Title

Spatiotemporal Gait Parameters and Variability in Individuals with Patellofemoral Pain Syndrome: A Comparative Study

Abstract

Background: Patellofemoral pain syndrome (PFPS) is one of the most prevalent musculoskeletal disorders among young females, potentially affecting gait patterns and increasing the risk of secondary injuries.
Objective: To compare spatiotemporal gait parameters and their variability between females with PFPS and healthy controls.
Design: This applied study used a quasi-experimental, post-event causal-comparative design.
Participants: Twenty-four females aged 18–25 were divided into two groups: PFPS (n=11) and healthy controls (n=13). Participants were selected via purposive and convenience sampling.
Methods: Participants walked for one minute at their self-selected speed on a treadmill while gait data were recorded using two IMU sensors. Parameters such as stride length, stride time, walking speed, cadence, heel clearance, and stance/swing percentages were extracted across 20 gait cycles. Gait variability was calculated as the standard deviation of each parameter. Data were analyzed using MANOVA at a significance level of 0.05.
Results: Significant differences were found in stride length and walking speed between the groups ($p<0.05$), with higher values in the healthy group. No significant differences were observed in other parameters or in gait variability.
Conclusion: Reduced stride length and speed in PFPS individuals may reflect compensatory mechanisms due to pain. These alterations may cause abnormal joint loading, increasing the risk of secondary injuries and long-term movement disorders.

Keywords: Patellofemoral Pain, Spatiotemporal Parameters, Variability, Gait

Introduction

The knee, as one of the major joints of the lower limb, plays a critical role in performing daily activities and achieving optimal athletic performance. Injuries and disorders affecting this joint can lead to significant movement impairments. Among these conditions, patellofemoral pain syndrome (PFPS) stands out as one of the most common causes of anterior knee pain, accounting for approximately 11% of musculoskeletal complaints (1), with a prevalence of nearly 25% in the general population (2). PFPS is characterized by pain behind or around the patella in the absence of any clear structural or intra-articular damage, and it is especially prevalent among adolescents and female athletes (3).

PFPS is frequently associated with altered movement patterns of the lower limb, including increased hip adduction and internal rotation, knee valgus, and external tibial rotation, collectively referred to as dynamic valgus (4). These abnormal kinematic patterns increase the Q-angle and lateral stress on the patellofemoral joint, thereby disrupting the normal tracking of the patella and reducing the joint contact area (5). Such alterations can contribute to heightened pain and reduced functional performance, particularly during gait (6).

Walking is a complex, coordinated process involving the central nervous system, muscles, joints, and both the upper and lower limbs, where the interaction between the trunk, pelvis, and upper extremities plays a crucial role (7). Reciprocal movement of the upper and lower limbs not only supports balance but also affects key biomechanical aspects of gait, such as step length, stride width, walking speed, and impact forces (8, 9).

Studies have shown that individuals with PFPS may modify their walking patterns as a strategy to reduce joint loading and pain (10). These individuals often reduce walking speed and joint loading in an effort to alleviate stress on the patellofemoral joint. However, such adaptations are frequently accompanied by impaired neuromuscular control, reduced knee joint moments, altered heel strike velocity, shortened step length, and an increased risk of falls (11).

Given the widespread effects of PFPS on gait mechanics, lower limb alignment, and joint loading, a thorough investigation of differences in spatiotemporal gait parameters between affected individuals and healthy controls is warranted. While previous studies have primarily focused on patellofemoral joint mechanics or static postural alterations, there is still a lack of comprehensive research addressing the functional responses and spatiotemporal gait characteristics under dynamic and real-world walking conditions. Since walking requires intricate coordination among the trunk, upper, and lower limbs, alterations in any of these components may disrupt gait and increase the risk of injury or falls. Therefore, the present study aims to investigate and compare spatiotemporal gait parameters and their variability between individuals with patellofemoral pain syndrome and healthy individuals.

Materials and Methods

Study Design

This applied study was conducted using a quasi-experimental, post-event causal-comparative design. The primary objective was to examine the differences in spatiotemporal gait parameters and their variability between young females diagnosed with patellofemoral pain syndrome (PFPS) and healthy individuals. The study received ethical approval under code "IR.IAU.KHUISF.REC.1403.230".

Participants

The statistical population consisted of young women aged 18 to 25 residing in Yazd, Iran. Participants were divided into two groups: those diagnosed with PFPS and healthy controls. Eleven participants with PFPS were purposively recruited via announcements at physiotherapy clinics in Yazd, while thirteen healthy participants were selected through convenience sampling from university students in the field of physical education. Inclusion criteria comprised: age between 18–25 years, a minimum of six weeks of anterior knee pain without identifiable structural or intra-articular injury, the ability to walk independently without assistive devices, and informed consent to participate. Exclusion criteria included any history of lower limb or spinal surgery, neuromuscular or balance disorders, pregnancy, use of medications affecting the neuromuscular system, or inability to complete the test procedures (12).

Procedure

After obtaining informed consent, participants' demographic data were collected through a questionnaire. Height and weight were measured using a standard measuring tape and a digital scale. Participants were then asked to walk for 10 minutes at a self-selected pace on a treadmill (Hp Cosmos Mercury, Germany), after which their preferred walking speed was recorded. In the main trial, two inertial measurement unit (IMU) sensors (NORAXON, USA) were mounted on the plantar surface of each foot. Participants were instructed to walk at their preferred speed for at least one minute, during which a minimum of 20 complete gait cycles were recorded (Figure 1). Data collection was repeated across three separate trials. Signals were recorded at a sampling frequency of 600 Hz and subsequently low-pass filtered using a 20 Hz Butterworth filter for smoothing.

Insert Figure 1 about here

Data Processing

The accelerometer data were captured and filtered using the MyoResearch software. The raw acceleration signals in the anterior-posterior, mediolateral, and vertical directions were exported in .csv format. MATLAB (version 2021b) was employed for biomechanical data analysis and parameter extraction. For instance, the moment of heel contact (HC) was identified based on the anterior-posterior acceleration component. This point is marked by a noticeable shift in acceleration, indicating the transition from swing to stance phase (Figure 2).

Insert Figure 2 about here

To determine the percentage of stance and swing phases during the gait cycle, the vertical acceleration component was used (Figure 3). The moment of toe-off, which marks the transition from stance to swing, was identified by processing the vertical acceleration signal. The number of samples within each phase divided by the total stride length was used to calculate phase percentages.

Insert Figure 3 about here

The spatiotemporal parameters analyzed in this study included stride length, stride time, percentages of swing and stance phases, walking speed, cadence, and heel clearance. To assess gait variability, each parameter was calculated across 20 consecutive gait cycles, and the standard deviation of each was taken as an indicator of its variability.

Statistical Analysis

For statistical analysis, descriptive statistics including mean, and standard deviation were used, while Inferential statistics involved multivariate analysis of variance (MANOVA) and post-hoc tests. The necessary assumptions for conducting inferential statistical tests including normality of data distribution, homogeneity of error variances, and equality of the variance-covariance matrix were examined using the Shapiro-Wilk test, Levene's test, and Box's M test, respectively. All analyses were conducted in SPSS version 27, with the significance level set at 0.05.

Results

The demographic characteristics of the participants and the homogeneity of the two groups in terms of age, height, weight, and body mass index (BMI) were examined using an independent samples t-test. The results are presented in Table 1. Women with PFPS showed higher values in both weight and BMI compared to healthy women. Therefore, to compare the research variables while accounting for these differences, a multivariate analysis of variance (MANOVA) was conducted, controlling for the effects of weight and BMI.

Insert Table 1 about here

The results of the Shapiro–Wilk, Levene’s, and Box’s M tests indicated that the data in both groups were normally distributed, the error variances were homogeneous, and the variance-covariance matrices were equal. The multivariate analysis of covariance (MANCOVA), based on Wilks’ Lambda statistic, revealed that after controlling for the effects of BMI and weight, the spatial gait parameters were significantly different between groups. This suggests that there was a significant difference between healthy individuals and those with PFPS in at least one of the spatial gait parameters (stride length and heel clearance) (Wilks' $\Lambda = 0.438$, $F(2, 19) = 7.413$, $p = 0.004$, $\eta^2 = 0.438$) (Table 2).

Insert Table 2 about here

To examine the between-group differences, follow-up univariate analyses of variance were conducted (Table 3). After controlling for the effects of BMI and weight, healthy individuals had significantly longer stride lengths compared to those with PFPS ($p = 0.001$, $\eta^2 = 0.436$).

Insert Table 3 about here

The analysis of temporal gait parameters (cadence, stride time, stance phase %, swing phase %, and speed) revealed notable differences between the groups (Table 4). This indicates that there is a statistically significant difference in at least one of these parameters between healthy individuals and those with knee pain (Wilks' $\Lambda = 0.288$, $F(4, 17) = 10.510$, $p < 0.001$, $\eta^2 = 0.712$).

Insert Table 4 about here

Follow-up univariate ANOVAs were conducted (Table 5), controlling for the effects of BMI and weight. The results showed that healthy individuals had significantly higher walking speed compared to those with knee pain ($p = 0.001$, $\eta^2 = 0.436$).

Insert Table 5 about here

The results of multivariate analysis of covariance (MANCOVA) showed that the variability of spatial gait parameters ($F(2,19) = 0.128$, $p = 0.881$, $\eta^2 = 0.013$) and the variability of temporal gait parameters ($F(4,17) = 0.799$, $p = 0.511$, $\eta^2 = 0.118$) were not statistically significant at the 5% error level. Therefore, no significant differences were found in the variability of either spatial or temporal gait parameters between the healthy group and the group with knee pain (Table 6).

Insert Table 6 about here

Discussions

The aim of the present study was to investigate the differences in the spatial-temporal gait components and their variability between individuals with patellofemoral pain syndrome (PFPS) and healthy individuals. The results of this study showed significant differences in the mean stride length and speed between healthy individuals and those with PFPS, with healthy participants exhibiting higher values in these two variables. Arazpour et al. (2016) noted that patellofemoral pain results in reduced stride length and walking speed, a finding also observed in this study (13). Willson et al. (2014) demonstrated that patients with PFPS tend to take shorter steps and have longer foot contact times, likely to reduce knee joint stress (14). Additionally, Bazett-Jones et al. (2023) reported reduced speed and kinematic disturbances in individuals with PFPS, which is consistent with our findings (15). Barton et al. (2015) stated that individuals with PFPS typically adopt compensatory movement strategies in the knee and hip joints due to pain, which can affect functional gait stability (16). The reduction in speed and stride length in these individuals is likely a compensatory mechanism in response to pain.

Regarding other variables such as heel clearance, cadence, stride time, percentage of stance and swing phase, no significant differences were observed between the groups. These results are in line with the study by Fereidouni et al. (2017), which showed that changes in these factors were not significant in individuals with PFPS (17). According to Fereidouni et al. (2017), although muscles such as the quadriceps undergo changes in their activity in individuals with PFPS, these changes do not affect the spatial-temporal gait variables (17).

Previous studies, such as those by Baellow et al. (2020) and Arrebola et al. (2020), also pointed out that motor disturbances, such as increased knee valgus, abnormal lower limb rotations, and changes in joint alignments, can lead to alterations in gait patterns, especially in spatial-temporal components (18, 19). In this study, delays in heel-off and reduced stride length were observed as compensatory mechanisms to maintain balance in individuals with PFPS, similar to the findings of McAndrews et al. (2012), who identified reduced stride length as a factor contributing to an increased risk of falls (20). The alterations in spatiotemporal gait variables, such as reduced stride length and speed, are likely to be considered risk factors for secondary injuries in individuals with patellofemoral pain syndrome (PFPS). These changes in movement patterns may lead to abnormal loading on adjacent joints and tissues, resulting in structural and functional impairments in the knee, hip, or spine. Specifically, these alterations could serve as predictors of chronic injury risks and long-term movement disorders.

One of the limitations of this study is the relatively small sample size, which may reduce the generalizability of the findings. Additionally, focusing on linear gait parameters and using simple spatiotemporal analyses, without simultaneously considering joint dynamics or neurophysiological assessments, may not provide a comprehensive picture of the patients' movement patterns. Conducting gait analysis at only a single speed and in laboratory conditions could also be another limitation, as real-world environments involve more diverse conditions.

Conclusion:

The findings of this study revealed that individuals with patellofemoral pain syndrome (PFPS) exhibit significant alterations in certain spatiotemporal gait parameters, particularly reduced stride length and walking speed, compared to healthy individuals. While these changes may serve as compensatory strategies to minimize pain and improve stability during gait, they could also impose abnormal and potentially harmful loads on other joints. Therefore, such gait alterations may act as risk factors for secondary injuries and long-term movement disorders in this population. These findings highlight the importance of targeted rehabilitative interventions to prevent future complications in individuals with PFPS.

Acknowledgements

The authors would like to express their gratitude to all those who contributed to the work of this research, especially the patients who participated in it.

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Figure 1. System Setup

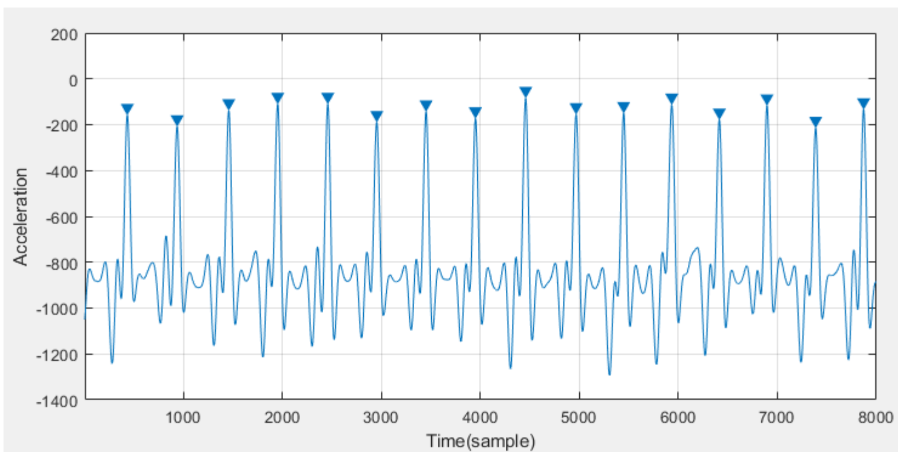

Figure 2. Gait Cycle Identification Using the Anterior–Posterior Acceleration Component

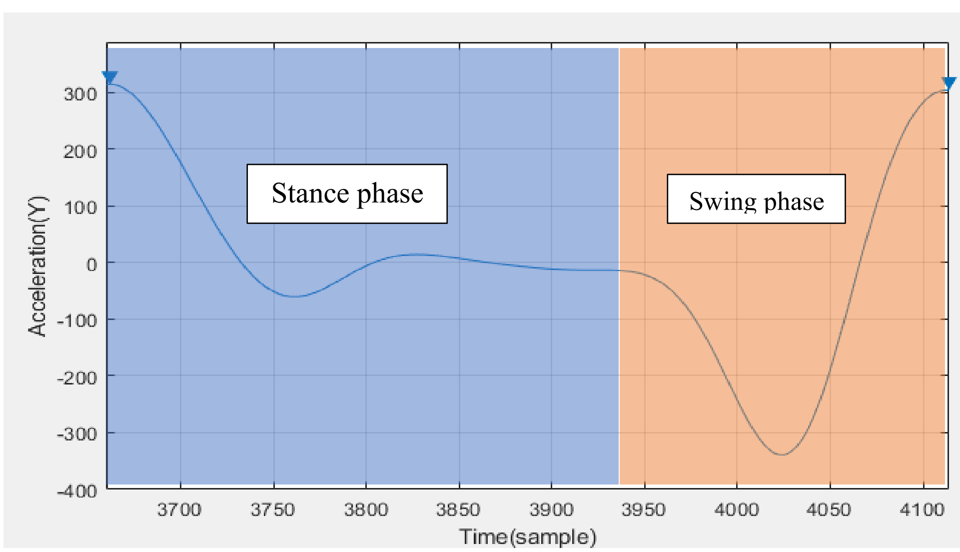

Figure 3. Identification of Swing and Stance Phase Percentages During Gait

Table 1. The demographic information of the research population participants

Groups	Numbers	Age (years)	Hight (cm)	Mass (kg)	BMI (kg/m^2)
Healthy	13	20.23±0.93	164.00±6.18	57.08±6.85	57.08±6.85
PFPC	11	21.73±2.20	164.45±6.12	72.91±6.85	72.91±6.85
t-value	--	-2.108	-0.180	-5.643	-6.062
P value	--	0.055	0.858	< 0.001*	< 0.001*

* Significant between groups differences of Independed t test.

Table 2. Multivariate Test Results (MANCOVA) for Spatial Gait Parameters Between Groups

Effect	Test Statistic	Value	F	df Effect	df Error	p-value	Effect Size (η²)
Group (Healthy vs. PFPS)	Wilks' Lambda	0.562	7.413	2.00	19.00	0.004*	0.438

* Significant between groups differences of Wilks' Lambda test.

Table 3. Results of Follow-up Univariate ANOVA for Comparing Spatial Gait Factors (Stride Length and Heel Clearance) Between Healthy and PFPS Groups

Variable	Healthy (Mean ± SE)	Knee Pain (Mean ± SE)	F Statistic	p-value	Effect Size (η²)
Stride Length	95.321 ± 3.670	68.639 ± 4.160	15.448	0.001*	0.436
Heel Clearance	58.001 ± 6.897	58.006 ± 7.819	0.000	1.000	<0.001

* Significant between groups differences

Table 4. Multivariate Test Results (MANCOVA) for Temporal Gait Parameters Between Groups

Effect	Test Statistic	Value	F	df Effect	df Error	p-value	Effect Size (η²)
Group (Healthy vs. PFPS)	Wilks' Lambda	0.288	10.510	4.00	17.00	<0.001*	0.712

* Significant between groups differences of Wilks' Lambda test.

Table 5. Results of Follow-up Univariate ANOVA for Comparing Temporal Gait Factors (Cadence, Stride Time, Stance Phase %, Swing Phase %, and Speed) Between Healthy and PFPS Groups

Variable	Healthy (Mean ± SE)	Knee Pain (Mean ± SE)	F Statistic	p-value	Effect Size (η²)
Cadence (steps/min)	103.686 ± 2.873	96.196 ± 3.257	1.987	0.174	0.090
Stride Time (ms)	1157.826 ± 34.706	1259.206 ± 39.345	2.494	0.130	0.111
Stance Phase (%)	63.461 ± 0.845	65.465 ± 0.958	1.645	0.214	0.076
Swing Phase (%)	36.539 ± 0.845	34.535 ± 0.958	1.645	0.214	0.076
Speed (m/s)	2.951 ± 0.084	1.949 ± 0.095	41.696	<0.001	0.676

* Significant between groups differences

Table 6. Multivariate Test Results (MANCOVA) for Variability of Spatiotemporal Gait Parameters Between Groups

Effect	Index	Test Statistic	Value	F	df Effect	df Error	p-value	Effect Size (η^2)
Group (Healthy vs. PFPS)	Spatial Variability Parameters	Wilks' Lambda	0.987	0.128	2.000	19.000	0.881	0.013
	Temporal Variability Parameters	Wilks' Lambda	0.882	0.799	3.000	18.000	0.511	0.118

* Significant between groups differences of Wilks' Lambda test.