



Group differences and associations between patient-reported outcomes and physical characteristics in chronic low back pain patients and healthy controls

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ABSTRACT

Background: Patients with chronic low back pain can exhibit altered slower gait, poor balance, and lower strength/power, and psychological dysfunctions such as pain catastrophizing and fear of movement. Few studies have investigated the relationships between physical and psychological dysfunctions. This study examined associations between patient-reported outcomes (pain interference, physical function, central sensitization, and kinesiophobia) and physical characteristics (gait, balance, and trunk sensorimotor characteristics).

Methods: Laboratory testing included a 4-m walk, balance, and trunk sensorimotor testing with 18 patients and 15 controls. Gait and balance were collected with inertial measurement units. Isokinetic dynamometry measured trunk sensorimotor characteristics. Patient-reported outcomes included PROMIS Pain Interference / Physical Function, Central Sensitization Inventory, and Tampa Scale of Kinesiophobia. Independent *t*-tests or Mann-Whitney *U* tests were used to compare between groups. Additionally, Spearman's rank correlation coefficient (r_s) established associations between physical and psychological domains, and Fisher *z*-tests compared correlation coefficient values between groups (significance $P < 0.05$).

Findings: The patient group had worse tandem balance and all patient-reported outcomes ($P < 0.05$) while no group differences were observed in gait and trunk sensorimotor characteristics. There were significant correlations between worse central sensitization and poor tandem balance ($r_s = 0.446\text{--}0.619$, $P < 0.05$) and lower peak force and rate of force development ($r_s = -0.429\text{--}0.702$, $P < 0.05$).

Interpretation: Observed group differences in tandem balance agree with previous studies, indicating impaired proprioception. The current findings provide preliminary evidence that balance and trunk sensorimotor characteristics were significantly associated with patient-reported outcomes in patients. Early and period screening could help clinicians further categorize patients and develop objective treatment plans.

1. Introduction

Low back pain (LBP) is one of the most commonly reported medical conditions and the leading cause of years lived with disability globally, and the United States has the highest LBP prevalence worldwide (Chen et al., 2022). Mechanical or nonspecific (no obvious tissue/structural damages/tears) is the most prevalent type of LBP that can last <6 weeks (acute), <3 months (sub-acute) to >3 months (chronic) (Cohen, 2015; Hooten and Cohen, 2015). Depending on the levels of pain and physical function, individuals with chronic LBP (cLBP) exhibit deficits in trunk

muscular sensorimotor characteristics such as delayed reaction time (Luoto et al., 1996), lower peak muscular force (Nagai et al., 2015) and slower rate of force development (RFD) (Rossi et al., 2017).

Other sensorimotor characteristics such as position replication (Newcomer et al., 2000), muscular force replication (Descarreaux et al., 2004), and motor unit recruitment (Descarreaux et al., 2004) have mixed findings in cLBP patients. Concurrently, cLBP patients with altered trunk sensorimotor characteristics exhibit whole-body motor control alterations during gait and balance. Specifically, a review paper summarized spatiotemporal gait characteristics in cLBP patients and

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concluded that they walk slower with shorter stride lengths and with greater activation of trunk muscles (known as ‘guarding gait’) (Smith et al., 2022). For standing balance, cLBP patients exhibit greater center-of-pressure displacement and higher center-of-pressure velocity than controls (Ruhe et al., 2011).

The above-mentioned alterations in trunk sensorimotor, gait, and balance characteristics can provide objective metrics in the physical domain for clinicians to customize cLBP treatment strategies. In addition to alterations in the physical domain, cLBP patients often exhibit alterations in the psychological domains (Tagliaferri et al., 2020). For example, some cLBP patients exhibit heightened sensitivity to pain, touch, heat, and pressure (Brumagne et al., 2019). This phenomenon is referred to as central sensitization (CS), defined as an amplification of neural signaling within the central nervous system that elicits pain hypersensitivity (Woolf, 2011). Specifically, pain hypersensitivity is thought to spread to multiple brain regions and cause various psychological dysfunctions (Aoyagi et al., 2019).

Individuals with cLBP with higher CS exhibit high levels of fear of movement (kinesiophobia), pain catastrophizing, and lower quality of life when compared to a group of individuals with cLBP with lower CS (Almeida et al., 2021). Increased fear of movement has shown to be associated with higher intensity of pain, disability, and lower quality of life in cLBP patients (Comachio et al., 2018). These psychological factors, in addition to pain characteristics, would likely make cLBP patients reluctant to engage in rehabilitation exercises and physical activities. It is critical to understand CS and kinesiophobia in cLBP patients as well as their associations with physical characteristics, so that clinicians take appropriate cLBP management steps to reduce psychological distress and improve physical function.

The current study has two aims. First, identify potential deficits in both physical characteristics (trunk-specific sensorimotor; standing balance during eyes-open, eyes-closed, and eyes-closed tandem; and spatiotemporal gait characteristics) and psychological characteristics from patient-reported outcomes (PROs; levels of pain interference, physical function, CS, and kinesiophobia) and compare them between cLBP patients and healthy controls. Second, establish associations between the levels of PROs and physical characteristics within each group and compare the associations between the groups. It was hypothesized that cLBP patients would exhibit both decreased physical characteristics and worse PROs when compared to healthy controls. Additionally, it was hypothesized that physical characteristics and PROs would exhibit significant correlation coefficient values, and there would be significant group differences on the coefficient values.

2. Methods

2.1. Participants

The study was approved by the Mayo Clinic Institutional Review Board (20–008859). This cross-sectional study had 2 groups: cLBP and control. Based on trunk extension peak force and RFD results and calculated effect size values (0.930–0.998) between cLBP and control groups from previous literature (Rossi et al., 2017), a power analysis using G*Power was conducted for $\alpha = 0.05$ (one-tailed), power (1– $\beta = 0.8$), and 2 independent groups. This analysis determined that 28 subjects were required. A total of 18 cLBP patients were screened and recruited by an investigator (BH). The study coordinator then consented each interested participant.

Inclusion criteria for cLBP group were: a) current patients with nonspecific cLBP and b) ages 18–65 years old. Individuals with a history of heart failure, cardiovascular disease, diabetes, or other neurological/cognitive disorders which would hinder their ability to focus and be attentive, were excluded from the study. Clinical characteristics of those 18 cLBP patients are as follows: a) types of cLBP (mechanical: $n = 18/18$, non-mechanical: $n = 0/18$), b) referred pain originating from an organ ($n = 0/18$), c) pain intensity (0–10 scale) during the most recent office

visit (4.6 ± 2.7), d) the location of cLBP (high lumbar spine: $n = 1/18$, low lumbar spine: $n = 15/18$, unknown: $n = 2$), and e) presence of radiating pain to the lower limbs (yes: $n = 3/18$, no: $n = 13/18$, unknown: $n = 2$). A total of 15 healthy control subjects were matched based on sex and age (± 10 years). Demographics are in Table 1. Participants visited the laboratory once for testing (~ 90 min). Laboratory testing consisted of surveys, 4-m walk, standing balance, force steadiness, visual-motor reaction time, peak force, and RFD testing.

2.2. Patient-reported outcomes

The Patient-Reported Outcomes Measurement Information System (PROMIS) was developed by the National Institutes of Health to improve quantification of changes in patient-reported outcomes. The PROMIS pain interference (PI) and physical function (PF) are relevant to cLBP patients (Kendall et al., 2018). The PI consists of 6 questions about how pain interferes with: a) enjoyment of life, b) ability to concentrate, c) day-to-day activities, d) enjoyment of recreational activities, e) doing tasks away from home, and f) socializing with others. This is related to cLBP-specific pain function survey – Roland-Morris Disability Questionnaire (Chen et al., 2019). The PF consists of 4 questions about an individual’s ability to: a) vacuum or do yard work, b) ascend and descend stairs, c) walk at least 15 min, and d) run errands or shop. Four other questions address physical limits: a) doing 2 h of physical labor, b) doing moderate work around the house, c) lifting or carrying groceries, and d) heavy work around the house (Marfeo et al., 2022).

The PI and PF are automatically scored and normalized based on the US population samples with a mean score of 50 and standard deviation of 10 points. Alternatively, the PROMIS raw scores can be calculated by adding points to each response (1: “Not at all” to 5: “Very much”) for PI [total score: 6 (no interference), 30 (maximum interference)] and PF [total score: 8 (no issues), 40 (major issues in physical function)]. In the current study, raw scores were used for the purpose of the study.

The level of CS was examined using the central sensitization inventory (CSI). It consisted of 25 questions about feeling tired, stiff/achy, pain, headaches, sleepless, restless, jaw pain, pelvic pain, etc. (Mayer et al., 2012). Total scores range from 0 to 100. Higher values correspond to higher levels of central sensitization (subclinical = 0–29; mild = 30–39; moderate = 40–49; severe = 50–59; and extreme = 60–100) (Neblett et al., 2017).

The TSK comprises 17 questions with the intent of quantifying fear of motion related to LBP. Responses range from: 1 (strongly disagree) to 2 (disagree), 3 (agree), and 4 (strongly agree). Four questions are reversed on scoring. Total TSK scores range from 17 to 68 (Kori et al., 1990). A total score of 37 and above is considered as having kinesiophobia (Vlaeyen et al., 1995).

Table 1
Demographics and self-reported patient-reported outcomes.

	Group Comparison: mean (SD)		
	cLBP ($n = 18$: 10F/8M)	CON ($n = 15$: 8F/7M)	Group Difference: P-value
Age, years old	44.0 (10.4)	37.1 (15.5)	0.122*
Height, cm	174.8 (10.3)	173.6 (8.9)	0.749
Weight, kg	85.4 (16.9)	79.0 (12.8)	0.293
Body Mass Index, kg/m ²	27.7 (5.3)	25.8 (3.4)	0.521*
PROMIS Pain Interference 6b, 6–30 pts	15.2 (5.6)	6.4 (1.1)	<0.001**
PROMIS Physical Function 8b, 8–40 pts	18.7 (7.0)	8.1 (0.3)	<0.001**
Central Sensitization Inventory, 0–100 pts	32.7 (16.8)	12.3 (9.6)	<0.001*
Tampa Scale of Kinesiophobia, 17–68 pts	35.8 (6.6)	30.1 (3.2)	0.004*

* $P < 0.05$. ** Non-parametric tests. PROMIS: Patient-Reported Outcomes Measurement Information Systems.

2.3. Balance and gait characteristics

For standing balance and walking tasks, Opal inertial motion units (IMUs) were utilized with the *Mobility Lab* software (APDM Wearable Technologies Inc., Portland, OR). The IMUs were positioned on the dorsum of the left and right feet and on the axial lumbar spine at waist level (Fig. 1). All sensors were anchored with Velcro straps to minimize motion between the IMU and the body segment. The sensors sampled at 128 Hz. The sensors contained 3 axes each of accelerometer (± 16 g), gyroscope ($\pm 2000^\circ/\text{s}$), and magnetometer (± 8 G). Orientation estimates of accuracy were 1.2° , 1.5° , and 2.8° for static roll/pitch, static yaw, and dynamic accuracy, respectively.

Balance tasks were implemented standing with eyes-open (3 trials), eyes-closed (3 trials), and eyes-closed tandem (heel-to-toe in a straight line, 3 trials) for 30 s each. A trapezoid-shaped plank (width: 7.5 in.; length: 7.75 in.; and angle: 17.3°) was used between the feet for the eyes-open and eyes-closed standing trials to standardize the distance between feet for all participants. For the eyes-closed tandem stance, everyone was allowed to select which foot they wanted in front but were required to maintain their feet in a line with the heel and the toe touching the opposite foot. Arms were instructed to remain at their side for all balance trials. Balance characteristics were measured from the



Fig. 1. OPAL IMU-Based Sensors for Gait and Balance Tests: one pelvic sensor and two foot sensors.

accelerometer placed at the lumbar spine (L5) and calculated automatically (*Mobility Lab*). The following accelerometer-based balance variables were included: sway area (area spanned from the acceleration signals normalized with respect to the duration of the measurement in m^2/s^4), jerk or jerk index (function of the time derivative of the acceleration; it is an index of sway smoothness in m^2/s^5), mean velocity (first integral of the acceleration signals in m/s), sway path length (total accelerometer trajectory length in m/s^2), RMS sway (root-mean square of the accelerations in m/s^2), range (range of acceleration signals in m/s^2) (Ghislieri et al., 2019). The average values of the three trials were used for statistical analyses.

For the walking trial, a long walkway was provided with taped lines at 0, 1, 5, and 6 m. The individuals were instructed to hold steady during a 3-s calibration and then walk at a comfortable pace to the 6-m line, turn around, and walk back to the start line. No specific instruction was provided on how to turn. Three walking trials were recorded. The following gait variables were included: gait speed (walking speed in m/s), cadence (walking steps per minute), stride length (the distance between two successive points of initial foot contact in meters), stance and swing phase (when the foot is in contact to the ground and in air, respectively, in percentage of the gait cycle time, %GCT), double- and single-support phase (further stance phase break-downs: two limbs and one limb are in contact to the ground, respectively, in %GCT), foot elevation in mid-swing in cm, and lateral step variability (the perpendicular deviation of the middle foot placement from the line connecting the first and the third step in three consecutive steps in cm) (Kobsar et al., 2020). The average values of three walking trials were analyzed for statistical analyses.

2.4. Trunk sensorimotor characteristics

For visual-motor reaction time (VMRT) and force steadiness testing, the HumacNORM dynamometer (CSMi, Stoughton, MA) with an affixed Trunk Modular Component (TMC) allowed for isometric measurements of trunk musculature. Participants stood on the TMC and were aligned with their lumbosacral junction at the rotation point of the TMC. Then, participants were secured with pads and straps (Fig. 2). Participants were asked to stand straight and tall and this angle was used as their baseline 'zero' angle. From there, patients were flexed to 25° and locked in that position for the isometric tasks.

Custom LabVIEW software (National Instruments, Austin, TX) was programmed to interface with the dynamometer torque output via the Delsys Trigno analog wireless sensor (Delsys, Natick, MA). For force steadiness, a trapezoid was displayed on the monitor with a 3-s rest, 3-s ramp up, 10-s hold, 3-s ramp down, and a 3-s rest. The force threshold was set to 54 Nm, which was established based on 33% of the average trunk extension peak force values by healthy individuals in our own investigation. Force steadiness variables were shown to depend on % peak force, and the target forces around 10–35% were most sensitive detecting higher force steadiness magnitude and complexity patterns in individuals with a major musculoskeletal injury (Hollman et al., 2021). The participants were asked to follow the trapezoid as closely as possible by using lumbar extension. Participants were allowed to practice the line trace with their lumbar extension until comfortable with the task. After this, 6 data traces were recorded with alterations of visual feedback and non-visual feedback. Thus, the odd trials had visual feedback and even trials emphasized muscle memory of force and proprioceptive awareness of the lower back to reproduce the prior waveform. During the non-visual feedback trials, participants were provided verbal cues to transition between each phase of the trapezoidal waveform. Variables of interest in the force steadiness testing included: mean force output and coefficient of variation (CoV: standard deviation / mean force output) with and without visual feedback (VF). The difference between the first (with VF) and second (without VF) trials was used as force replication sense. The same procedures (trunk extension steadiness at the target of 54 Nm with VF, followed by without VF) were repeated three times after



Fig. 2. Trunk Sensorimotor Testing. The monitor was later positioned in front of the subject during actual testing to provide visual cues and feedback for visual-motor reaction time and force steadiness testing, respectively.

three practices. Overshooting and undershooting without VF, when compared to force output with VF, resulted in positive and negative values. The average of three force differences with both positive and negative values and only absolute values was used for statistical analyses.

For VMRT, participants were provided a visual interface that displayed a bidirectional force meter which moved upward with extension and downward with flexion. At a random time between 3 and 10 s after trial start, a large arrow appeared pointing either up or down. Once the arrow appeared, the participants were instructed to extend (arrow up) or flex (arrow down) their trunk at maximal effort for at least 3 s. The time between the initiation of arrow appearance and the minimum force threshold (>5 Nm) was used to measure VMRT. Peak force was the highest point during force exertion. RFD was the rate of force changes over specific time points, at: 50 ms, 100 ms, 150 ms, and 200 ms from the initial force threshold. Force output was expressed in Newton-meters (Nm). RFD was expressed in Newton-meters per second (Nm/s) at each time point (RFD50, RFD100, RFD150, and RFD200). Both peak force and RFD were normalized to body weight. Participants were provided a

minimum of 3 practice trials with as many practice trials as needed prior to data collection. For data collection, 6 trials were randomized with 3 flexion and 3 extension trials captured. The average of three trials was used for statistical analyses.

2.5. Statistical analyses

Descriptive statistics (means and standard deviations) were calculated for all variables. Based on the normality testing (Shapiro-Wilk test), the cLBP group and the control (CON) group were compared using independent *t*-tests or Mann-Whitney *U* tests (nonparametric equivalent). Significance was set a priori at $P < 0.05$. The relationship between the physical characteristics and psychological variables was analyzed using Spearman's rank correlation coefficient (r_s) on each group: cLBP and CON. Coefficient values were categorized as none ($r_s = 0$), poor ($r_s = + - 0.1-0.29$), fair ($r_s = + - 0.3-0.59$), moderate ($r_s = + - 0.6-0.79$), very strong ($r_s = + - 0.8-0.99$), and perfect ($r_s = + - 1.0$) (Akoglu, 2018). Significant correlation coefficient was set at $P < 0.05$. In order to examine significant difference between two correlation coefficient

values from each group, Fisher z-test was used. Significance was set a priori at $P < 0.05$ for Fisher z-test values (between-group comparison). Independent t-tests, Mann-Whitney U tests, and Spearman's rank correlation coefficient tests were run using the IBM SPSS Statistical Software v25 (IBM Corp., Armonk, NY).

3. Results

Descriptive statistics and group comparisons for patient-reported outcomes, balance, gait, and sensorimotor characteristics are reported in Table 1-4, respectively. The cLBP group had significantly higher scores than the CON group in all 4 patient-reported outcomes: PI (cLBP: 15.2 ± 5.6 , CON: 6.4 ± 1.1 , $P < 0.001$), PF (cLBP: 18.7 ± 7.0 , CON: 8.1 ± 0.3 , $P < 0.001$), CSI (cLBP: 32.7 ± 16.8 , CON: 12.3 ± 9.6 , $P < 0.001$), and TSK (cLBP: 35.8 ± 6.6 , CON: 30.1 ± 3.2 , $P = 0.004$) in Table 1. For balance variables, the cLBP group exhibited worse balance than the CON group only during the tandem balance task: tandem RMS sway (cLBP: $0.4 \pm 0.26 \text{ m/s}^2$, CON: $0.27 \pm 0.12 \text{ m/s}^2$, $P = 0.044$) and tandem range (cLBP: $3.32 \pm 1.48 \text{ m/s}^2$, CON: $2.10 \pm 1.17 \text{ m/s}^2$, $P = 0.010$) in Table 2. There were no significant group differences in gait and trunk sensorimotor characteristics ($P > 0.05$) in Table 3-4.

Spearman's rank correlation coefficients between the patient-reported outcomes (PI, PF, CSI, and TSK) and gait, balance, and trunk sensorimotor characteristics are seen in Fig. 3. Among patient-reported outcomes, the cLBP group had very strong correlation value between the PI and PF ($r_s = 0.884$, $P < 0.001$) while the CON group had poor correlation value ($r_s = 0.260$, $P = 0.349$). This magnitude difference on the correlation values were significantly different between the groups ($z = -2.91$, $P = 0.036$).

For balance variables, Spearman's rank correlation coefficients between the CSI and tandem balance variables were fair to moderate with mostly significant values in the cLBP group (Sway Area: $r_s = 0.619$, $P = 0.008$; Jerk: $r_s = 0.446$, $P = 0.072$; Mean Velocity: $r_s = 0.617$, $P = 0.008$; Path Length: $r_s = 0.449$, $P = 0.071$; RMS Sway: $r_s = 0.535$, $P = 0.027$; Range: $r_s = 0.591$, $P < 0.012$) while no significant associations were found in the CON group. ($r_s = -0.437$ - 0.086 , $P = 0.118$ - 0.771).

Table 2
Balance characteristics.

	Group Comparison: mean (SD)		
	cLBP (n = 18: 10F/8M)	CON (n = 15: 8F/7M)	Group Difference: P-value
EO Sway Area, m^2/s^4	0.02 (0.02)	0.02 (0.02)	0.681 [^]
EO Jerk, m^2/s^5	0.64 (0.38)	1.10 (1.11)	0.262 [^]
EO Mean Velocity, m/s	0.14 (0.07)	0.15 (0.09)	0.625 [^]
EO Path Length, m/s^2	4.24 (1.32)	4.87 (1.85)	0.278
EO RMS Sway, m/s^2	0.07 (0.03)	0.07 (0.03)	0.625 [^]
EO Range, m/s^2	0.35 (0.17)	0.36 (0.17)	0.860 [^]
EC Sway Area, m^2/s^4	0.02 (0.03)	0.02 (0.02)	0.518 [^]
EC Jerk, m^2/s^5	1.28 (1.03)	1.31 (0.70)	0.570 [^]
EC Mean Velocity, m/s	0.13 (0.13)	0.16 (0.09)	0.100 [^]
EC Path Length, m/s^2	5.43 (1.89)	5.45 (1.28)	0.983
EC RMS Sway, m/s^2	0.08 (0.05)	0.09 (0.05)	0.316 [^]
EC Range, m/s^2	0.38 (0.22)	0.44 (0.18)	0.215 [^]
Tandem Sway Area, m^2/s^4	1.71 (2.14)	0.82 (0.78)	0.077 [^]
Tandem Jerk, m^2/s^5	176.0 (115.4)	104.6 (105.1)	0.092 [^]
Tandem Mean Velocity, m/s	0.62 (0.41)	0.41 (0.15)	0.059 [^]
Tandem Path Length, m/s^2	58.1 (28.2)	40.3 (19.0)	0.054
Tandem RMS Sway, m/s^2	0.40 (0.26)	0.27 (0.12)	0.044^{^*}
Tandem Range, m/s^2	3.32 (1.48)	2.10 (1.17)	0.010^{^*}

^{*} $P < 0.05$. [^] Non-parametric tests. EO: Eyes-Open. EC: Eyes-Closed. RMS: Root Mean Square.

Table 3
Gait characteristics.

	Group Comparison: mean (SD)		
	cLBP (n = 18: 10F/8M)	CON (n = 15: 8F/7M)	Group Difference: P-value
Gait Speed L, m/s	1.05 (0.19)	1.12 (0.18)	0.337
Gait Speed R, m/s	1.03 (0.17)	1.09 (0.16)	0.329
Cadence L, steps/min	100.8 (9.6)	105.0 (7.6)	0.196
Cadence R, steps/min	100.7 (9.4)	104.8 (7.4)	0.191
Stride Length L, m	1.25 (0.14)	1.27 (0.14)	0.596
Stride Length R, m	1.22 (0.12)	1.24 (0.13)	0.651
Stance Phase L, %GCT	61.1 (2.3)	59.9 (1.4)	0.111
Stance Phase R, %GCT	61.0 (2.1)	60.0 (1.4)	0.186 [^]
Swing Phase L, %GCT	38.9 (2.3)	40.0 (1.4)	0.111
Swing Phase R, %GCT	39.0 (2.1)	40.0 (1.4)	0.186 [^]
Double-Support Phase L, %GCT	22.1 (4.4)	20.0 (2.7)	0.246 [^]
Double-Support Phase R, %GCT	22.2 (4.3)	20.0 (2.6)	0.200 [^]
Single-Leg Support Phase L, %GCT	39.0 (2.2)	40.0 (1.4)	0.246 [^]
Single-Leg Support Phase R, %GCT	38.9 (2.2)	40.0 (1.5)	0.246 [^]
Foot Elevation in Mid-Swing L, cm	1.26 (0.60)	1.49 (0.98)	0.416
Foot Elevation in Mid-Swing R, cm	1.39 (0.74)	1.53 (0.75)	0.592
Lateral Step Variability L, cm	3.26 (1.17)	3.53 (1.38)	0.518 [^]
Lateral Step Variability R, cm	3.15 (1.26)	3.73 (1.11)	0.149 [^]

[^] Non-parametric tests. L: Left. R: Right. GCT: Gait Cycle Time.

Table 4
Trunk Sensorimotor Characteristics.

	Group Comparison: mean (SD)		
	cLBP (n = 18: 10F/8M)	CON (n = 15: 8F/7M)	Group Difference: P-value
VMRT Ext, ms	558.8 (54.8)	597.6 (100.9)	0.208
Peak Force Ext, Nm/kg	2.8 (1.0)	3.1 (1.2)	0.421
RFD50 Ext, Nm/s/kg	5.8 (2.9)	7.7 (6.2)	0.981 [^]
RFD100 Ext, Nm/s/kg	12.8 (7.0)	17.4 (16.9)	0.790 [^]
RFD150 Ext, Nm/s/kg	21.6 (12.6)	27.9 (29.9)	0.680 [^]
RFD200 Ext, Nm/s/kg	30.6 (18.1)	31.9 (28.0)	0.716 [^]
VMRT Flex, ms	617.0 (65.3)	673.2 (123.3)	0.188
Peak Force Flex, Nm/kg	2.1 (0.8)	2.5 (1.0)	0.301
RFD50 Flex, Nm/s/kg	6.0 (2.9)	8.3 (6.9)	0.981 [^]
RFD100 Flex, Nm/s/kg	13.6 (7.0)	19.2 (19.0)	0.753 [^]
RFD150 Flex, Nm/s/kg	23.0 (12.4)	29.1 (27.6)	0.451 [^]
RFD200 Flex, Nm/s/kg	30.4 (16.9)	32.8 (24.8)	0.790 [^]
Force VF, Nm	52.4 (1.6)	51.8 (3.3)	0.503 [^]
CoV VF, %	1.4 (0.7)	1.5 (0.9)	0.812 [^]
Force No VF, Nm	55.3 (10.4)	56.0 (11.9)	0.861
CoV No VF, %	3.4 (1.7)	3.3 (1.3)	0.843
Force Sense, Nm	2.8 (9.5)	4.2 (11.1)	0.730
Force Sense Absolute, Nm	8.4 (5.7)	9.5 (7.4)	0.746

[^] Non-parametric tests. VMRT: Visual Motor Reaction Time. RFD: Rate of Force Development. VF: Force Output with Visual Feedback. CoV: Coefficient of Variation.

Consequently, there were significant group differences in those

Demographics / PRO	cLBP (n=18)				CON (n=15)				Force Characteristics	cLBP (n=18)				CON (n=15)			
	PI	PF	CSI	TSK	PI	PF	CSI	TSK		PI	PF	CSI	TSK	PI	PF	CSI	TSK
Height	-0.10	-0.162	-0.378	.164	-.324	.100	-.091	-.014	VMRT Extension	-.418 [^]	-.298	-.266	.255	.378 [^]	-.100	.191	.038
Weight	.001	.296 [^]	.200	.506	-.230	-.452 [^]	-.242	-.120	Peak Force Extension	-.374	-.445	-.429 [^]	-.325	.163	-.251	.457 [^]	.0110
Body Mass Index	-.029	.218	.350	.140	.127	-.205	.039	.023	RFD50 Extension	-.107	-.035	-.342	-.405	-.135	-.401	.159	-.225
Age	.125	.271	-.047	-.252	-.513	-.046	-.526 [*]	.234	RFD100 Extension	-.397	-.382	-.449	-.391	.067	-.100	.200	-.133
PF	.884 ^{**^}	-	-	-	.260 [^]	-	-	-	RFD150 Extension	-.525 [*]	-.511 [*]	-.608 ^{**^}	-.418	.135	-.400	.245	-.010
CSI	.418	.422	-	-	.683 [*]	.182	-	-	RFD200 Extension	-.509 [*]	-.511 [*]	-.572 ^{**^}	-.439	.054	-.500	.109 [^]	.010
TSK	.200	.242	.434	-	.104	-.116	.219	-	VMRT Flexion	.261	.143	.196	.224	.499	-.100	.327	.524
Force Steadiness	PI	PF	CSI	TSK	PI	PF	CSI	TSK	Peak Force Flexion	-.606 [*]	-.730 ^{**^}	-.585 ^{**^}	-.295	-.108	-.100 [^]	.127 [^]	-.124
Force VF	.139	.006	.071	-.043	.192	-.463	.407	.181	RFD50 Flexion	-.448	-.459	-.392	-.135	-.243	.100	.100	.105
CoV VF	.404	.460	.540 [*]	.513 [*]	.280	.386	.324	.266	RFD100 Flexion	-.492	-.470	-.545 [*]	-.118	-.229	.100	-.036	.029
Force No VF	-.422	-.516 [*]	-.300	.007 [^]	.201	-.386	.143	.678 ^{**^}	RFD150 Flexion	-.489	-.439	-.693 ^{**^}	-.382	-.128	.001	-.100	-.076
CoV No VF	.406	.491	.396	.573 [*]	.402	.001	.137	.232	RFD200 Flexion	-.511 [*]	-.466	-.702 ^{**^}	-.424	-.175	-.200	-.091 [^]	-.238
Force Sense	-.425	-.498	-.321	-.027 [^]	.140	.001	.055	.656 ^{**^}	Gait Characteristics	PI	PF	CSI	TSK	PI	PF	CSI	TSK
Force Sense ABS	-.372	-.463	-.371	.113	.323	-.309	.225	.328	Gait Speed L	.052	-.102	-.099	-.200	-.601 [*]	-.152	-.361	-.196
Balance Characteristics	PI	PF	CSI	TSK	PI	PF	CSI	TSK	Gait Speed R	.004 [^]	-.118	-.139	-.201	-.699 ^{**^}	-.101	-.367	-.124
Sway Area EO	.375	.500 [*]	.357	.085	.234	.560 [*]	.444	.027	Cadence L	.005	-.102	-.078	-.424	-.365	-.101	-.345	-.119
Jerk EO	.148	.267	.324	-.237	.460	.253	.314	.250	Cadence R	-.034	-.137	-.121	-.448	-.405	-.101	-.385	-.173
Mean Velocity EO	.305	.377	.221	.114	.509	.253	.363	-.011	Stride Length L	-.081	-.250	-.184	-.082	-.668 ^{**}	-.051	-.358	-.225
Path Length EO	.177	.228	.286	-.006	.282	.253	.332	.176	Stride Length R	-.119	-.267	-.255	-.025	-.670 ^{**}	-.076	-.256	-.045
RMS Sway EO	.204	.314	.307	-.116	.516	.457	.297	-.058	Stance Phase L	.032	.248	.287	.195	.454	.101	.253	.115
Range EO	.256	.392	.356	-.093	.579 [*]	.405	.367	.045	Stance Phase R	.047	.188	.314	.270	.579 [*]	-.051	.420	.142
Sway Area EC	.315	.362	.337	.023	.172	.456	.147	-.167	Swing Phase L	-.032	-.248	-.287	-.195	-.454	-.101	-.253	-.115
Jerk EC	-.103	.129	.231	-.123	.478	.152	.152	.320	Swing Phase R	-.047	-.188	-.314	-.270	-.579 [*]	.051	-.420	-.142
Mean Velocity EC	.288	.296	.592 [*]	.060	.549 [*]	.456	.099	-.171	Double-Support Phase L	.077	.262	.311	.243	.512	.051	.305	.158
Path Length EC	-.010	.183	.272	.064	.110	-.203	-.011	.095	Double-Support Phase R	.070	.234	.323	.262	.512	.001	.297	.160
RMS Sway EC	.155	.268	.400	-.068	.561 [*]	.482	.055	-.014	Single-Leg Support Phase L	-.160	-.321	-.361	-.258	-.579 [*]	-.051	-.376	-.097
Range EC	.111	.272	.343	-.099	.588 [*]	.506	.081	-.101	Single-Leg Support Phase R	-.079	-.272	-.357	-.219	-.405	-.152	-.222	-.185
Sway Area TD	.212	.279	.619 ^{**^}	.512 [*]	-.205	-.152	-.288 [^]	.191	Foot Elevation L	.002	.117	-.167	-.092	-.260	-.203	-.121	-.425
Jerk TD	.151	.146	.446 [^]	.392	-.414	-.405	-.358 [^]	.063	Foot Elevation R	.007	.130	-.195	-.345	-.360	-.355	-.548 [*]	-.396
Mean Velocity TD	.352	.403	.617 ^{**^}	.497 [*]	.043	-.203	-.086 [^]	.216	Lateral Step Variability L	.544 ^{**^}	.560 [*]	.414	-.217	-.270 [^]	.152	-.279	.254
Path Length TD	.105	.112	.449 [^]	.368	-.561 [*]	-.203	-.437 [^]	.086	Lateral Step Variability R	.496 ^{**^}	.378	.244	.128	-.411 [^]	-.101	-.398	.115
RMS Sway TD	.176	.295	.535 ^{**^}	.410	-.215	-.203	-.314 [^]	.190									
Range TD	.300	.392	.591 ^{**^}	.435	-.254	-.304	-.393 [^]	.194									

Fig. 3. Correlation matrix between patient-reported outcomes [PROMIS pain interference scale (PI), PROMIS physical function scale (PF), central sensitization inventory scale (CSI), and tampa scale of kinesiophobia (TSK)] and demographics, patient-reported outcomes, balance / gait / trunk sensorimotor characteristics in the control (CON) and chronic low back pain (cLBP) groups. VMRT: Visual-Motor Reaction Time, RFD50/100/150/200: Rate of Force Development at 50/100/150/200 ms, VF: Visual Feedback, CoV: Coefficient of Variation, ABS: Absolute values, L: left, R: right, EO: Eyes-Open, EC: Eyes-Closed, and TD: Tandem. * Significant correlation test: $P < 0.05$. ** Significant correlation test: $P < 0.01$. ^ Significant Fisher z-test between the groups: $P < 0.05$.

correlation values ($z = -2.08-2.83, P = 0.005-0.038$).

For gait characteristics, Spearman's rank correlation coefficients between the PROMIS PI and lateral step variability were significant (Lateral Step Variability L/R: $r_s = 0.544/0.496, P = 0.024/0.043$) while no significant correlations were observed within the CON group (Lateral Step Variability L/R: $r_s = -0.270/-0.411, P = 0.351/0.145$), resulting the significant group difference (Lateral Step Variability L/R: $z = -2.28/-2.53, P = 0.022/0.0114$). Other significant Spearman's rank correlation coefficients were found between the PI and slower gait characteristics within the CON group (Gait Speed L/R: $r_s = -0.602/-0.699, P = 0.023/0.005$; Stride Length L/R: $r_s = -0.668/-0.670, P = 0.009/0.009$; Swing Phase R: $r_s = -0.579, P = 0.030$; Single-Leg Support Phase L: $r_s = -0.579, P = 0.030$).

For force characteristics, Spearman's rank correlation coefficients between the patient-reported outcomes (PI, PF, and CSI) were negatively associated with peak force and RFD, resulting several significant correlation values ($r_s = -0.509-0.730, P = 0.001-0.044$) in Fig. 3. For trunk sensorimotor characteristics, higher CSI and TSK values were associated with larger CoV values (less steady) within the cLBP group ($r_s = 0.540-0.573, P = 0.020-0.042$).

4. Discussion

4.1. Demographics and patient-reported outcomes

In the current investigation, the PI, PF, CSI, and TSK values in the cLBP group were lower than the values reported in the previous studies (Kendall et al., 2018; MA Ma et al., 2023; Shaw et al., 2022; Zheng et al., 2022). All cLBP patients were current patients under the care of a chiropractor and co-author (BH), and due to the nature of physical testing, we have recruited only cLBP patients without any history of general health issues such as heart/lung, diabetes, and/or neurological/cognitive issues. Other than cLBP and related-issues, patients were active and able to work. Based on the clinical threshold of CSI (over 40 points) and TSK (over 37 points), there were 6 cLBP patients with positive CSI (33%), 7 cLBP patients with positive TSK (38%), and 3 cLBP

patients with both (16.7%).

Among the patient-reported outcomes, the association between the PI and the PF values in the cLBP group was very strong ($r = 0.884$) in the current study, which is higher than the previous reported correlation values ($r = 0.480-0.717$) (Karayannis et al., 2023; Kendall et al., 2018). It is reasonable to assume that cLBP can interfere with daily activities and physical functions. Additionally, there is significant association between higher body weight and the PF (more issues with physical function) was more pronounced in the cLBP group as obesity as one of most commonly reported risk factor for low back pain (Zhang et al., 2018).

On the other hand, associations among other patient-reported outcomes did not reach statistically significance ($P = 0.072-0.426$) which is also in agreement with the previous study (Karayannis et al., 2023). Different patient-reported outcomes such as CSI and TSK address individual's psychological dysfunctions specific to pain centralization and fear of movement, respectively. Physiologically, functional magnetic resonance imaging studies in cLBP revealed that cLBP patients are associated with the dysfunction in the thalamus, transmitting sensory/nociceptive information and motor impulses, the primary/secondary somatosensory (S1/2) and motor cortex (M1), and the thalamocortical circuits (Mao et al., 2022) while LBP patients with fear of movement is associated with the extended amygdala and its connectivity to the anterior insula (Meier et al., 2016). Central sensitivity is rather associated with the gray matter volume decreased in the anterior cingulate and prefrontal cortex (Cagnie et al., 2014). Accordingly, there is an ongoing effort to evaluate physical, psychological, and social functioning, and health-related quality of life domains separately for better cLBP management (Tagliaferri et al., 2020).

4.2. Balance characteristics

Balance deficits are one of common clinical signs and physical testing for cLBP patients as they often exhibit decreased somatosensory function. These balance deficits are often exacerbated by reduced visual feedback (eyes-closed condition) or different head positions for

vestibular disturbance as the proprioceptive feedback has to contribute more to maintain their upright posture (Berenshteyn et al., 2019). In the current study protocol, eyes-closed tandem balance was the most challenging task compared to simpler eyes-open/–closed standing balance with feet apart. While all accelerometer-based balance variables were worse in the cLBP group than in the CON group ($P = 0.010$ – 0.092), eyes-closed tandem balance RMS sway and range were significantly different between the groups ($P = 0.044$ and $P = 0.010$, respectively).

More challenging tandem eyes-closed balance tasks might have elicited psychological disturbances such as negative emotion (processed by the anterior cingulate cortex) and fear of movement (processed by the amygdala). This contention was partially supported as the current findings that the correlations between the tandem balance variables and CSI were fair to moderate ($r_s = 0.446$ – 0.619 , $P = 0.012$ – 0.072) (Fig. 2). These positive correlations between poor balance characteristics and higher CSI were found only in the cLBP group, resulting significant group differences ($z = -2.08$ – 2.83 , $P = 0.085$ – 0.0271). To a lesser degree, fair positive association between poor tandem balance variables and higher TSK were found ($r_s = 0.368$ – 0.512 , $P = 0.036$ – 0.146) while no group differences in the correlation values were found ($z = -0.63$ – 0.96 , $P = 0.337$ – 0.523) (Fig. 2). These preliminary findings support the previous report suggesting that cLBP patients with CS comprise a separate and distinctly different subcategory of cLBP patients (Aoyagi et al., 2019). A larger sample size is needed to confirm this finding in future investigations.

4.3. Gait characteristics

Although the cLBP patients walked at slower speed (less step cadence and stride length), there were no group differences in spatiotemporal gait characteristics in the current investigation ($P > 0.05$). Similarly, correlation coefficients between the levels of CSI and TSK and gait characteristics were not significant within the cLBP group ($r_s = -0.361$ – 0.414 , $P = 0.098$ – 0.765), rejecting the hypotheses. Traditionally, trunk muscular activities with surface electromyography is used to examine if cLBP patients walk with ‘guarding gait strategy’, and walking at faster speed could further activate more trunk muscles and provoke pain catastrophizing emotion to alter walking gait (Pakzad et al., 2016). It is likely that the current self-selected 4 m-walk test was too easy for most cLBP patients. Similar to the balance tasks with eyes-open standing, easy tasks have failed to differentiate between the cLBP and the CON groups. Within the cLBP group, only significant associations were found between greater lateral step variability and the PI/PF values ($r_s = 0.496$ – 0.560 , $P = 0.019$ – 0.043), and those correlations values were significantly different between groups ($z = -2.29$ – 2.53 , $P = 0.0114$ – 0.022). It is speculated that cLBP patients with higher PROMIS PI/PF values (more issues) might also have exhibited proprioceptive deficits, which could result in larger gait variability (Hamacher et al., 2016).

Interestingly, significant negative correlations were found between the walking speed and stride length and the PI values within the CON group ($r_s = -0.601$ – 0.699 , $P = 0.009$ – 0.023). It is possible that spatiotemporal gait characteristics of ‘guarding gait’ such as slower walking speed, smaller stride length, more stance time, and less swing phase might be early signs of pain interference in the CON group. As analytics and prediction models get more sophisticated and accurate with help of the Artificial Intelligence and Machine Learning, simple 4-m walk with biomechanical variables might be able to provide clinicians early sub-clinical warning signs so that LBP could potentially be prevented from pain chronification and pain catastrophizing. Indeed, a recent Machine Learning model of walking gait in cLBP patients revealed that cLBP patients use a ‘loose control’ strategy with more variability while cLBP patients with clinical CS use a ‘tight control’ strategy with more regular, less variable, and predictable gait pattern (Zheng et al., 2022). Future studies could incorporate these complex analytics and add clinical relevance for simple physical tests.

4.4. Trunk sensorimotor characteristics

Although cLBP patients produced less peak force and RFD, none of the trunk sensorimotor characteristics were significantly different between the cLBP group and the CON group, rejecting the hypothesis. Specifically, the current study is one of the first studies to have examined VMRT; but, it appears that VMRT does not seem to be affected by cLBP at all, contrary to the previous finding (Luoto et al., 1996). On the other hands, associations between higher levels of the patient-reported outcomes (PI/PF, CSI, and TSK) and weaker trunk extension and flexion peak force and RFD were significant in several variables, partially supporting the hypothesis. Chronic pain could influence both the somatosensory cortex (S1/S1) and the primary motor cortex (M1) to reduce the corticospinal excitability, resulting a reduced muscular force (Chang et al., 2018). This inhibition is likely underlying physiological mechanisms of the current findings. Specifically, the associations between the CSI and the trunk extension and flexion RFDs were more pronounced in the late RFD phase (150/200 ms) than the early RFD phase (50/100 ms). This current finding is in agreement with the previous finding (strength deficits in LBP patients more pronounced in the later RFD phase (100/200 ms) than early RFD phase (30/50 ms) (Rossi et al., 2017). The authors highlighted that early and late RFD were related to the neural characteristics and muscular size / force production capabilities, respectively.

For force steadiness characteristics, there were no group differences on force accuracy and force steadiness (CoV), rejecting the hypothesis. The previous study reported that cLBP patients generally underestimate the target force when visual feedback is removed while the controls do the opposite (overshooting) (Coppeters et al., 2021). No such differences were observed in the current study that utilized force replication as a means to examine conscious proprioception. Force sensing mechanoreceptors (i.e. primarily, the golgi tendon organ) might not be affected by cLBP, unless it is tested under the fatigued condition. Instead, based on fMRI study with trunk muscle vibration, muscle spindle Ia afferents and its processing center at the somatosensory cortex might be contributing proprioceptive deficits in the cLBP patients. Instead of force proprioception testing, threshold to detect movement proprioception modality might be preferred for targeting the muscle spindles.

Despite a lack of group differences in force steadiness and accuracy, significant positive correlations were found between CSI/TSK and CoV within the cLBP group. In the current study, CoV was used as force steadiness during submaximal isometric contractions. This simple task is influenced by several factors: oscillations in the neural drive to muscle, the number of motor units, motor unit recruitment, and the contractile properties of the motor units (Enoka and Farina, 2021). While there have not been any studies on CoV with and without clinical CSI/TSK in cLBP patients, to our knowledge, CoV were shown to increase under the emotional conditions (pleasant picture: smiling/happy face, unpleasant picture: venomous snake) (Blakemore et al., 2016). Given the fact that chronic pain, central sensitization, and fear of movement could affect the brain structures that are linked with emotions (the amygdala, the insula, and the prefrontal cortex), positive correlation between higher variability and high CSI/TSK could be explained.

4.5. Limitations

cLBP patients were convenient samples at the institution and inclusion/exclusion criteria were vaguely defined, resulting that the majority of cLBP patients were relatively healthy without clinical signs of CSI/TSK. Clinical pain scores were taken only during the clinical visit prior to laboratory testing. In other words, we failed to collect pain level on the day of actual laboratory testing (pre-/post-testing). A larger study sample size could categorize the cLBP group into subgroups: without CSI/TSK, with CSI, with TSK, and with CSI/TSK. Similarly, it is important to recognize that laboratory testing variables and patient-reported

outcomes as well as epidemiology of cLBP differ between prior injury/disease history, socioeconomic status, races, sexes, ages, occupations, etc. The current findings could lack generalizability.

5. Conclusions

The current study demonstrated balance deficits in cLBP patients. Self-reported patient-outcome reports such as the PI/PF/CSI/TSK were significantly associated with balance, gait, and trunk sensorimotor characteristics within the cLBP group. Future studies should explore potential multi-domain cLBP treatments.

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CRediT authorship contribution statement

Nathan Schilaty: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Nathaniel Bates:** Methodology, Formal analysis, Investigation, Writing – review & editing. **Benjamin Holmes:** Conceptualization, Writing – review & editing, Supervision. **Takashi Nagai:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare no conflicts of interest.

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