trunk stiffness, including myotonometry [12], ultrasound-based methods [13][11], and biomechanical modeling [14].

However, each approach has its limitations. Biomechanical modeling underestimates spinal stability by overlooking factors such as intra-abdominal pressure and muscle contributions [1]. It overestimates trunk stability by ignoring energy losses in viscoelastic structures, assumes identical anatomy among individuals, and lacks the capability to directly record all muscle activity in real-world conditions [14]. Ultrasound-based and myotonometry techniques primarily assess muscle stiffness, which limits their ability to

provide a comprehensive understanding of trunk stiffness. Moreover, numerous methodologies depend on intricate second-order linear calculations[15][16], which do not constitute direct measurements of the trunk segment's stiffness and may inadequately reflect actual conditions encountered in practical settings.

There are various methods to perturb trunk posture, including moving platforms, unloading or loading the upper limbs, and applying trunk perturbations. Among these, the perturbation method is preferred for assessing trunk system stability because it isolates the trunk, introduces unpredictable perturbations, and applies controlled force directly to the trunk. This results in small, manageable fluctuations around the target points [15]. Considering the limitations of older methods for assessing trunk stiffness in real-world settings, a direct and practical approach that incorporates individual features, rather than relying on second-order linear modeling and derivatives, greatly enhances the understanding of overall trunk segment stiffness.

Recently, Stamenkovic et al. (2021) introduced the Trunk Compliance Index, a straightforward and unique biomarker that assesses trunk compliance, which is the inverse of stiffness (i.e., higher stiffness means lower compliance). It measures trunk compliance, the inverse of stiffness, by evaluating shoulder displacements relative to the normalized applied force on the trunk in three planes, using direct measurements from the affected segment. The study utilized a quick (100 ms), external, unexpected, and multi-directional perturbation force that minimizes voluntary muscle engagement and emphasizes reflex responses [16].

Considering that individuals with LBP often have stiffer spines, why do some interventions aim to increase trunk co-contraction? Furthermore, can these individuals

85 effectively stiffen (or decrease compliance) of their trunk when prompted to do so? Are
86 they as skilled as healthy individuals in co-contracting their trunk muscles, which may
87 already be contracted? Accordingly, this study aimed to measure and compare the TCI
88 assessed at rest and during maximal contractions between people with LBP and healthy
89 controls. The first hypothesis was that the CLBP group would exhibit a lower compliance
90 index in response to unexpected multidirectional perturbations, indicating increased trunk
91 stiffness when at rest in a seated position. The second hypothesis proposed that females
92 within the CLBP group would have lower compliance—suggesting higher stiffness—
93 compared to males in the same group. The third hypothesis was that the LBP group would
94 demonstrate a reduced ability to stiffen their trunks, resulting in a higher compliance index
95 compared to healthy controls when instructed to stiffen maximally against directional
96 perturbations.

97 ## 2.2. Methods

98 ### *2.2.1. Participants*

99 Participant recruitment was carried out via announcements on university online
100 platforms, including Instagram and Telegram channels, as well as emails, campus
101 monitors, the prior registry (IRB number HM20020513), and flyers distributed across
102 university colleges and departments. After conducting 108 phone pre-screenings in which
103 the study criteria were explained and a brief overview was provided, 41 participants were
104 deemed eligible. A previous study focused on young individuals due to their faster
105 increase in LBP prevalence over time [17][18]. However, the incidence of LBP remains
106 higher in older age groups [19], despite rapid growth in the young population.
107 Consequently, we expanded the age range to include participants aged 18-60 who

experienced episodes of low back pain within the past six months. They reported an average pain score of 3 or higher on a 0-10 Numerical Pain Rating scale and were classified as < 4 on the Quebec Task Force scale for spinal disorders. Participants had no history of spinal surgery, structural deformities, osteoporosis, facet osteophytes, or diagnosed neurological, musculoskeletal, or inflammatory conditions. One participant (#14) was excluded due to severe pain and limited lumbar movement.

The sample size for all aims was calculated based on a recent study by Stamenkovic and Thomas. Using the partial eta-squared (η^2p) from the ANOVA test and averaging the values, the initial estimated total sample size was 8, which is quite small. To ensure sufficient power, we adopted the most conservative and smallest effect size, resulting in a total sample size of 40. Participants were divided relatively equally into four groups: LBP (22 participants, including 11 males) and healthy controls (18 participants, including 9 males). A power analysis confirmed that this sample size provides at least 80% power with an alpha level of $p=0.05$.

2.2.2. data collection

This study was carried out during a single session. After participants received the IRB-approved electronic informed consent via email before data collection, they signed and returned it electronically. The signed consent forms were securely downloaded and stored in the protected REDCap database. Participants experiencing low back pain then completed three surveys: NPRS, ODI, and TSK (refer to Appendix). Following this, a physical examination was carried out, starting with measuring the trunk's range of motion

in six directions: flexion, extension, side bending to both sides, and clockwise and counterclockwise rotation. The clinician also evaluated the myotomes, dermatomes, knee and ankle reflexes, and performed specific tests, including the prone instability test and the active and passive straight leg raise (SLR) tests.

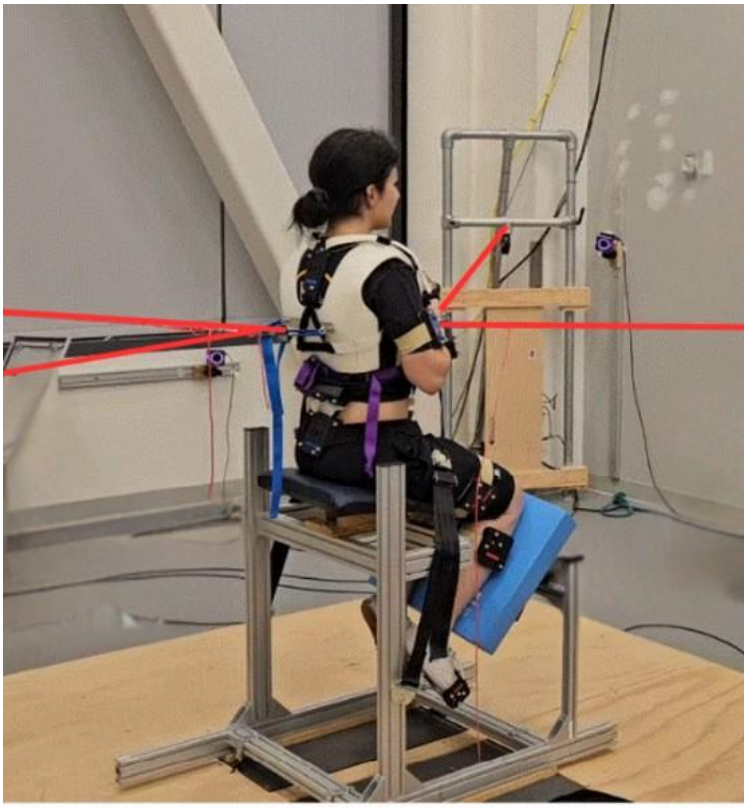
2.2.3. Measuring TCI in 6 Directions

After collecting anthropometric data such as weight, height, and age through screening, and completing surveys and physical exams, the EMG preparation was conducted to lower skin impedance [7]. EMG sensors were attached to the muscles following established methods from previous literature[20]. Subjects were equipped with Avanti surface EMG sensors placed on trunk segments, including bilateral recordings from the abdominal muscles (RA, IO, EO) and lumbar spinal areas (MF and ES). Reflective markers were attached to various body segments—namely the head, thorax, lumbar region, pelvis, as well as the upper and lower limbs, including the upper arm, forearm, hand, thigh, shank, and foot—to facilitate whole-body motion tracking.

Kinematic data collection was carried out using a 12-camera Vicon system (Vero v1.3, Vicon Motion Systems Ltd.), which captured the three-dimensional coordinates of reflective marker clusters placed on the limb and trunk segments with a spatial resolution of 0.1 mm. Each cluster was linked to a specific map of attached reflective markers and pre-assigned to corresponding body segments, such as the head, thorax, lumbar, sacrum, thigh, shank, foot, upper arm, lower arm, and hands, as defined in the Motion Monitor (TMM) software. Afterward, the participant was instructed to stand in a T pose on

two embedded force plates and undergo body calibration. The custom-designed backless chair was then moved into the puller space and positioned on the force plates (see Figure 1). The participant wore a snug-fitting, custom-designed harness around the trunk and sat in the designated chair, which features a slightly forward-sloped seat to maintain mid-range lumbar lordosis. The knees rested on a cushion supported by the chair, while a sturdy belt stabilized the lower limbs.

Figure 1. *The puller system and the costume chair design were used in this study*.



Four lightweight, double-braided polyester cords extend from four actuator motors, arranged in a cross configuration. They are attached to the hooks on the harness at the level of the T3 vertebra—connecting the front hooks to the front right and left motors, and the back hooks to the right and left back motors. (Please check reference [18] for more graphic info on the puller system used in this study.) All cables from the four actuator

motors are pre-tensioned to a force-controlled 5 lbs. (2.25 kg) using custom-designed LabVIEW software (version 2012, National Instruments, Austin, USA). This software was developed to deliver a sufficient and precise impulse to the trunk segment, inducing a 2-inch (5.08 cm) linear displacement within 100 milliseconds. It features a force feedback mechanism utilizing load cells installed in the puller system. Participants were informed that they would experience 30 unexpected, multidirectional perturbations—five trials in each of six directions—delivered one at a time. This initial set of perturbations, performed while resting, aimed to assess trunk compliance. The order of directions was randomized to ensure unpredictability, and participants received no visual or auditory cues about when or where the perturbations would occur. Subsequently, they completed another 30 trials in a similar setup, with six directions and five repetitions each, but this time, they received verbal instructions about the timing and direction of the perturbations. They were instructed to stiffen their trunk completely and resist the perturbations as strongly as possible without moving.

2.2.4. Data reduction

Both the load cell analog signals and the kinematic data were processed with a 41-point, fourth-order Savitzky-Golay filter, which is highly effective smoothing algorithm with minimal attenuation of the original signal [16].

The linear displacement of the left glenohumeral joint, based on the directions of the pulling force, was estimated by subtracting the start point coordinates at rest. These

coordinates were extracted from the TMM XGEN export data, which was calculated using the reflective cluster located on the body segment.

2.2.5. Statistical analysis

Considering the five trials per direction, we accounted for variability among trials to improve our model. Each direction was analyzed separately. The study focused on three factors: gender, perturbation type (unexpected or expected), and pain status (low back pain or healthy). We used linear mixed-effect models (LMMs) in RStudio to test our hypotheses. To examine the effect of each factor individually (Sex × Perturbation Type × Pain Condition), we conducted six separate Type III ANOVAs for specific aims. Effect sizes (partial R^2) were calculated afterwards. These analyses aimed to identify the main effects and interactions of all three factors across repeated measures.

2.3. Results

2.3.1. Participants

A total of 41 participants attended the in-person data collection session. However, participant #14 experienced severe pain and was unable to sit for a few minutes, leading to their exclusion at the beginning of the session. Ultimately, 40 participants completed the single-session data collection, consisting of 22 with LBP (11 male) and 18 healthy participants (9 male). Their data were included in the analysis. No significant differences were observed between groups—in terms of pain and pain-free status—in variables such as age, weight, height, and BMI. Demographic details are presented in Table 1.

Table 1. *Demographic Information of the participants*

	Healthy			***LBP***					
	Male	***Female***	***Total***	***Male***	***Female***	***Total***	***p-value: males H vs LBP***	***p-value: females H vs LBP***	***Total p-value***
n	9	9	18	11	11	22			
Age (yrs)	27.67 (6.91)	31.44 (10.42)	29.56 (8.79)	35.64 (11.89)	32.91 (12.34)	34.27 (11.91)	0.093	0.781	0.171
Weight (Kg)	84.85 (8.47)	70.15 (20.10)	77.50 (16.77)	85.91 (16.88)	73.32 (17.94)	79.62 (18.18)	0.866	0.714	0.707
Height (cm)	176.09 (2.85)	166.49 (8.63)	171.29 (7.95)	178.70 (8.15)	168.30 (8.96)	173.50 (9.91)	0.374	0.653	0.449
BMI (kg/m2)	27.37 (2.74)	25.10 (5.84)	26.24 (4.58)	26.79 (4.15)	25.83 (5.72)	26.31 (4.90)	0.722	0.783	0.963

2.3.2 Survey Results

There were no significant differences in NPRS, TSK, and ODI scores between male and female participants in the low back pain group (Table 2).

Table 2. *Summary of the survey within the LBP group*

	LBP			
	Male	***Female***	***P-value<0.05***	***Cohen's -d***
NPRS	*3.18*±2.36	*1.73*±1.32	*0.115*	-0.702
TSK	*37.3*±9	*35.6*±5.70	*0.616*	*-0.217*
ODI	*7.82*±6.13	*7.45*±5.30	*0.883*	*-0.0635*

2.3.3 TCI values

This analysis provides a statistical review of the models and ANOVAs related to TCIs and three perturbation factors: unexpected versus expected, group classifications (LBP vs. healthy), and biological sex (male vs. female) in Table 3. The main interpretative interactions are summarized in Table 6. Table 4 shows the model-based pairwise comparisons aligned with our study hypotheses, while Table 5 presents the descriptive data for these comparisons.

Our results indicate no significant differences in TCIs across all directions during multidirectional perturbations at rest (aim 1) nor between individuals with back pain and healthy controls (Tables 4 and 5, Figure 2). Additionally, no notable TCI differences emerged between genders (aim 2)—except during left-side bending perturbations, where females with back pain exhibited significantly lower compliance than males (Tables 4 and 5, Figure 3(B)). In the second phase involving expected trials, TCI values did not differ significantly between the LBP and healthy groups across any direction (aim 3) (Tables 4 and 5, Figure 2). As anticipated, the type of perturbation significantly affected all TCIs across genders and groups (Table 3), with the exception of LSB, where expected perturbations resulted in lower TCI or higher stiffness than unexpected ones (Tables 4, Figure 2).

Finally, Figure 4 illustrates all the data categorized by type, showing the overall trends of gender and groups across all six directions during both resting and maximal trunk stiffening.

Table 3*. Summary of Linear Mixed Model Analyses: Effects of Perturbation Type, Group, and Sex on TCI Values in All Six Directions (all main effects and interactions (significant and non-significant)*

Effect	TCI Flex	TCI Ext	TCI LSB	TCI RSB	TCI LRT	TCI RRT
Type	*F(1,337.10)*=41.04 ***p*<.001 *** $\eta 2_p$=0.021 *CI*=[0.058 , 0.002]	*F*(1,347.11)=233.8 ***p*<.001 *** $\eta 2_p$=0.152 *CI*=[0.219, 0.094]	*F*(1,341.27)=3.55 *p*=0.060 **~** $\eta 2_p$=0.002 *CI*=[0.022, 0.000]	*F*(1,342.09)=125.7 ***p*<.001 *** $\eta 2_p$=0.083 *CI*=[0.141, 0.038]	*F*(1,337.04)=327.69 ***p*<.001 *** $\eta 2_p$=0.318 *CI*=[0.389, 0.248]	*F*(1,329.65)=407.10 ***p*<.001*** $\eta 2_p$=0.365 *CI*=[0.435, 0.295]
Group	*F(1,35.04)*=0.4234 *p*=0.51 $\eta 2_p$=0.009 *CI*=[0.037, 0.000]	F(1,36.03)=0.00 *p*=0.99 $\eta 2_p$=0.000 *CI*=[0.013, 0.000]	*F*(1,36.08)=1.63 *p*=0.20 $\eta 2_p$=0.031 *CI*=[0.073, 0.006]	*F*(1,36.01)=3.17 *p*=0.083 $\eta 2_p$=0.057 *CI*=[0.108, 0.021]	*F*(1,35.61)=1.62 *p*=0.20 $\eta 2_p$=0.021 *CI*=[0.058, 0.002]	*F*(1,34.09)=2.89 *p*=0.098 $\eta 2_p$=0.037 *CI*=[0.083, 0.009]
Sex	*F(1,35.04)*=0.67 *P*=0.41 $\eta 2_p$=0.014 *CI*=[0.047, 0.000]	*F(1,36.03)* =0.78 *P*=0.38 $\eta 2_p$=0.014 *CI*=[0.046, 0.001]	*F*(1,36.08)=10.31 ***P*=0.002*** $\eta 2_p$=0.167 *CI*=[0.236 0.107]	*F*(1,36.01)=0.87 *p*=0.35 $\eta 2_p$=0.016 *CI*=[0.050, 0.001]	*F*(1,35.61)=0.83 *p*=0.36 $\eta 2_p$=0.011 *CI*=[0.041, 0.000]	*F*(1,34.09)=0.05 *p*=0.80 $\eta 2_p$=0.001 *CI*=[0.017, 0.000]
Type × Group	*F*(1, 337.10)=3.47 *p*=.063 $\eta 2_p$=0.002 *CI*=[0.020, 0.000]	*F(1,347.11)*=0.56 *P*=0.45 $\eta 2_p$=0.000 *CI*=[0.015, 0.000]	*F(1,341.27)*=0.29 *P*=0.58 $\eta 2_p$=0.000 *CI*=[0.014, 0.000]	*F(1,342.09)*=0.00 *p*=0.98 $\eta 2_p$=0.000 *CI*=[0.013, 0.000]	*F*(1,337.04)=2.56 *p*=0.11 $\eta 2_p$=0.004 *CI*=[0.025, 0.000]	*F(*1,329.65)=1.66 *p*=0.19 $\eta 2_p$=0.002 *CI*=[0.022, 0.000]
Type × Sex	*F(1, 337.10)*=0.03 *P*=0.84 $\eta 2_p$=0.000 *CI*=[0.013, 0.000]	*F(,347.11)*=0.79 *P*=0.37 $\eta 2_p$=0.001 *CI*=[0.016, 0.000]	*F(1,341.27)*=18.29 ***p*<.001 *** $\eta 2_p$=0.012 *CI*=[0.043, 0.000]	*F(1,342.09)*=3.47 *p*=0.063 $\eta 2_p$=0.002 *CI*=[0.022, 0.000]	*F*(1,337.04)=9.8 ***p*=0.00*** $\eta 2_p$=0.014 *CI*=[0.046, 0.000]	*F*(1,329.65)=1.04 *p*=0.30 $\eta 2_p$=0.001 *CI*=[0.019, 0.000]
Group× Sex	*F(1,35.04)*=0.06 *P*=0.79 $\eta 2_p$=0.019 *CI*=[0.019, 0.000]	*F(1,36.03)*=0.97 *P*=0.32 $\eta 2_p$=0.018 *CI*=[0.052, 0.001]	*F(1,36.08)*=1.28 *P*=0.26 $\eta 2_p$=0.024 *CI*=[0.063, 0.003]	*F(1,36.01*)=0.00 *p*=0.99 $\eta 2_p$=0.000 *CI*=[0.013, 0.000]	*F*(1,35.61)=0.00 *p*=0.92 $\eta 2_p$=0.000 *CI*=[0.014 , 0.000]	*F(*1,34.09)=0.16 *p*=0.69 $\eta 2_p$=0.002 *CI*=[,0.022, 0.000]
Type × Group × Sex	*F(1, 337.1)*=8.026 ***P*=0.004 *** $\eta 2_p$=0.004 *CI*=[0.027, 0.000]	*F*(1,347.11)=2.17 *P*=0.14 $\eta 2_p$=0.002 *CI*=[0.019, 0.000]	*F(1,341.27)*=0.36 *P*=0.54 $\eta 2_p$=0.000 *CI*=[0.014, 0.000]	*F*(1,342.09)=1.74 *p*=0.18 $\eta 2_p$=0.001 *CI*=[0.018, 0.000]	*F(*1,337.04)=4.85 ***p*=0.02*** $\eta 2_p$=0.007 *CI*=[0.033, 0.000]	*F*(1,329.65)=0.00 *p*=0.92 $\eta 2_p$=0.000 *CI*=[0.013, 0.000]

Table .4. *Model-based pairwise comparisons of hypothesis-relevant effects across all six directions. The first three columns of data represent the exploratory aims derived from the analysis.*

	Type* Group		Group	Group*Type		Group*Type*Sex
	LBP	**Healthy**	**H-LBP**	**Unexp**	**Exp**	**LBP**
	Exp-Unexp	*Exp-Unexp*	est = -0.674 SE = 1.04 df = 35 p.val =0.519	*H – LBP* **(Aim1)**	*H – LBP***(Aim 3)**	*Unexp*
TCI Flex	est = -0.739 SE = 0.241 df = 337 p.val**= 0.002***	est = -0.739 SE = 0.241 df = 337 p.val**= 0.002***		est = 1.05 SE = 1.04 df = 36.7 p.val =0.357	est = -0.371 SE = 1.05 df = 36.9 p.val =0.725	*Female– Male* **(Aim 2)** est = -0.629 SE = 1.43 df = 36.6 p.val =0.661
TCI Ext	est = -2.89 SE = 0.268 df = 347 p.val <.**0001 ***	est = -3.19 SE = 0.293 df = 347 p.val **<.0001 ***	est = -0.001 SE = 0.973 df = 36 p.val =0.998	est = 0.147 SE = 0.993 df = 39.1 p.val =0.882	est = -0.150 SE = 0.992 df = 39 p.val =0.883	est = -0.571 SE = 1.33 df = 39.1 p.val =0.670
TCI LSB	est = -0.338 SE = 0.189 df = 341 p.val= 0.0744	est = -0.186 SE = 0.204 df = 341 p.val=0.362	est = -0.964 SE = 0.755 df = 36 p.val =0.209	est = -1.040 SE = 0.768 df = 38.5 p.val =0.183	est = -0.888 SE = 0.767 df = 38.4 p.val =0.253	est = -3.790 SE = 1.03 df = 38.7 p.val =**0.0007***
TCI RSB	est = -2.04 SE = 0.246 df = 342 p.val <.**0001***	est =-2.05 SE = 0.269 df = 342 p.val <.**0001 ***	est =-1.67 SE =0.936 df = 36 p.val =0.083	est = -1.67 SE = 0.954 df = 38.8 p.val =0.0887	est = -1.67 SE = 0.954 df = 38.8 p.val =0.0874	est = 0.777 SE = 1.28 df = 38.8 p.val =0.547
TCI LRT	est = -17.9 SE = 1.48 df = 338 p.val <.**0001***	est = -21.4 SE = 1.59 df = 337 p.val <.**0001 ***	est = -4.2 SE = 3.29 df = 35.9 p.val =0.209	est = -2.46 SE = 3.47 df = 44.2 p.val =0.481	est = -5.94 SE = 3.47 df = 44.0 p.val =0.0934	est = -9.12 SE = 4.67 df = 44.8 p.val =0.0572**~**
TCI RRT	est = -19.6 SE = 1.41 df = 333 p.val <.**0001***	est = -22.3 SE = 1.52 df = 331 p.val <.**0001 ***	est = -5.46 SE = 3.21 df = 36 p.val =0.097	est = -4.12 SE = 3.39 df = 44.5 p.val =0.230	est = -6.80 SE = 3.36 df = 43.1 p.val =**0.0492***	est = -1.675 SE = 4.58 df = 45.5 p.val =0.716

Figure 2. *This figure presents both groups in the study—with and without pain—based on the type of perturbation. It allows for comparison of the baseline or resting trunk compliance between the low back pain and healthy groups, which showed no significant difference across six directions. Additionally, it illustrates the maximally stiffened state of the trunk across all six directions, with no significant differences between the groups, except for RRT, which was only apparent in comparison tests but not in the model, and could be due to the type I error. This graph essentially visualizes Table 4.*

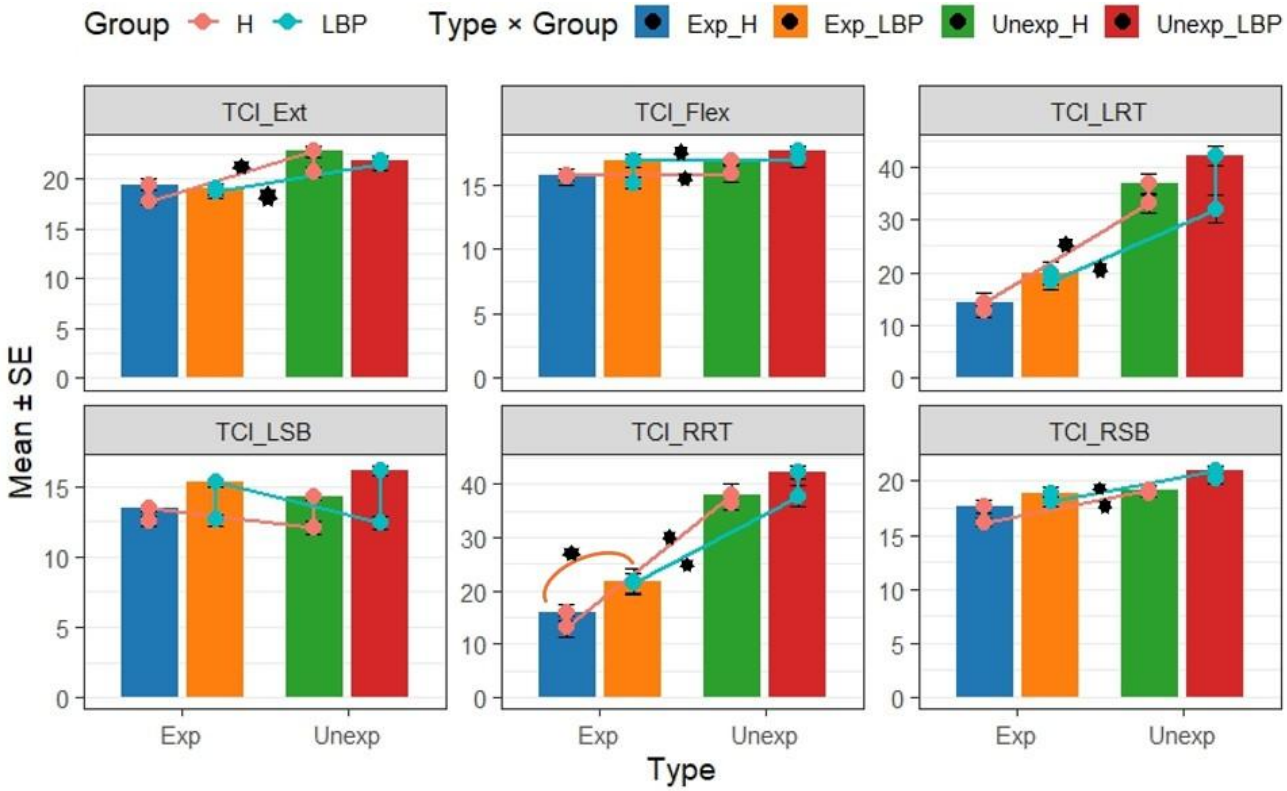


***Table 5**. Descriptive statistics (Means ± SE) for Table 4.*

	Group-Type				Group		LBP-Unexp	
	LBP		Healthy		LBP	Healthy	Female	Male
	Type	*mean± SE*	*Type*	*mean± SE*	*mean± SE*	*mean± SE*	*mean± SE*	*mean± SE*
TCI Flex	*Exp*	15.9 ±0.713	*Exp*	15.5 ±0.771	16.6± 0.704	15.9 ±0.760	16.9 ±1.030	17.6 ± 0.983
	Unexp	17.3 ±0.713	*Unexp*	16.3± 0.769				
TCI Ext	*Exp*	18.7 ± 0.666	*Exp*	18.5 ± 0.735	20.1± 0.653	20.1 ±0.721	21.3 ±0.944	21.9 ± 0.941
	Unexp	21.6 ± 0.666	*Unexp*	21.7 ± 0.736				
TCI LSB	*Exp*	13.9 ±0.515	*Exp*	13.0 ±0.568	14.1 ±0.507	13.1 ±0.559	12.3 ± 0.731	16.1 ± 0.728
	Unexp	14.2 ±0.516	*Unexp*	13.2 ±0.569				
TCI RSB	*Exp*	18.6 ±0.640	*Exp*	16.9 ±0.707	19.6 ±0.628	17.9 ±0.694	21.0 ± 0.906	20.2 ± 0.905
	Unexp	20.6 ±0.640	*Unexp*	18.9 ±0.707				
TCI LRT	*Exp*	19.4 ±2.33	*Exp*	13.5 ±2.56	28.4± 2.21	24.2 ±2.44	32.8 ± 3.31	41.9 ± 3.29
	Unexp	37.4 ±2.34	*Unexp*	34.9 ±2.57				
TCI RRT	*Exp*	21.7 ±2.26	*Exp*	14.9 ±2.49	31.5 ±2.16	26.1 ±2.38	40.5 ± 3.29	42.2 ± 3.18
	Unexp	41.4 ±2.29	*Unexp*	37.2 ±2.50				

Table 6. *Post-hoc Pairwise Comparisons for Significant Interactions Identified in Table 3.*

Directions	***Type*Sex***					***Type* Group*Sex***				
Flex	----					**Group = LBP, Sex = Female:**				
						Contrast: Exp-Unexp	Estimate= -1.840	SE= 0.315	Df= 337	*p-value* <.0001 *
						Group = LBP, Sex = Male:				
						Contrast: Exp-Unexp	Estimate=-0.853	SE= 0.303	Df= 337	p-value 0.005 *
LRT	**Sex = Female:**					**Group = LBP, Sex = Female:**				
	Contrast: Exp-Unexp	Estimate= -16.3	SE= 1.54	Df= 338	p-value <.0001 *	Contrast: Exp-Unexp	Estimate= -12.1	SE= 2.12	Df= 338	p-value <.0001*
	Sex = Male:					**Group = LBP, Sex = Male:**				
	Contrast: Exp-Unexp	Estimate= -23.1	SE= 1.53	Df= 337	p-value <.0001 *	Contrast: Exp-Unexp	Estimate= -23.7	SE= 2.07	Df= 337	p-value <.0001*
LSB	**Sex = Female:**					-----				
	Contrast: Exp-Unexp	Estimate= 0.332	SE= *0.198*	Df= *341*	p-value *0.0935*					
	Sex = Male:									
	Contrast: Exp-Unexp	Estimate= -0.856	SE= 0.195	Df= 341	p-value <.0001 *					

Figure 5 *compares the index between individuals with low back pain and healthy controls across perturbation types (see the three-way interaction in Table 6). Panel (A) illustrates the TCIs across six different directions, segmented by sex and group. Notably, four three-way interactions are significant in the Flex and LRT directions, in which both females and males in the low back pain group exhibit significantly lower compliance at maximal stiffening than at resting compliance levels. Panel (B) presents the same information as Panel (A) but combines gender and group data across the six directions. It shows that females with low back pain have higher baseline stiffness than males with pain in the LSB direction.*



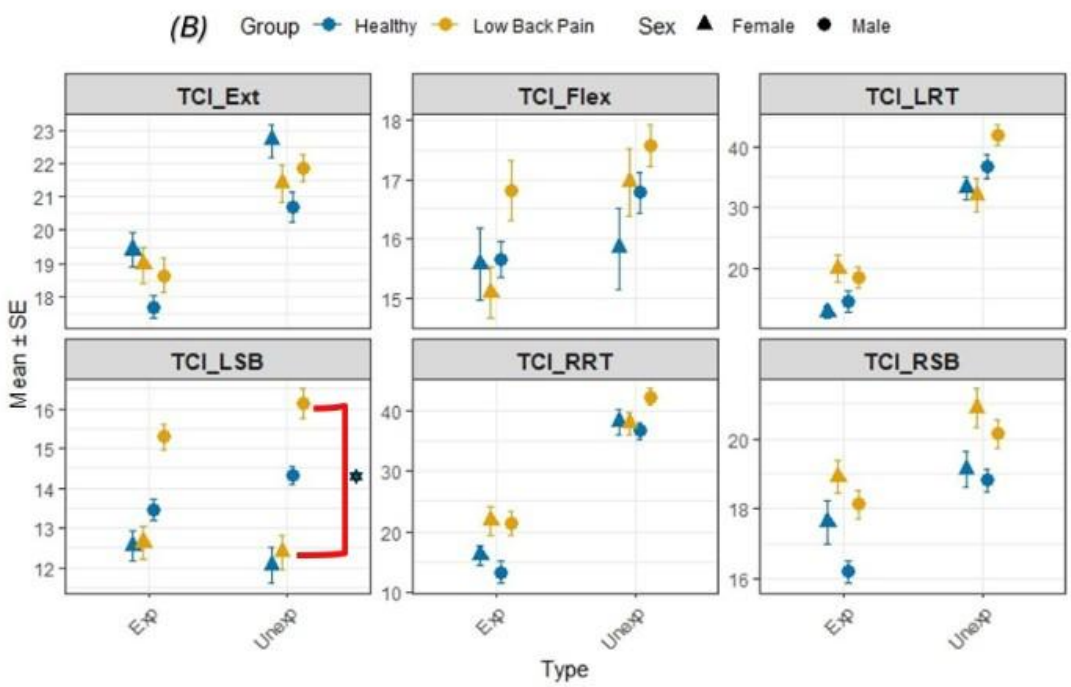
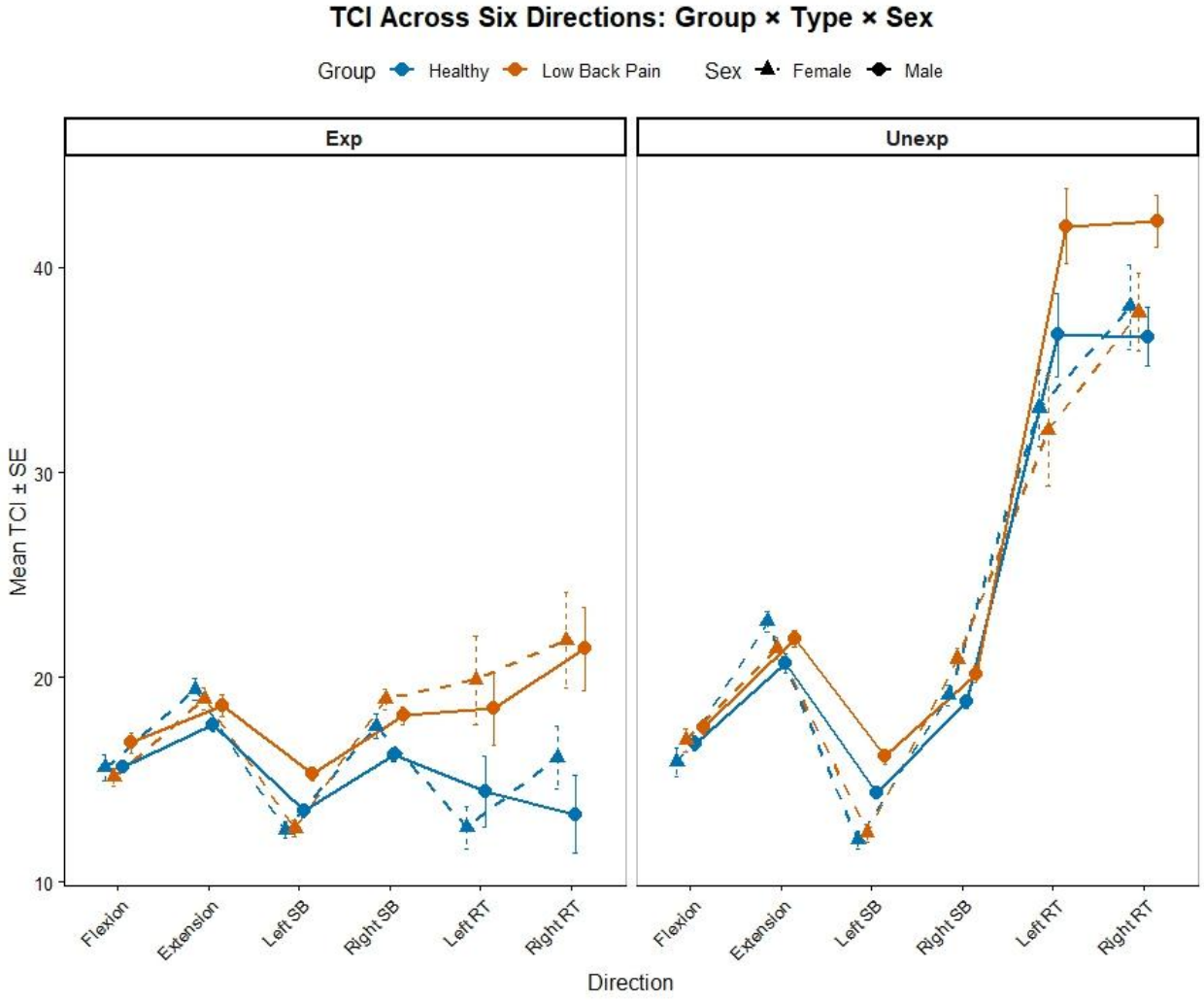

(B)
Group
Healthy
Low Back Pain
Sex
Female
Male
TCI_Ext
TCI_Flex
TCI_LRT
TCI_LSB
TCI_RRT
TCI_RSB
Mean ± SE
Exp
Unexp
Type

Figure 6 *illustrates the trend of indices across all directions between groups and genders. Including unexpected elements that resemble recent studies on this index, which demonstrate that side bendings exhibit the minimum and rotations exhibit the maximum compliance in reaction to unexpected perturbations.*



2.4. Discussion

This study represents an innovative extension of previous research, focusing on examining TCI across a broader age range. It is also the first experiment to measure trunk compliance in three planes—sagittal, frontal, and horizontal—both at rest and during maximally resisted perturbations. The findings are particularly relevant for healthcare practitioners working with individuals experiencing chronic low back pain, as they increase awareness of trunk stiffness and emphasize its importance in developing effective treatment strategies. The research investigates resting trunk stiffness, the ability to fully stiffen the trunk to counter external impulses in various directions, and how these traits may differ among individuals with and without back pain.

2.4.1.Group Factor

Previous research, including a recent study that employed the same methodology and measurement tool (TCI), consistently showed that individuals with low back pain tend to have decreased trunk compliance (i.e., increased stiffness) in various directions when seated. However, the current study unexpectedly found no significant differences in baseline compliance (the resting position) between individuals with CLBP and healthy controls, which was contrary to our initial hypothesis. This lack of difference may be explained by the milder pain levels reported by the low back pain group in this study, compared to the mild-to-moderate pain levels observed in previous research.

During the initial pre-screening, all participants scored at least 3 on the NPRS; however, during the in-person data collection, a few participants reported pain scores

below 3. Consequently, their pain scores at that time fell within the mild category of the NPRS. Additionally, spinal stiffness may decrease in people with low back pain once they recover, as Latimer and Lee (1996) measured segmental postero-anterior spine stiffness in the lumbar region. They found greater stiffness in the low back pain group compared to healthy controls. However, after the participants' pain subsided by more than 80%, a significant reduction in stiffness was observed during the follow-up test [21]. This suggests that the lack of differences between the pain and pain-free groups, despite previous findings indicating that trunk compliance varied across five out of six directions, might be attributed to lower pain levels leading to decreased stiffness.

In the study by Karayiannis et al., which investigated the relationship between high- and low-fear patients and their correlation with stiffness, they emphasized a significant connection: higher fear levels were associated with increased stiffness when subjects were exposed to a forward perturbation [22]. This study reveals that individuals with higher levels of fear tend to have increased stiffness in their trunks compared to those with lower fear levels [22]. In our study, male participants with CLBP had an average Tampa Scale of Kinesiophobia (TSK) score of 37.3 ± 9, whereas female participants had an average score of 35.6 ± 5.70. Notably, only the male group (n=11) exceeded the typical threshold of 37, aligning with findings from some other studies [22]. Our fear scores were typically lower compared to those reported in other studies [23][24][25]. Among our participants, 3 out of 11 males and 4 out of 11 females scored above 37. This may suggest that the fear of movement was not sufficiently high to induce the necessary trunk stiffness to reveal a difference, contrary to earlier findings. As a result, the study did not observe

363 significant trunk stiffness in the sagittal plane, which is inconsistent with previous research
364 [22].

365 The study found that the average duration of CLBP among participants in the pain
366 group was approximately 74 months (73.7 ± 69.5). This duration is slightly longer than
367 what was reported in a previous study conducted by Stamenkovic [16]. However, the
368 milder pain levels observed in the current study could explain why there was no difference
369 in the compliance index between the pain group and the pain-free group, despite the
370 increased duration of chronicity.

371 One possible reason for the results could be the small sample size in our study.
372 We analyzed a total of 40 samples, whereas the earlier study included more than twice
373 that number [16]. Our findings support the 2016 study by Wong et al., which found no link
374 between low back pain and stiffness [26]. This suggests that individuals with low back
375 pain do not necessarily have greater spinal stiffness than healthy controls. Additionally,
376 our findings partially align with Hodges' 2009 study, which employed external perturbation
377 and modeled the trunk as a second-order linear system. That study found that trunk
378 stiffness was significantly higher in the forward direction but not during extension
379 movements, a result comparable to our observations in the pain group relative to matched
380 healthy controls [27]. It is important to recognize that CLBP is a highly heterogeneous
381 condition, exhibiting significant variability among individuals. Factors such as duration
382 (whether chronic, acute, or subacute), medical history, severity, and underlying pathology

all contribute to this diversity. This high level of variability makes it challenging to identify distinct patterns or differences, even when they are present [28]. The findings indicate that the connection between back pain and compliance is more intricate than previously believed, highlighting the necessity for further investigation.

Our study did not replicate the findings of Keller et al.'s early 1980s in vitro experiment, which used cadaveric spine segments to analyze the spine's viscoelastic properties under vertical axial pressure. Their results suggested that spine segments with greater disc degeneration demonstrate reduced stiffness and increased instability compared to less degenerated segments [29]. Unlike their study, our research did not incorporate clinical or paraclinical evidence confirming disc degeneration among our low back pain patients. Additionally, it is important to highlight that Keller's experiment focused solely on the biomechanical viscoelastic properties of the spine, excluding neural and muscular factors from the stiffness evaluation [29]. While other research indicates that factors such as reduced passive stability can cause low back pain and instability, muscular elements may compensate by increasing co-contraction, thereby improving stiffness [30]. In conclusion, our study clearly shows that there are no significant differences in compliance indices—neither increases nor decreases—between individuals with low back pain and healthy control subjects.

2.4.2.Biological Sex Factor

Our findings partially support our second hypothesis, indicating that females with low back pain show greater initial trunk stiffness than males when unexpectedly perturbed during left-side bending. This is in contrast to other directions and aligns with a previous study in TCI, which found that females with low back pain demonstrate significantly lower compliance during left-side bending and extension perturbations [16]. Additionally, our results suggest that, similar to the relaxing state, females exhibited greater stiffness and lower compliance than males when asked to maximally stiffen their spines against left-side bending perturbations. One possible reason why females with pain might not show higher stiffness than males in extension or other directions—except during leftward bending—is that they may have experienced less pain overall compared to their male counterparts. This could imply that the level of pain influences and potentially masks gender differences, leading to no observable differences between males and females within the CLBP group.

One possible reason why the low back pain group might not have exhibited greater stiffness at baseline in the resting position compared to healthy peers is the absence of instability or comparable destabilizing features in the targeted area, which supposedly require higher muscle activity or co-contraction to stabilize the segment. Our study didn't include specific diagnostic measurements, such as X-rays or clinical para-clinical tests, that would have possibly confirmed the presence of any kind of instability or hypermobility. However, the Prone Instability Test was performed on all participants during the physical screening examination. According to a 2015 literature review, the prone instability test, one of the most commonly used tests for evaluating lumbar functional impairments [34],

has demonstrated fair to moderate sensitivity and specificity for diagnosing lumbar instability [31]. Our findings from this test, in the physical examination section of the study, indicated that only 1 of 22 subjects in the pain group had a positive test result. Since this test identifies posterior instability or hypermobility, we can conclude that the result did not indicate significant posterior instability. Consequently, there was no need for compensatory activity of the trunk muscles to decrease compliance or lead to a general stiffening of the trunk. This aligns with the absence of a statistical difference in extension direction between the pain and pain-free groups.

In contrast, the findings of this study were inconsistent with Vazirian's 2016 research on the impact of sex on resting-state stability. While Vazirian's study suggested that asymptomatic males exhibit greater stiffness against forward perturbations compared to females, it measured stiffness while subjects were standing, a position in which the lower back muscles are actively engaged, reducing the likelihood of passive elements being involved [32], and did not present the effective trunk stiffness, which considers both intrinsic (passive and active stiffness) and reflexive responses to impulses [33]. In contrast, in our research, participants were seated in a backless chair with their lower back relaxed and their active muscular elements not engaged. We found no significant difference in stiffness level between the male and female groups across six directions, except for left-side bending, where females in the low back pain group had higher stiffness than their male peers. This difference may result from the different methods used; Vazirian's focus on voluntary muscle activity in an upright position contrasts with our approach, which involves an entirely relaxed lower back. Thus, although Vazirian observed notable stiffness differences between the sexes, with males having a higher

447 level, their target group consisted of asymptomatic subjects [34], whereas ours consisted
448 of subjects with CLBP. Therefore, differences between biological sex in that research may
449 not be generalizable to the low back pain group.

450 One of our method's strengths is that it uses the force feedback mechanism in the
451 load cell, which generates force separately for each individual to create a 2-inch linear
452 displacement over 100 ms. This highlights the uniqueness of generating force tailored to
453 each person, unlike other studies that apply the same force amount to all individuals,
454 regardless of trunk mass or gender [34][35], which may not reflect each individual's actual
455 stiffness, and also the comparison between both genders. In our study, not only was force
456 generated for each individual separately, but we also normalized the force to each
457 individual’s trunk weight to control for potential confounding effects of trunk weight and,
458 consequently, its inertia effect on stiffness.

459 *2.4.3. Expected versus Unexpected Trunk Perturbations*

460 Our study revealed that trunk compliance is significantly affected by perturbation
461 type (expected versus unexpected) in five of six directions, except for left-side bending in
462 females within the pain group. This also confirms that the compliance index system can
463 reliably detect and distinguish different levels of trunk stiffness across various
464 movements, proving its effectiveness and validity. Showing higher stiffness in expected
465 directions can indicate a higher level of muscle activity in response to expected directions
466 and support our findings as consistent with those of others, as individuals actively engage
467 their trunk muscles to counteract disturbances during directional movements [36][37][38],
468 which can result in lower compliance. Feedforward control, in which verbal cues from
469 clinicians about upcoming sensory signals at specific times (temporal anticipation)

activate voluntary muscles [39]. This process supplements reflex muscle activity by recruiting additional muscle fibers, increasing trunk stiffness, improving movement control and minimizing displacement.

One possible reason for the absence of a significant difference in trunk stiffness between the maximally stiffening state and the resting or no-active-contraction state during left-side bending could be the influence of cross-modal spatial cues, such as auditory or verbal directional signals. These cues might have biased motor responses toward the cued side, which in our study was the right side. Kreyenmeier et al. found that sounds consistently influence how we move toward their source [40]. Many studies have shown that both spoken words and sounds can influence how we orient ourselves and where we reach. This means that external cues can change how we plan and execute movements, which may also impact our trunk or body posture when these cues are present [40][41][42]. Words like “left” and “right” have a similar effect to spatial sounds, guiding the attention and shaping the responses toward the indicated side. This suggests that even verbal cues, without accompanying spatial sounds, can automatically direct the focus to a specific location. Research on verbal and auditory cues[41][40] shows that when a cue matches the intended direction, performance improves and movements tend toward that side. Conversely, mismatched cues make it more difficult. In this case, since the verbal cues came from the right side of the person sitting down, they likely led to more movements toward the right, making it easier to move. Giving verbal cues while doing left-side bending from the right side didn’t make that much difference.

This study did not find strong evidence to support the third hypothesis, which proposed that individuals with low back pain have a reduced ability to stiffen their trunk

compared to healthy controls. As a result, we reject our central hypothesis that patients with low back pain have less capacity than healthy individuals. This may be because our participants did not have severe enough back pain to cause long-term changes such as trunk muscle co-contraction, fatigue, inefficiency, or spinal or segmental instability. Segmental instability is characterized by a lack of stiffness during spine movement. It often results in pain under normal external loads, necessitating different motor recruitment patterns to manage the discomfort [43]. Previous research indicates that due to the variability of low back pain and its numerous subdivisions of non-specific LBP, it is challenging to draw clear conclusions about trunk muscle activity in individuals with LBP is challenging [44], especially since trunk muscle activity is essential for maintaining spinal stability. Therefore, it is not surprising that we observed no significant difference in the ability to maximally stiffen the trunk between the two groups.

In a different study, Descarreaux et al. investigated isometric force in individuals with LBP and healthy controls, finding no difference in the ability to generate isometric force during flexion and extension. When the researchers subdivided the pain group into high-pain and low-pain categories, they measured isometric force in both groups, as well as in the no-pain group. The high-pain group had a Visual Analog Scale (VAS) score of 43 ± 9, while the low-pain group scored 14 ± 8. Participants were verbally instructed to produce maximum isometric force against a harness in a standing, neutral posture during both flexion and extension. The results revealed no difference between the high-pain group and controls. However, the low-pain group took longer and generated less isometric force compared to both the high-pain and control groups. The authors suggested that pain intensity does not have a straightforward, linear relationship with

force production deficits. They noted that individuals with high pain levels can sometimes produce normal maximal isometric force during simple tasks by modifying their movement patterns, and some may even exert extra effort to compensate. Additionally, higher pain levels might lead these individuals to bypass protective mechanisms such as muscle guarding or reflex responses, potentially due to adaptation to their pain [45]. Given that our group's pain scores (male = 3.18 ± 2.36, female = 1.73 ± 1.32) fall between the high- and low-pain categories from this study, and considering the self-regulation techniques that people with chronic low back pain often develop to manage their pain, it's not surprising that we observed no significant differences between the groups.

2.4.1 Limitation

The presence of symptomatic patients with mild fear and pain levels may introduce variability that could potentially skew our research outcomes. To achieve a more comprehensive understanding, future studies should consider including individuals with moderate to severe symptoms, allowing for better comparisons across different severity groups. Additionally, investigating the correlation between age and stiffness could provide valuable insights, as age-related physiological changes may significantly influence symptom severity and patient experiences. Increasing the sample size is also essential; a larger cohort would improve the statistical power of our results, leading to more reliable conclusions. Exploring the impact of verbal cues synchronized with movement direction

might help reduce the influence of spatial cues, potentially enhancing patient outcomes and treatment effectiveness. Lastly, examining the relationship between handedness or dominant side and directional stiffness—especially in the frontal plane—could shed light on how these factors affect trunk range of motion. Such variations may contribute to muscle imbalances, alter motor adaptation around the trunk, and increase the complexity of low back pain.

2.4.2. Data Availability

The data used to support the findings of this current study are available, but restrictions apply to their accessibility, and they are not publicly available. However, the data are available upon request and with the permission of the University.

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