ORIGINAL ARTICLE

Nr 2024;14 (4):601-613

Comparison of Intersegmental Coordination and Movement Variability in Athletes with and without Persistent Low Back Pain

Sajjad Abdollahi[1], Rahman Sheikhhoseini[1], Wendy E. Huddleston[2]

[1] *Department of Corrective Exercise & Sport Injury, Faculty of Physical Education and Sport Sciences, Allameh Tabataba'i University, Tehran, Iran*

[2] *Department of Rehabilitation Sciences & Technology, College of Health Sciences, University of Wisconsin-Milwaukee, Milwaukee (WI), U.S.A.*

CORRESPONDING AUTHOR:
Rahman Sheikhhoseini
Department of Corrective Exercise & Sport Injury
Faculty of Physical Education and Sport Sciences
Allameh Tabataba'i University
Western Azadi Sport Complex Boulevard
Tehran, Iran
E-mail: Rahman.pt82@gmail.com

DOI:
10.32098/mltj.04.2024.10

LEVEL OF EVIDENCE: 4

SUMMARY

Background. Persistent Low Back Pain (PLBP) is a prevalent musculoskeletal disorder affecting 70-85% of the world population during their lifetime. PLBP may alter intersegmental coordination and movement variability. The current study aimed to compare pelvic, trunk, and lower extremity inter-segmental coordination patterns and movement variability in athletes with and without PLBP during free-speed gait.

Methods. In this cross-sectional study, kinematic data were collected using an eight-camera motion analysis system (Vicon, Oxford Metrics, London, England) from 24 male basketball players' gait at their own pace (n = 12 in the PLBP group and n = 12 in the non-PLBP group). The trunk-pelvis and bilateral pelvis-thigh, thigh-shank, and shank-foot coordination pattern and variability over the stance and swing phases of gait were quantified by deriving the mean absolute relative phase (MARP) and deviation phase (DP). Independent Samples T-test was used to compare group means for DP and MARP.

Results. The PLBP group exhibited stronger synchronization and less movement variability between the trunk and pelvis during different phases of movement. Moreover, the PLBP participants showed less consistent coordination between the pelvis and thigh in the sagittal, frontal, and transverse (rotational) planes during various phases of walking. Specifically, we observed that the PLBP group had more in-phase coordination between the thigh and shank in the sagittal and frontal planes, as well as between the shank and foot in the sagittal and transverse planes. These findings collectively suggest that individuals with persistent low back pain exhibit distinct patterns of movement coordination compared to those without low back pain.

Conclusions. It seems that the presence of PLBP may change lower extremity, pelvic, and trunk coordination and movement variability in all planes of motion. More in-phase coordination and less movement variability in athletes with PLBP may be the possible explanation for the high prevalence of reoccurrence of LBP in patients.

KEY WORDS

Low back pain; athletes; gait analysis; biomechanics; coordination; movement variability.

INTRODUCTION

Persistent Low Back Pain (PLBP) is a prevalent musculoskeletal disorder affecting 70-85% of the world population during their lifetime (1). Up to 85% of LBP cases, however, are classed as non-specific LBP or LBP with undetermined etiology (2). Some consider low back pain to be the most common disorder among athletes (3-5), and athletes who experience low back pain may experience a reduction in athletic performance (6). Numerous athletes who suffer from low back discomfort may also incur significant functional impairments after retiring from competition (4). Thus, the identification of modifiable risk factors is necessary to reduce the incidence of LBP in athletes. Athletes' specific LBP movement patterns and risk factors of injury differ from a non-athlete population (7, 8) and warrant special consideration. Moreover, researchers and physiotherapists have created suggested rehabilitation regimens to address the harmful adverse effects of PLBP, but these protocols are not always effective (9-12). This may be because rehabilitation regimens do not sufficiently address the causes of, and impairments in, neuromuscular function.

Extensive studies have explored the impact of PLBP on gait parameters due to the essential role of locomotion in human life. Kinematics/kinetics assessments consistently indicate reduced walking speed, swing time, and step lengths among athletes suffering from PLBP (13, 14). Furthermore, Muller *et al.* (15) demonstrated that individuals affected by PLBP present reduced ground reaction forces and pelvic rotation amplitude during level gait. Additionally, these subjects exhibited significantly greater extension in knee joint angles upon touch-down. (15). In addition, athletes with low back pain prefer to walk with their knees extended during the load acceptance phase of gait (16), or walk with an anterior pelvic tilt, excessive hip flexion, decreased knee flexion capacity during the swing phase, and restricted ankle power production during push-off (17). These biomechanical changes noted in persons with PLBP may be associated with balance impairment (18), impaired motor control (19), altered control strategies (20), and altered trunk muscular activity (21).

In spite of generally consistent observations regarding the impact of PLBP on gait in a general population, the biomechanical strategies used by athletes during walking is not well understood. Human gait is a complex activity requiring a high level of motor control to produce coordinated limb motions (22) such that quantifying such movements with kinematic/kinetic parameters alone has been difficult (23, 24). Complex movements are not created exclusively from the single joint movement summation (25). Thus, spatial and temporal gait characteristics or single-joint kinematics/kinetics analyses cannot serve as an accurate indicator of pathology (26), or accurately demonstrate changes in neuromuscular control (22).

Recent advancements in the field of non-linear dynamics propose that capturing the underlying coordination dynamics in motor tasks can be more effectively achieved by utilizing collective variables, specifically intersegmental/inter-joint coordination (ISC/IJC). This approach contrasts with the conventional gait analysis that primarily focuses on lower-order variables like kinematic/kinetic measures. The utilization of collective variables, such as ISC/IJC, is suggested to provide a more comprehensive understanding of the coordination dynamics involved in motor tasks (27, 28). These measurements are extraordinarily helpful for understanding how the neuromusculoskeletal system organizes redundant joint degrees of freedom (DoF) to achieve precise and fluid functional movement. Inter-segment/inter-joint coordination analysis identifies movement patterns by characterizing the spatiotemporal structure of segments/joints (29). The maintenance of precise interconnections between limb segments or joints is essential for facilitating sequential functional movement (30).

Continuous relative phase analysis (CRP) is a technique used to quantify coordination patterns based on the theory of dynamic systems (31). The CRP approach correlates the angular position and velocity of two segments or joints continuously during the gait cycle (32). Furthermore, the variability of these correlations can be used to quantify the neuromuscular system consistency (33). It has been proclaimed that these parameters are better suited for discerning the motor control mechanisms implicated in gait (34, 35). In simple words, the coordination pattern and variability are considered essential features of human movements. These measures can also provide rich information about how motor control is changed in persons with PLBP (21).

Many locomotion problems in athletes with PLBP have been attributed to relatively poor coordination (21). The evaluation of inter-segmental coordination in PLBP subjects during gait can reveal how motor control is altered in PLBP (21). Several research studies have indicated that individuals with PLBP exhibit aberrant coordination patterns and heightened variability during dynamic activities such as gait (21, 34), running (34, 36), or other activities (33, 37). Regarding these investigations, PLBP is primarily associated with trunk-pelvis coordination, and athletes afflicted with this condition typically encounter challenges in adapting their coordination during higher speeds or demanding tasks.

It has been stated, however, that "the trunk is part of a system, the human body" (38). Therefore, the spine should not be evaluated regardless of the lower extremities in PLBP patients (39). Song *et al.* stated that the movements of the lower limbs are substantial factors associated with the perma-

nence or development of PLBP (40). Moreover, Muller indicated that trunk and lower limb movements interact with each other (15). As alterations in lumbopelvic control may impact the lower extremities (41), it is crucial to investigate the potential consequences of PLBP on the movement patterns and coordination of the lower extremities.

Many studies have demonstrated changes in the biomechanical parameters of individual segments or joints in relation to LBP during gait (22, 42-46), with comparatively little attention on the movement patterns across the torso and lower limb. To the best of our knowledge, many studies have evaluated PLBP among non-athletes. Still, research needs to be replicated in athletes with different activities for many reasons, including physiological and psychosocial differences between athletes and non-athletes. Furthermore, there is a lack of research investigating the correlation between PLBP and coordination patterns as well as variability in lower limb movements during gait among athletes. Therefore, the purpose of this research was to explore and compare the ISC and coordination variability of the lower extremities in conjunction with the pelvis and trunk in sagittal, frontal, and transverse planes of motion during gait among athletes with and without PLBP. We hypothesize that athletes with PLBP would illustrate more in-phase ISC patterns with more stable pattern variability in all planes of motion planes in some couples/phases of the gait cycle between left and right limbs in comparison to athletes' left and right limbs without PLBP.

METHODS

Participants

For the current cross-sectional study to have 90% statistical power with an alpha level of 0.05, it would require at least a total of 24 volunteers according to data from a previous investigation on how low back pain impacts coordination and variability of the trunk segment. The power calculations were based on an effect size of 1.42 when investigating the impact of low back pain on coordination and variability values for pelvic-lumbar in the sagittal plane (47). The inclusion criteria for athletes with PLBP and non-PLBP were: players ranging from 20 to 35 years old who have at least four years' history of playing in the Iranian basketball super-league and first division league. Additionally, testing included athletes with nonspecific PLBP (≥ 12-week duration). A professional physical therapist with 15 years of experience treating musculoskeletal pain issues made the diagnosis of PLBP in the athlete. Also, disability levels based on the reliable and valid Persian version of the Oswestry Disability Index (ODI) (48) ranged from 21% to 60%. The exclusion criteria for athletes with PLBP or without PLBP were athletes with previous history of lumbar surgery or a medical condition with the contraindication of movement therapy, history of acute (not re-occurring) low back injury occurring during the last 12 weeks, presence of radiculopathy signs including radiating pain to the lower extremities, presence of lower limb motor deficit and muscle weakness in physical exam, and history of vertebral fractures in the spinal column. Prior to starting the investigation, study approval was obtained from the Biomedical Research Ethics Committee of Allameh Tabatab'i University (ATU) (Ethics code: IR.ATU.REC.1399.015 – date of approval: May 19, 2020), and all participants gave written informed consent. All participants wore spandex bike shorts, sports shoes, and a sports brassier during the test.

Data collection

The study employed an eight-camera motion analysis system (Vicon, Oxford Metrics, London, England) with a sampling rate of 1,200 Hz to record kinematic data. Twenty-four infrared-retroreflective markers, following Visual 3D guidelines, were strategically placed on specific bony landmarks, such as the spinous processes of C7 and T10, iliac spines, greater trochanters, femoral condyles, malleoli, metatarsal heads, and calcanei (**figure 1**). The data collection methods were performed based on our previous study (49). This marker setup facilitated the creation of a comprehensive 6-degree of freedom model, allowing detailed analysis of participants' movement patterns and joint dynamics. Participants underwent a 10-minute general warm-up, followed by a standing static trial for model development. Gait trials involved participants walking barefoot at a self-selected pace, maintaining eye contact with a fixed point at eye level. Athletes initiated

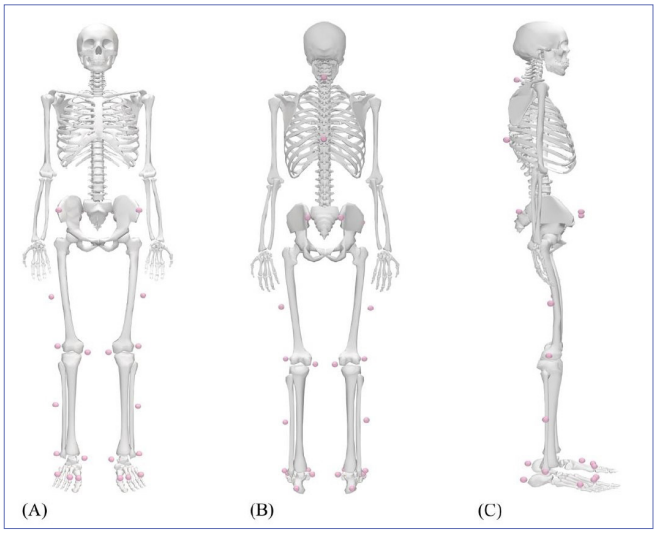


Figure 1. Placement of the Plug-in-Gait Model
(A) Anterior; **(B)** Posterior; **(C)** Lateral.

movement after the command "walk" and had three practice runs before data collection. At least 10 complete gait cycles per limb were captured across six walking trials.

The recorded data were processed using Visual3D motion analysis software, employing a low-pass, fourth-order Butterworth filter (cutoff frequency: 6 Hz). The body model included eight stiff components (trunk, pelvis, thighs, shanks, and feet), and segmental angles in each motion plane were computed using custom MATLAB software (MathWorks Inc., Natick, MA, USA). The entire process was overseen by a biomechanics laboratory operator and analyzed by a biomechanics expert.

Inter-segmental coordination analysis

In this study, the high pass algorithm (HPA) technique was employed to accurately identify heel strike and toe-off events in gait patterns, demonstrating its precision in both normal and pathological cases. To ensure the reliability of detected events, a visual inspection was conducted to eliminate any inaccuracies arising from missing marker data. Inter-segmental coordination (ISC) was evaluated using the continuous relative phase (CRP) method, with custom MATLAB code facilitating the calculation of coordination parameters. To enhance consistency, cubic spline interpolation was applied to segmental angle time series, covering the entire gait cycle for each stride. Empirical mode decomposition confirmed assumptions for phase portrait and dynamic system analysis. Segmental angular velocities were derived, enabling measurement in three directions. CRP analysis involved creating phase portraits and computing phase angles, with normalization mitigating amplitude and frequency variations. The CRP, indicating segment coupling during a task, was calculated, and values near 0 suggested "in-phase" motion, while values near 180 indicated "out of phase" motion. Correction for discontinuity at 0/360 was applied. Ensemble averaging generated parameters, including Mean Absolute Relative Phase (MARP) and Deviation Phase (DP), characterizing inter-segment coordination. Low MARP values signified more "in-phase" coupling, while low DP values indicated less variation in inter-segment coordination. Group means were calculated for these metrics and segmental relationships across stance and swing phases. All of the above measurements were performed based on the previous published paper (50).

Statistical analysis

The statistical analysis of the data was conducted using IBM® SPSS version 24.0 (IBM Corp, Armonk, NY, USA). To evaluate the normal distribution of the data, the Shapiro-Wilk test was employed. The Independent Samples t-test was employed to compare demographic characteristics between the two groups, as well as to compare the means of DP and MARP values during both the stance and swing phases of gait. Data were compared within groups, specifically ipsilaterally (*e.g.*, right leg of the PLBP group to the right leg of the non-PLBP control group). Additionally, the data were separately analyzed by plane and stance/swing phases. A significance level of 0.05 was set for all statistical analyses. Furthermore, Partial Etta Squared values were provided as effect sizes (ES) to gauge the clinical significance of mean changes. According to Cohen, an ES between 0.5 and 0.8 indicates a substantial clinical difference in biological systems, while an ES exceeding 0.8 signifies a large clinical difference (51).

RESULTS

Characteristics of the participants

There were no statistically significant differences in age, height, body mass, or BMI between the groups. However, the mean preferred gait pace in the PLBP group was considerably slower than in the non-PLBP control group ($p < 0.001$; **table I**).

Table I. Participant demographics.

Variable	PLBP (n = 12)	Non-PLBP (n = 12)	P-value†
	Mean ± SD	Mean ± SD	
Age (years)	23.8 ± 1.8	23.5 ± 2.2	0.241
Height (cm)	183.9 ± 6.7	188.0 ± 7.8	0.264
Body Mass (kg)	79.6 ± 8.9	87.0 ± 10.2	0.227
BMI (kg/m²)	23.4 ± 1.3	24.5 ± 1.1	0.498
Gait Speed (m/s)	0.98 ± 0.1	1.17 ± 0.2	< 0.010**
VAS (mm)	7.9 ± 0.6	N/A	-
ODI (pts)	22.9 ± 11.9	N/A	-

BMI: Body Mass Index; VAS: Visual Analogue Scale; ODI: Oswestry Disability Index; PLBP: Persistent Low Back Pain. †Statistically significant differences between the PLBP and Non-PLBP groups; **P-value ≤ 0.05 is considered statistically significant.

Trunk-pelvis coordination

In the sagittal plane, the PLBP group's trunk-pelvis coordination was significantly more in-phase (less out of phase) than the non-PLBP group throughout both stance ($p < 0.001$) and swing ($p < 0.001$) phases of gait (**figure 2(A1,A2)**, **table II**). In the frontal plane, during the stance and swing phases of gait, the PLBP group had lower CRP coordination variability (DP) than the non-PLBP group ($p < 0.001$) (**figure 2(B1)**, **table II**). The PLBP group also demonstrated lower DP in this plane during swing phase of gait than the non-PLBP group ($p < 0.001$) (**figure 2(A-C)**, **table II**).

Lower extremity coordination

Pelvis-thigh coordination

The pelvis-thigh coordination analysis in sagittal plane showed that the means of couple MARP in the stance and swing phases differed significantly between two groups on the right side ($p < 0.001$ and $p < 0.001$, respectively) (**figure 3(A1)**, **table III**). Moreover, the right lower extremity pelvis-thigh DP in stance and swing phases differed significantly ($p < 0.016$ and $p < 0.001$, respectively) (**figure 3(B1)**, **table III**). On the left side, the pelvis-thigh DP only differed significantly during swing phase ($p < 0.001$) (**figure 3(B1)**, **table III**). In the frontal plane, the means of couple MARP in the stance phase exhibited significant differences between two groups on the right side ($p < 0.001$) (**figure 3(A2)**, **table III**). The right pelvis-thigh DP values in the stance and swing phases of gait also differed significantly ($p < 0.003$ and $p < 0.033$, respectively) (**figure 3(B2)**, **table III**). The pelvis-thigh coordination analysis in transverse plane showed significant variations in coupled MARP in the stance and swing phase between two groups on the right side ($p < 0.001$ and $p < 0.001$, respectively) (**figure 3(A3)**,

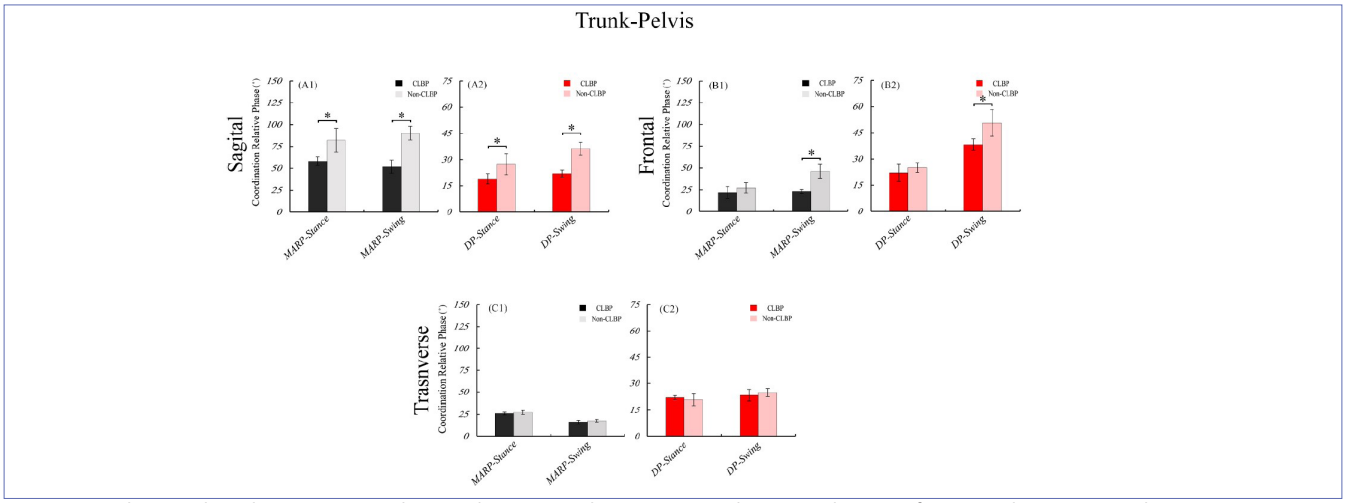


Figure 2. The trunk-pelvis MARP and DP values over the stance and swing phases of gait in the PLBP and non-PLBP groups were measured in all three planes of motion.

(A) Sagittal; **(B)** Frontal; **(C)** Transverse. Standard error is shown by error bars. *Significance of mean differences ($p \leq 0.05$).

Table II. Means and standard deviations of the MARP and DP comparison between the PLBP and non-PLBP groups over the stance and swing phases of gait in the right/left trunk-pelvis all three planes of motion (sagittal, frontal, and transverse).

Variables		MARP-Stance			MARP-Swing			DP-Stance			DP-Swing		
		Mean ± SD	†P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES
Sagittal	PLBP	58.1 ± 4.9	<0.001**	0.59	51.8 ± 7.5	<0.001**	087	18.9 ± 2.9	<0.001**	0.46	21.9 ± 2.0	<0.001**	0.86
	Non-PLBP	82.0 ± 13.7			90.3 ± 7.9			27.2 ± 5.9			36.2 ± 3.6		
Frontal	PLBP	21.8 ± 6.7	0.051	0.16	23.2 ± 2.2	<0.001**	0.81	22.0 ± 4.9	0.079	0.13	38.1 ± 3.2	<0.001**	0.70
	Non-PLBP	27.1 ± 5.7			46.1 ± 7.7			25.0 ± 2.7			55.6 ± 7.6		
Transverse	PLBP	25.9 ± 1.5	0.141	0.09	16.2 ± 2.0	0.053	0.16	21.8 ± 1.1	0.246	0.06	22.5 ± 3.3	0.080	0.13
	Non-PLBP	27.2 ± 2.2			17.7 ± 1.4			20.6 ± 3.2			24.6 ± 2.3		

†Statistically significant differences between the PLBP and Non-PLBP groups; **P-value ≤ 0.05 is considered statistically significant; Rt: right: Lt: left: PLBP: Persistent Low Back Pain; ES: effect size.

table III). In additional, the pelvis-thigh DP values in swing phase of the right and left sides were significantly different ($p < 0.001$ and $p < 0.005$, respectively) (**figure 3(A-C)**, **table III**).

Thigh-shank coordination

The thigh-shank coordination analysis in sagittal plane showed that the means of couple MARP in the swing phase differed significantly between two groups on the left side

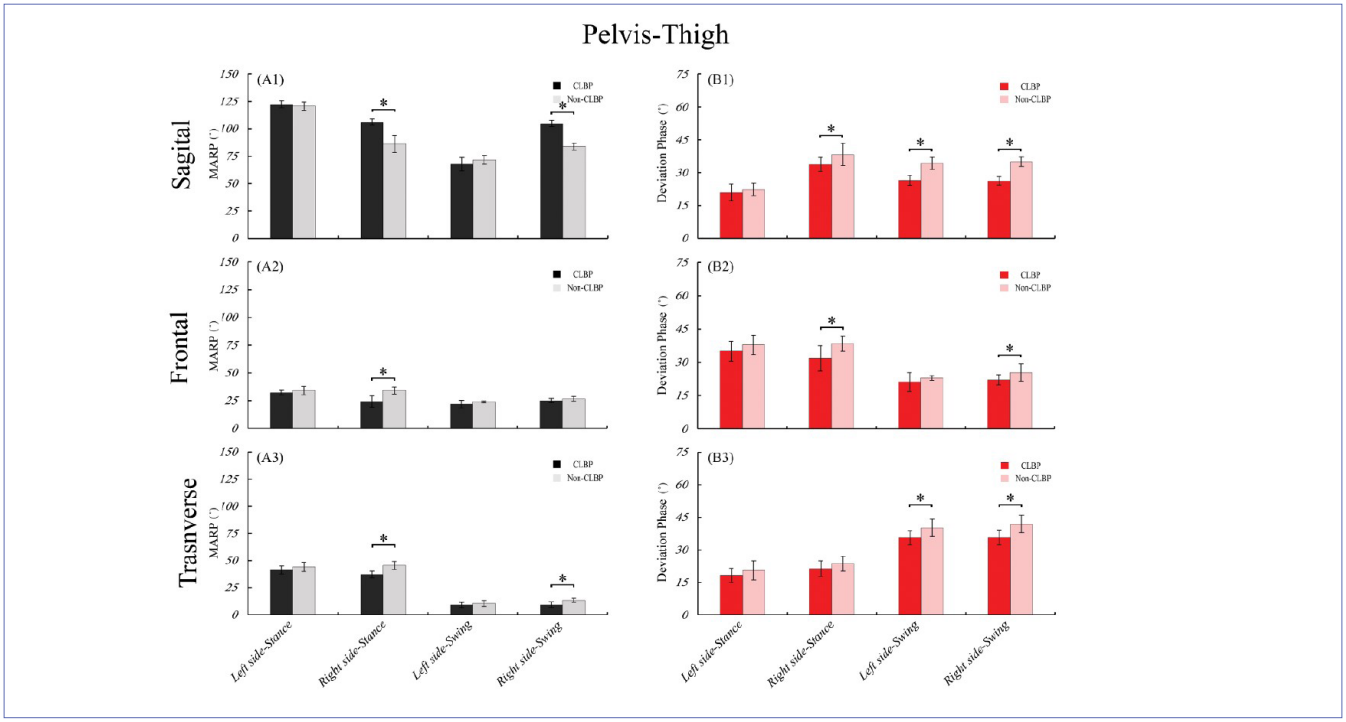


Figure 3. The left/right MARP (left side) and DP (right side) values along the pelvis-thigh in all three planes of motion.
(A) Sagittal; **(B)** Frontal; **(C)** Transverse during the stance and swing phases of gait in the PLBP and non-PLBP groups. Standard error is shown by error bars. *Significance of mean differences ($p \leq 0.05$).

Table III. Means and standard deviations of the MARP and DP comparison between the PLBP and non-PLBP groups over the stance and swing phases of gait in the right/left pelvis-thigh all three planes of motion (sagittal, frontal, and transverse).

Variables			MARP-Stance			MARP-Swing			DP-Stance			DP-Swing		
			Mean ± SD	†P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES
Sagittal	Right	PLBP	106.0 ± 2.9	<0.001**	0.75	104.8 ± 2.9	<0.001**	0.92	33.7 ± 3.2	< 0.016**	0.24	26.2 ± 1.9	<0.001**	0.82
		Non-PLBP	86.1 ± 7.7			83.8 ± 3.2			34.2 ± 2.7			34.9 ± 2.1		
	Left	PLBP	122.4 ± 3.1	0.241	0.06	67.6 ± 6.0	0.072	0.14	20.9 ± 3.7	0.360	0.03	26.4 ± 2.3	<0.001**	0.71
		Non-PLBP	120.7 ± 3.7			71.6 ± 4.0			22.1 ± 2.8			34.9 ± 2.1		
Frontal	Right	PLBP	24.2 ± 4.9	<0.001**	0.60	25.0 ± 1.9	0.050	0.16	31.7 ± 5.7	< 0.003**	0.35	22.3 ± 2.3	<0.033**	0.19
		Non-PLBP	34.1 ± 3.7			26.6 ± 1.9			38.3 ± 3.4			25.3 ± 3.8		
	Left	PLBP	32.1 ± 2.0	0.118	0.11	21.7 ± 3.5	0.063	0.15	34.9 ± 4.4	0.122	0.10	21.0 ± 4.2	0.170	0.08
		Non-PLBP	34.1 ± 3.7			23.8 ± 1.0			37.8 ± 4.3			22.9 ± 1.0		
Transverse	Right	PLBP	37.1 ± 3.0	<0.001**	0.62	9.2 ± 2.3	<0.001**	0.51	21.3 ± 3.7	0.130	0.10	35.7 ± 3.4	<0.001**	0.42
		Non-PLBP	45.5 ± 3.6			13.3 ± 1.8			23.6 ± 3.4			41.8 ± 4.0		
	Left	PLBP	41.3 ± 3.7	0.095	0.12	9.1 ± 2.3	0.170	0.17	18.9 ± 3.2	0.311	0.04	35.5 ± 3.2	<0.005**	0.30
		Non-PLBP	44.2 ± 4.3			10.5 ± 2.6			20.5 ± 4.4			40.1 ± 3.8		

†Statistically significant differences between the PLBP and Non-PLBP groups; **P-value ≤ 0.05 is considered statistically significant; Rt: right: Lt: left: PLBP: Persistent Low Back Pain; ES: effect size.

($p < 0.001$) (**figure 4(A1)**, **table IV**). The thigh-shank coordination analysis in frontal plane showed that the means of couple MARP in the swing phase exhibited significant differences between two groups on the left side ($p < 0.001$) (**figure 4(A2)**, **table IV**). The left sides thigh-shank DP values in the stance phase of gait also differed significantly ($p < 0.001$) (**figure 4(B2)**, **table IV**). Moreover, the right thigh-shank DP in swing phase differed significantly ($p < 0.007$) (**figure 4(B2)**, **table IV**). The thigh-shank coordination analysis in transverse plane showed significant variations in couple MARP in the swing phase between two groups on the left and right sides ($p < 0.005$ and $p < 0.001$, respectively) (**figure 4(A3)**, **table IV**). In additional, the thigh-shank DP values in swing phase of the right and left sides were significantly different ($p < 0.001$ and $p < 0.004$, respectively) (**figure 4(A-C)**, **table IV**).

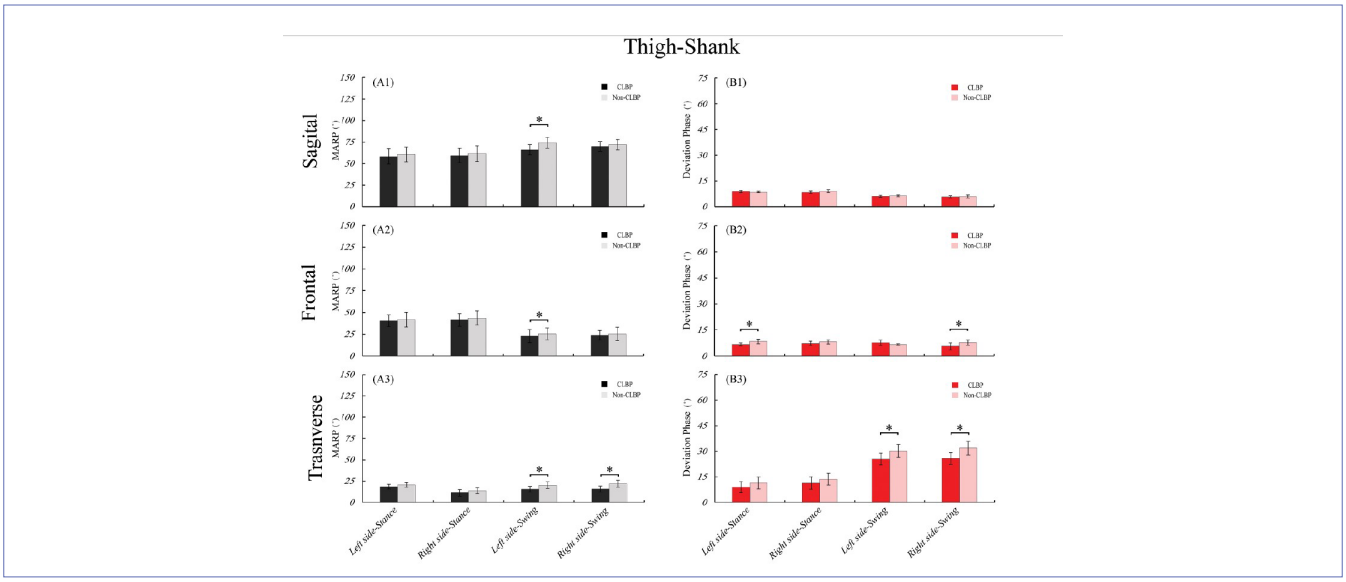


Figure 4. The left/right MARP (left side) and DP (right side) values along the thigh-shank in all three planes of motion.
(A) Sagittal; **(B)** Frontal; **(C)** Transverse during the stance and swing phases of gait in the PLBP and non-PLBP groups. Standard error is shown by error bars. *Significance of mean differences ($p \leq 0.05$).

Table IV. Means and standard deviations of the MARP and DP comparison between the PLBP and non-PLBP groups over the stance and swing phases of gait in the right/left thigh-shank all three planes of motion (sagittal, frontal, and transverse).

Variables			MARP-Stance			MARP-Swing			DP-Stance			DP-Swing		
			Mean ± SD	†P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES
Sagittal	Right	PLBP	59.3 ± 2.9	0.073	0.13	70.0 ± 2.6	0.058	0.15	6.0 ± 0.5	0.053	0.05	5.7 ± 0.6	0.441	0.02
		Non-PLBP	61.6 ± 3.0			72.0 ± 2.3			9.0 ± 0.7			5.9 ± 0.8		
	Left	PLBP	58.2 ± 4.4	0.104	0.11	66.0 ± 2.5	<0.001**	0.68	8.4 ± 0.6	0.153	0.09	6.0 ± 0.5	0.118	0.10
		Non-PLBP	60.7 ± 2.5			74.1 ± 3.1			8.6 ± 0.3			6.3 ± 0.4		
Frontal	Right	PLBP	41.5 ± 2.8	0.090	0.12	23.8 ± 1.2	0.083	0.13	7.2 ± 1.2	0.089	0.08	5.5 ± 1.9	<0.007**	0.29
		Non-PLBP	43.5 ± 2.8			25.3 ± 2.4			8.0 ± 1.0			7.7 ± 1.4		
	Left	PLBP	40.2 ± 2.9	0.357	0.03	22.9 ± 1.0	<0.002**	0.37	6.6 ± 0.8	<0.001**	0.38	7.5 ± 1.5	0.053	0.17
		Non-PLBP	41.6 ± 4.1			25.4 ± 2.2			8.3 ± 1.3			6.6 ± 0.4		
Transverse	Right	PLBP	11.3 ± 3.7	0.128	0.10	15.7 ± 3.4	<0.001**	0.42	11.3 ± 3.7	0.130	0.10	25.7 ± 3.4	<0.001**	0.42
		Non-PLBP	13.6 ± 3.4			21.8 ± 4.0			13.6 ± 3.6			31.8 ± 4.0		
	Left	PLBP	18.5 ± 2.9	0.092	0.12	15.5 ± 3.2	<0.005**	0.30	8.9 ± 3.2	0.090	0.12	25.4 ± 3.3	<0.004**	0.31
		Non-PLBP	20.5 ± 2.6			20.1 ± 3.8			11.3 ± 3.5			30.1 ± 3.8		

†Statistically significant differences between the PLBP and Non-PLBP groups; **P-value ≤ 0.05 considered statistically significant; Rt: right: Lt: left: PLBP: Persistent Low Back Pain; ES: effect size.

Shank-foot coordination

The shank-foot coordination analysis in sagittal plane showed that the means of couple MARP in the swing phase differed significantly between two groups on the left side ($p < 0.001$) (**figure 5(A1)**, **table V**). The shank-foot coordination analysis in frontal plane showed that the means of DP in the stance phase exhibited significant differences between two groups on the right side ($p < 0.001$) (**figure 5(B2)**, **table V**). The shank-foot coordination analysis in transverse plane showed significant variations in couple MARP in the swing phase between two groups on the left side ($p < 0.001$) (**figure 5(A3)**, **table V**). In additional, the shank-foot DP values in swing phase of the left side was significantly different ($p < 0.002$) (**figure 5(A-C)**, **table V**).

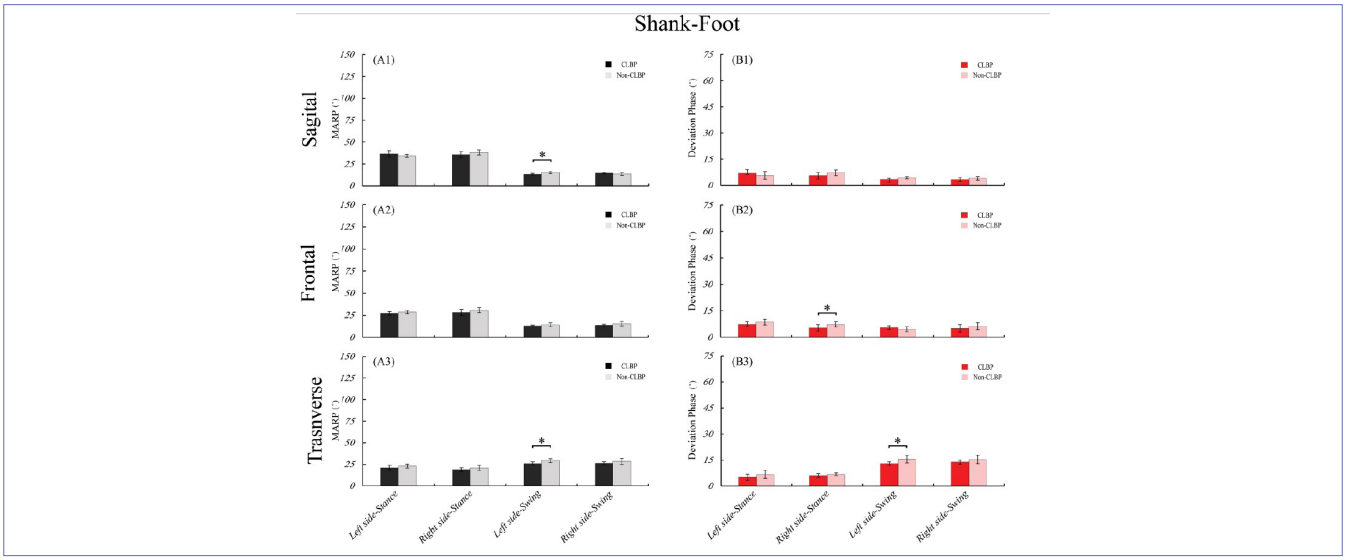


Figure 5. The left/right MARP (left side) and DP (right side) values along the shank-foot in all three planes of motion.

(A) Sagittal; **(B)** Frontal; **(C)** Transverse during the stance and swing phases of gait in the PLBP and non-PLBP groups. Standard error is shown by error bars. *Significance of mean differences ($p \leq 0.05$).

Table V. Means and standard deviations of the MARP and DP comparison between the PLBP and non-PLBP groups over the stance and swing phases of gait in the right/left shank-foot all three planes of motion (sagittal, frontal, and transverse).

Variables			MARP-Stance			MARP-Swing			DP-Stance			DP-Swing		
			Mean ± SD	†P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES	Mean ± SD	P-value	ES
Sagittal	Right	PLBP	35.7 ± 3.3	0.064	0.14	14.6 ± 0.9	0.083	0.13	5.6 ± 2.0	0.063	0.14	3.2 ± 1.0	0.092	0.12
		Non-PLBP	38.2 ± 2.8			13.6 ± 1.4			7.1 ± 1.6			4.0 ± 1.0		
	Left	PLBP	36.6 ± 3.7	0.061	0.15	13.3 ± 0.9	<0.001**	0.42	6.8 ± 0.6	0.094	0.13	3.2 ± 1.6	0.067	0.15
		Non-PLBP	34.3 ± 1.7			15.0 ± 1.1			5.6 ± 2.1			4.2 ± 0.6		
Frontal	Right	PLBP	28.2 ± 3.4	0.068	0.14	13.8 ± 1.2	0.083	0.13	5.3 ± 1.8	<0.010**	0.26	4.9 ± 2.1	0.154	0.09
		Non-PLBP	30.7 ± 2.8			15.3 ± 2.4			7.2 ± 1.4			6.2 ± 1.9		
	Left	PLBP	27.2 ± 1.9	0.102	0.11	12.9 ± 1.0	0.090	0.13	7.3 ± 1.3	0.061	0.15	5.4 ± 1.0	0.062	0.15
		Non-PLBP	28.5 ± 1.9			14.2 ± 2.2			8.5 ± 1.6			4.4 ± 1.4		
Transverse	Right	PLBP	18.9 ± 2.1	0.075	0.13	26.2 ± 1.9	0.068	0.14	5.9 ± 1.1	0.086	0.12	13.8 ± 1.2	0.083	0.13
		Non-PLBP	20.8 ± 2.7			28.4 ± 3.4			6.7 ± 0.9			15.3 ± 2.4		
	Left	PLBP	21.0 ± 2.6	0.068	0.14	25.9 ± 2.1	<0.001**	0.38	5.0 ± 1.7	0.060	0.15	12.9 ± 1.0	<0.002**	0.37
		Non-PLBP	23.0 ± 2.3			29.3 ± 2.3			6.6 ± 2.2			15.4 ± 2.2		

†Statistically significant differences between the PLBP and Non-PLBP groups; **P-value ≤ 0.05 is considered to be statistically significant; Rt: right: Lt: left: PLBP: Persistent Low Back Pain; ES: effect size.

DISCUSSION

The aim of this research was to conduct a comparative analysis of the sagittal, frontal, and transverse plane coordination and coordination variability of the pelvis, trunk, and lower extremities during the stance and swing phases of gait between athletes with PLBP and non-PLBP. The application of dynamic system theory analysis techniques has been employed to conduct phase analysis of various couplings in the sagittal, frontal, and transverse plane, including the trunk-pelvis, right and left pelvis-thigh, thigh-shank, and shank-foot couplings. The present study posited that individuals with PLBP who engage in athletic activities would exhibit greater coordination in relation to phase, as well as reduced variability in some couples/phases of the gait cycle compared to athletes without PLBP. The findings of the study provided evidence in support of the aforementioned hypothesis. The main findings were the greater degree of consistency in the trunk-pelvis coordination during the gait cycle in the sagittal and frontal planes among individuals with PLBP compared to controls. Additionally, reduced variability in the pelvis-thigh coordination existed across all planes of motion throughout the gait cycle, as well as a more synchronized pelvis-thigh coordination on both the left and right sides during the stance and swing phases in the sagittal plane among the PLBP group. The group of individuals with prolonged low back pain exhibited reduced variability in the coordination between the left and right thigh-shank and shank-foot during both the stance and swing phases, across the sagittal, frontal, and transverse planes. The left side exhibits greater thigh-shank coordination in-phase in both sagittal and frontal planes throughout the stance and swing phases of the gait cycle.

Trunk-pelvis coordination

Athletes with PLBP had more in-phase trunk-pelvis coordination during the stance and swing phases of gait than controls. These findings are similar to recent studies that found decreased trunk-pelvis coordination in athletes with PLBP during repetitive flexion-extension exercises (52), variable gait and running speeds (21, 53), and prolonged manual material handling (37). They, overall, found that individuals with PLBP exhibited a tendency to synchronize and rigidly move their pelvic and trunk regions. These investigators believed that individuals who suffer from PLBP exhibit inferior motor control and adopt a more cautious gait pattern during ambulation.

In athletes with PLBP, decreased MARP and DP values of trunk-pelvis connection in the sagittal plane suggest "guarded gait" or "protective guarding behavior" (34). Motor control system strategies for enhanced walking control may include reduced DoF or DP values and more in-phase ISC dynamics (43). However, simultaneously diminished MARP and DP may predispose gait imbalances and slow limb recovery after gait disturbances (43).

It has been suggested that modifications in the coordination of the trunk-pelvis and fluctuations in individuals with PLBP during ambulation may arise due to the management of diverse issues linked with PLBP. Pain has the potential to impact neuromuscular coordination control, which may be caused by atypical afferent discharges originating from the joint receptors (54). The present investigation revealed that athletes with PLBP exhibited noticeable discomfort, thereby indicating that the impact of pain on coordination cannot be disregarded (13). According to several authors, PLBP can lead to changes in the control of trunk muscles' activity (neuromuscular control), which may result in "protective guarding behavior" or "protective guarding splinting" (55). Also, athletes with PLBP have been suggested to have abnormal rectus abdominus activity (56), and it has also been proposed that athletes PLBP have abnormal rectus abdominus activity (57). Hence, these athletes endeavor to immobilize the lumbar region via co-activation of muscles (58). In addition to experiencing pain and abnormal muscle activity, athletes with PLBP may also exhibit impaired proprioception, which can negatively impact their perception of joint position and movement (59), potentially leading to abnormal coordination in athletes with PLBP.

Lower extremities coordination

The values of MARP in both the right and left pelvis and thighs were affected by PLBP. Athletes who suffered from PLBP had less variation in the pelvis-thigh coordination patterns they presented while gait across all three planes of motion when compared to non-PLBP athletes. In addition, the study showed that the MARP values for the left thigh-shin and shank-foot were more in phase in the PLBP group during the swing phase than they were in the non-PLBP group.

Our findings demonstrated that PLBP has had an impact on the coordination of bilateral limb movements. The lumbopelvic region plays an important role in the human body, and the pelvis is a crucial segment that connects the upper and lower limb segments. Biomechanically, the pelvis is located in the center of the body's multi-segmental structure (60). Consequently, in the event that the typical movements of the pelvis encounter any issue, there will be an impact on the regulation of movement in the hips and other interconnected segments and joints (23). The concept of the "spinal-engine" was introduced by Gracovetsky as

a significant contributor to the mechanics of human gait (61). The importance of maintaining stability in the pelvis and trunk during movements involving the upper and lower extremities has been established (62). Consequently, alterations in the coordination, control, or stability of the lumbopelvic region may impact the lower extremities (63). In this regard, a study found that the movement patterns of the lower extremities differ between subjects with and without LBP (41). Furthermore, Müller *et al*. demonstrated that the presence of PLBP affected lower limb movements in addition to the trunk during both walking and running (15). The findings suggest that individuals experiencing lower back pain do not merely exhibit spinal rigidity while ambulating.

The present investigation revealed that both limbs (left and right limb) of PLBP group exhibited lower DP values of the pelvis thigh compared to the non-PLBP group. From the dynamic system perspective, a decrease in variability indicates a reduction in the flexibility and adaptability of the locomotor system, which is considered an alteration in the motor control pattern (27, 46). Athletes with PLBP exhibit impairments in postural stability during both static and dynamic conditions (19, 64). Consequently, these individuals employ diverse motor control strategies to sustain balance (65, 66).

Since it has been shown that the proximal joints play a significant role in regulating dynamic balance (44), the observed reduction in variability of the pelvis-thigh in athletes with PLBP may be a compensatory mechanism to address the compromised balance in these athletes. The athletes with PLBP appear to have chosen decreased variability as a motor control strategy. Reduced variability is often associated with locomotion stability, which in turn plays a role in controlling dynamic balance (67). The decreased variability in coupling suggests the segments are capable of limited repetitive motion, potentially leading to additional stress on the soft tissues and consequent degenerative alterations (68). So, the reduced variability observed in athletes with PLBP indicates an unhealthy condition.

The values of the left thigh-shank and shank-foot MARP in the athletes with PLBP exhibited a significant increase in phase coherence during the swing phase, as compared to the non-PLBP group. The coordination movement of interacting segments, which results in decreased individual segment autonomy, may be a motor control response aimed at generating protective movements (33, 34). The observed reduction in MARP values during the swing phase, without any significant changes in DP, may indicate the system's response in order to partly maintain itself (69). The adjustment resulting from changing the CRP pattern in both the thigh-shank and shank-foot occurred exclusively on the left (non-dominant) side of the body and during the swing phase of gait in both the sagittal and frontal planes.

Although proximal joints are considered to play a more significant role in balance control during walking than distal joints, the adjustment of the distal segment is also important during walking (22, 44). According to some studies, normal coordination patterns between distal joints and segments can help fine-tune foot trajectories to ensure secure foot clearance and progression against falling (22, 70). Strengthening the coupling between the thigh and shank, as well as between the shank and foot, maybe a compensatory strategy to reduce the likelihood of future perturbations. Moreover, it is possible that increasing the strength of thigh-shank and shank-foot couplings during the swing phase is the result of a compensatory approach to reduce the likelihood of future disturbances. Thus, athletes who suffer from PLBP are unable to deal with circumstances in an appropriate and effective manner and the risk of lower extremity injuries may increase with a compensatory approach for athletes with PLBP.

Generally, according to the "Functional asymmetry" hypothesis, the primary and most important role of the non-dominant limb is to provide safe gait stability. This can also be expressed as the non-dominant limb "securing" the gait (71, 72). As a result, the PLBP group may have employed compensatory mechanisms for their non-dominant limb (left side) during gait, which could be a safety compensatory strategy since recovering from stumbling is more difficult in the non-dominant leg (73, 74). Also, it should be highlighted that in athletes with PLBP, the considerably altered coordination pattern may lead to joint injuries and an increase in falls because it shifts motor control and reduces the lower limbs' capacity to act as a shock-absorbing system (69).

Limitations

Our study was conducted with male basketball players, so it is important to exercise caution when applying our findings to athletes of other disciplines and female athletes. Additionally, the cross-sectional nature of our study limits our ability to understand the true relationship between the study variables and lower extremity injuries. Furthermore, since our study only examined gait, our results may not be generalizable to other sports or tasks such as jump landing or cutting maneuvers. The lack of simultaneous muscle electromyography also limits our understanding of the muscle activity associated with these changes. Future research is needed to determine which variable is more determinant or relevant for athletes' performance hazards, as the potential relationship between the study factors and sports performance remains unclear.

CONCLUSIONS

This study found that lower back pain can affect the coordination pattern and variability of the lower extremities, pelvis, and trunk in both the sagittal and frontal planes during gait. Although this effect in the transverse plane had a very minimal impact. Taking into account the level of pain and disability, the current findings indicate that therapists prescribing treatment protocols for athletes with PLBP should go beyond the coordination of the lumbopelvic area for more efficient and suitable rehabilitation. Additionally, the results show that the assessments based on the dynamical systems approach may be helpful for improving clinical gait pattern assessment and enhancing the efficacy of rehabilitation programs for athletes with PLBP.

FUNDINGS

None.

DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS

SA, RS: conceptualization, data collection. SA, RS, WEH: writing – original draft, writing – review & editing.

ACKNOWLEDGMENTS

This manuscript is drafted from MSc thesis of Faculty of Physical Education and Sport Sciences, Allameh Tabataba'i University, Tehran, Iran.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

REFERENCES

1. Andersson GB. Epidemiological features of chronic low-back pain. Lancet. 1999;354(9178):581-5. doi: 10.1016/S0140-6736(99)01312-4.
2. White AA 3rd, Gordon SL. Synopsis: workshop on idiopathic low-back pain. Spine. 1982;7(2):141-9. doi: 10.1097/00007632-198203000-00013.
3. Bono CM. Low-back pain in athletes. J Bone Joint Surg Am. 2004;86(2):382-96. doi: 10.2106/00004623-200402000-00027.
4. Gurd DP. Back pain in the young athlete. Sports Med Arthrosc Rev. 2011;19(1):7-16. doi: 10.1097/JSA.0b013e318205e373.
5. Moradi V, Memari AH, ShayestehFar M, Kordi R. Low Back Pain in Athletes Is Associated with General and Sport Specific Risk Factors: A Comprehensive Review of Longitudinal Studies. Rehabil Res Pract. 2015;2015:850184. doi: 10.1155/2015/850184.
6. Trompeter K, Fett D, Platen P. Prevalence of Back Pain in Sports: A Systematic Review of the Literature. Sports Med. 2017;47(6):1183-207. doi: 10.1007/s40279-016-0645-3.
7. Abdelaziz W, Abdelmajeed S, Elhabashy H, Abdelmegeed M. Electromyographic Activity of Posterior Oblique Sling Muscles During Gait in Subjects with Chronic Non-Specific Low Back Pain versus Healthy Controls. Muscles Ligaments Tendons J. 2023;13(1):148-55. doi: 10.32098/mltj.01.2023.01.
8. Maselli F, Ciuro A, Mastrosimone R, et al. Low back pain among Italian rowers: A cross-sectional survey. J Back Musculoskelet Rehabil. 2015;28(2):365-76. doi: 10.3233/bmr-140529.
9. Pergolizzi JV Jr, LeQuang JA. Rehabilitation for Low Back Pain: A Narrative Review for Managing Pain and Improving Function in Acute and Chronic Conditions. Pain Ther. 2020;9(1):83-96. doi: 10.1007/s40122-020-00149-5.
10. Tousignant-Laflamme Y, Martel MO, Joshi AB, Cook CE. Rehabilitation management of low back pain - it's time to pull it all together! J Pain Res. 2017;10:2373-85. doi: 10.2147/jpr.S146485.
11. Petit A, Roche-Leboucher G, Bontoux L, et al. Effectiveness of three treatment strategies on occupational limitations and quality of life for patients with non-specific chronic low back pain: Is a multidisciplinary approach the key feature to success: study protocol for a randomized controlled trial. BMC Musculoskelet Disord. 2014;15:1-9. doi: 10.1186/1471-2474-15-64.
12. Oliva F, Agnes MN, Castellano Vitaterna M, et al. Low Back Pain in Weightlifters: Personalised Exercise Protocols for Elite Athletes. Muscles Ligaments Tendons J. 2023;13(2):187-200. doi: 10.32098/mltj.02.2023.03.
13. Keefe FJ, Hill RW. An objective approach to quantifying pain behavior and gait patterns in low back pain patients. Pain. 1985;21(2):153-61. doi: 10.1016/0304-3959(85)90285-4.
14. Lee D, Sung P. Gait Asymmetry Comparison between Subjects with and without Nonspecific Chronic Low Back Pain. Symmetry. 2021;13(11):2129. doi: 10.3390/sym13112129.
15. Müller R, Ertelt T, Blickhan R. Low back pain affects trunk as well as lower limb movements during walking and running. J Biomech. 2015;48(6):1009-14. doi: 10.1016/j.jbiomech.2015.01.042.
16. Agostini V, Schieroni MP, Siccardi M, Campagnoli M, Knaflitz M. Gait characteristics of persons with chronic low back pain. Gait Posture. 2009;30:S28. doi: 10.1016/j.gaitpost.2009.07.011.
17. Vismara L, Cimolin V, Galli M, Crivellini M, Capodaglio P. Quantitative analysis of the effects of obesity and low back pain on gait. Gait Posture. 2009;30:S34. doi: 10.1016/jgaitpost200907020.
18. Ruhe A, Fejer R, Walker B. Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. Eur Spine J. 2011;20(3):358-68. doi: 10.1007/s00586-010-1543-2
19. Etemadi Y, Salavati M, Arab AM, Ghanavati T. Balance recovery reactions in individuals with recurrent nonspecific low

back pain: effect of attention. Gait Posture. 2016;44:123-7. doi: 10.1016/j.gaitpost.2015.11.017.
20. Lamoth CJC, Daffertshofer A, Meijer OG, Beek PJ. How do persons with chronic low back pain speed up and slow down?: Trunk–pelvis coordination and lumbar erector spinae activity during gait. Gait Posture. 2006;23(2):230-9. doi: 10.1016/jgaitpost200502006.
21. Lamoth CJ, Meijer OG, Daffertshofer A, Wuisman PI, Beek PJ. Effects of chronic low back pain on trunk coordination and back muscle activity during walking: changes in motor control. Eur Spine J. 2006;15(1):23-40. doi: 10.1007/s00586-004-0825-y.
22. Chiu S-L, Chou L-S. Variability in inter-joint coordination during walking of elderly adults and its association with clinical balance measures. Clin Biomech (Bristol, Avon). 2013;28(4):454-8. doi: 10.1016/j.clinbiomech.2013.03.001.
23. Chiu S-L, Lu T-W, Chou L-S. Altered inter-joint coordination during walking in patients with total hip arthroplasty. Gait Posture. 2010;32(4):656-60. doi: 10.1016/jgaitpost201009015
24. Seay Jr JF. Lumbo-sacral loads and pelvis-trunk coordination in runners with chronic and resolved acute low back pain: University of Massachusetts Amherst; 2008.
25. Cordo PJ, Gurfinkel VS. Motor coordination can be fully understood only by studying complex movements. Prog Brain Res. 2004;143:29-38. doi: 10.1016/S0079-6123(03)43003-3.
26. Nematollahi M, Razeghi M, Mehdizadeh S, et al. Inter-Segmental Coordination Pattern in Patients with Anterior Cruciate Ligament Deficiency during a Single-Step Descent. PLOS ONE. 2016;11(2):e0149837 doi: 10.1371/journalpone0149837.
27. Hamill J, Haddad JM, McDermott WJ. Issues in quantifying variability from a dynamical systems perspective. J Appl Biomech. 2000;16(4):407-18. doi: 10.1123/jab.16.4.407.
28. Yen H-C, Chen H-L, Liu M-W, Liu H-C, Lu T-W. Age effects on the inter-joint coordination during obstacle-crossing. J Biomech. 2009;42(15):2501-6 doi: 10.1016/jjbiomech200907015
29. Hutin E, Pradon D, Barbier F, Gracies J-M, Bussel B, Roche N. Lower limb coordination patterns in hemiparetic gait: Factors of knee flexion impairment. Clin Biomech (Bristol, Avon). 2011;26(3):304-11. doi: 10.1016/jclinbiomech201010007.
30. Ghanavati T, Salavati M, Karimi N, et al. Intra-limb coordination while walking is affected by cognitive load and walking speed. J Biomech. 2014;47(10):2300-5. doi: 10.1016/jjbiomech201404038.
31. Kelso JS. Dynamic patterns: The self-organization of brain and behavior: MIT press; 1995.
32. Blyton SJ, Snodgrass SJ, Pizzari T, Birse SM, Likens AD, Edwards S. The impact of previous musculoskeletal injury on running gait variability: A systematic review. Gait Posture. 2023;101:124-133. doi: 10.1016/j.gaitpost.2023.01.018.
33. Ippersiel P, Preuss R, Fillion A, Jean-Louis J, Woodrow R, Zhang Q, Robbins SM. Inter-joint coordination and the flexion-relaxation phenomenon among adults with low back pain during bending. Gait Posture. 2021;85:164-70. doi: 10.1016/j.gaitpost.2021.02.001.
34. Gaffney BMM, Thomsen PB, Leijendekkers RA, Christiansen CL, Stoneback JW. Lumbopelvic movement coordination during walking improves with transfemoral bone anchored limbs: Implications for low back pain. Gait Posture. 2024;109:318-326. doi: 10.1016/j.gaitpost.2024.02.015.
35. Worster K, Valvano J, Carollo JJ. Sagittal plane coordination dynamics of typically developing gait. Clin Biomech (Bristol, Avon). 2015;30(4):366-72. doi: 10.1016/jclinbiomech201502013.
36. Seay JF, Van Emmerik RE, Hamill J. Trunk bend and twist coordination is affected by low back pain status during running. Eur J Sport Sci. 2014;14(6):563-8. doi: 10.1080/174613912013866167.
37. Seay JF, Sauer SG, Patel T, Roy TC. A history of low back pain affects pelvis and trunk coordination during a sustained manual materials handling task. J Sport Health Sci 2016;5(1):52-60. doi: 10.1016/jjshs201601011.
38. Mientjes MIV, Frank JS. Balance in chronic low back pain patients compared to healthy people under various conditions in upright standing. Clin Biomech (Bristol, Avon). 1999;14(10):710-6. doi: 10.1016/S0268-0033(99)00025-X.
39. McGregor AH, Hukins DW. Lower limb involvement in spinal function and low back pain. J Back Musculoskelet Rehabil. 2009;22(4):219-22. doi: 103233/bmr-2009-0239.
40. Song AY, Jo HJ, Sung PS, Kim YH. Three-dimensional kinematic analysis of pelvic and lower extremity differences during trunk rotation in subjects with and without chronic low back pain. Physiotherapy. 2012;98(2):160-6. doi: 10.1016/jphysio201102005.
41. Lee DC, Ham YW, Sung PS. Effect of visual input on normalized standing stability in subjects with recurrent low back pain. Gait Posture. 2012;36(3):580-5. doi: 10.1016/jgaitpost201205020.
42. Chiu SL, Chang CC, Chou LS. Inter-joint coordination of overground versus treadmill walking in young adults. Gait Posture. 2015;41(1):316-8. doi: 10.1016/jgaitpost201409015.
43. Chiu SL, Chang CC, Dennerlein JT, Xu X. Age-related differences in inter-joint coordination during stair walking transitions. Gait Posture. 2015;42(2):152-7. doi: 10.1016/jgaitpost201505003.
44. Chiu SL, Chou LS. Effect of walking speed on inter-joint coordination differs between young and elderly adults. J Biomech. 2012;45(2):275-80. doi: 10.1016/jjbiomech201110028.
45. Christe G, Kade F, Jolles BM, Favre J. Chronic low back pain patients walk with locally altered spinal kinematics. J Biomech. 2017;60:211-8. doi: 10.1016/jjbiomech201706042.
46. Dingwell JB, Marin LC. Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. J Biomech. 2006;39(3):444-52. doi: 10.1016/jjbiomech200412014.
47. Pelegrinelli ARM, Silva MF, Guenka LC, Carrasco AC, Moura FA, Cardoso JR. Low back pain affects coordination between the trunk segments but not variability during running. J Biomech. 2020;101:109605. doi: 10.1016/jjbiomech2020109605.
48. Mousavi SJ, Parnianpour M, Mehdian H, Montazeri A, Mobini B. The Oswestry Disability Index, the Roland-Morris Disability Questionnaire, and the Quebec Back Pain Disability Scale: Translation and Validation Studies of the Iranian Versions. Spine. 2006;31(14):E454-E9. doi: 10.1097/01brs0000222141 61424f7.

49. Abdollahi S, Sheikhhoseini R, Roostayi MM, Huddleston WE. The effect of fatigue on electromechanical response times in basketball players with and without persistent low back pain. Sci Rep. 2022;12(1):17849. doi: 10.1038/s41598-022-21940-8.
50. Ebrahimi S, Kamali F, Razeghi M, Haghpanah SA. Comparison of the trunk-pelvis and lower extremities sagittal plane inter-segmental coordination and variability during walking in persons with and without chronic low back pain. Hum Mov Sci. 2017;52:55-66. doi: 10.1016/jhumov201701004.
51. Cohen J. Statistical power analysis for the behavioral sciences: Routledge; 1988.
52. Mokhtarinia HR, Sanjari MA, Chehrehrazi M, Kahrizi S, Parnianpour M. Trunk coordination in healthy and chronic nonspecific low back pain subjects during repetitive flexion-extension tasks: Effects of movement asymmetry, velocity and load. Hum Mov Sci 2016;45:182-92. doi: 10.1016/jhumov201511007.
53. Seay JF, Van Emmerik RE, Hamill J. Low back pain status affects pelvis-trunk coordination and variability during walking and running Clin Biomech (Bristol, Avon) 2011;26(6):572-8. doi: 10.1016/jclinbiomech201011012.
54. Radin EL, Yang KH, Riegger C, Kish VL, O'Connor JJ. Relationship between lower limb dynamics and knee joint pain. J Orthop Res. 1991;9(3):398-405. doi: 10.1002/jor1100090312.
55. Ahern DK, Follick MJ, Council JR, Laser-Wolston N, Litchman H. Comparison of lumbar paravertebral EMG patterns in chronic low back pain patients and non-patient controls. Pain. 1988;34(2):153-60. doi: 10.1016/0304-3959(88)90160-1.
56. Abernethy B. Training the visual-perceptual skills of athletes Insights from the Study of Motor Expertise. Am J Sports Med. 1996;24(6 Suppl):S89-92.
57. Newcomer KL, Jacobson TD, Gabriel DA, Larson DR, Brey RH, An K-N. Muscle activation patterns in subjects with and without low back pain. Arch Phys Med Rehabil. 2002;83(6):816-21. doi: 10.1053/apmr200232826.
58. Lamoth CJ, Beek PJ, Meijer OG. Pelvis-thorax coordination in the transverse plane during gait. Gait Posture. 2002;16(2):101-14. doi: 10.1016/s0966-6362(01)00146-1.
59. Wang TM, Yen HC, Lu TW, et al. Bilateral knee osteoarthritis does not affect inter-joint coordination in older adults with gait deviations during obstacle-crossing. J Biomech. 2009;42(14):2349-56. doi: 10.1016/jjbiomech200906029.
60. Khamis S, Yizhar Z. Effect of feet hyperpronation on pelvic alignment in a standing position. Gait Posture. 2007;25(1):127-34. doi: 10.1016/jgaitpost200602005.
61. Gracovetsky S. An hypothesis for the role of the spine in human locomotion: A challenge to current thinking. J Biomed Eng. 1985;7(3):205-16. doi: 10.1016/0141-5425(85)90021-4.
62. Bouisset S. Relationship between postural support and intentional movement: biomechanical approach. Arch Int Physiol Biochim Biophys. 1991;99(5):A77-92. doi: 103109/13813459109145919.
63. Jo HJ, Song AY, Lee KJ, Lee DC, Kim YH, Sung PS. A kinematic analysis of relative stability of the lower extremities between subjects with and without chronic low back pain. Eur Spine J. 2011;20(8):1297-303. doi: 10.1007/s00586-010-1686-1.
64. Iordache S, Cursaru A, Cretu B, Niculae CF, Popa M, Costache MA, Serban B, Cirstoiu C. Predictive Factors for Total Knee Arthroplasty: An Observational Study. Cureus. 2024;16(8):e67519. doi: 10.7759/cureus.67519.
65. Descarreaux M, Blouin JS, Teasdale N. Repositioning accuracy and movement parameters in low back pain subjects and healthy control subjects. Eur Spine J. 2005;14(2):185-91. doi: 10.1007/s00586-004-0833-y.
66. Popa T, Bonifazi M, Della Volpe R, Rossi A, Mazzocchio R. Adaptive changes in postural strategy selection in chronic low back pain. Exp Brain Res. 2007;177(3):411-8. doi: 10.1007/s00221-006-0683-4.
67. Ranavolo A, Donini LM, Mari S, et al. Lower-limb joint coordination pattern in obese subjects. Biomed Res Int. 2013;2013:142323. doi: 10.1155/2013/142323.
68. Hamill J, van Emmerik RE, Heiderscheit BC, Li L. A dynamical systems approach to lower extremity running injuries. Clin Biomech (Bristol, Avon). 1999;14(5):297-308. doi: 10.1016/s0268-0033(98)90092-4.
69. Stergiou N, Jensen JL, Bates BT, Scholten SD, Tzetzis G. A dynamical systems investigation of lower extremity coordination during running over obstacles. Clin Biomech (Bristol, Avon). 2001;16(3):213-21 doi: 10.1016/s0268-0033(00)00090-5.
70. Winter DA, Bishop PJ. Lower extremity injury Biomechanical factors associated with chronic injury to the lower extremity. Sports Med. 1992;14(3):149-56. doi: 102165/00007256-199214030-00001.
71. Sadeghi H, Allard P, Prince F, Labelle H. Symmetry and limb dominance in able-bodied gait: a review. Gait Posture. 2000;12(1):34-45. doi: 10.1016/s0966-6362(00)00070-9.
72. Seeley MK, Umberger BR, Shapiro R. A test of the functional asymmetry hypothesis in walking. Gait Posture. 2008;28(1):24-8. doi: 10.1016/j.gaitpost.2007.09.006.
73. Perry MC, Carville SF, Smith IC, Rutherford OM, Newham DJ. Strength, power output and symmetry of leg muscles: effect of age and history of falling. Eur J Appl Physiol. 2007;100(5):553-61. doi: 10.1007/s00421-006-0247-0.
74. Pijnappels M, Reeves ND, Maganaris CN, van Dieën JH. Tripping without falling; lower limb strength, a limitation for balance recovery and a target for training in the elderly. J Electromyogr Kinesiol. 2008;18(2):188-96. doi: 10.1016/j.jelekin.2007.06.004.