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Changed Muscular Synergy of Specific Lower Limb Muscles in Subjects with Patellofemoral Pain Syndrome during Walking

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ABSTRACT

Aims: Patellofemoral Pain Syndrome (PFPS) refers to a range of conditions or anatomical irregularities that lead to pain in the front part of the knee, and it is one of the primary contributors to this type of discomfort. This study aims first to identify the muscle synergies of individuals with and without PFPS while walking, and then to analyze and compare their synergy patterns and associated activation coefficients throughout the gait cycle.

Method and Materials: The statistical population of this study consisted of adults aged 25 to 35, divided into two groups: a healthy group (n = 12) and a group diagnosed with patellofemoral pain syndrome (n = 9). The research utilized a force plate, a motion analysis system, and Electro Myo Graphy (EMG), adhering to specific inclusion and exclusion criteria. Data were analyzed through specialized software and statistical techniques, including HALS, frequency analysis, and t-tests.

Findings: This groundbreaking research in Iran examined muscle synergies during walking among individuals with patellofemoral pain syndrome, uncovering unique neural control patterns. The number of muscle synergies and the contribution of each lower limb muscle in the extracted synergies did not significantly differ between the control and affected groups ($p \leq 0.05$).

Conclusion: The absence of statistical significance may be attributed to the small sample size and inconsistencies in measurement techniques, underscoring the need for targeted rehabilitation that considers the impact of this condition on balance.

Keywords: Patellofemoral Pain Syndrome, Muscular Synergy, Gait

Introduction

Lower limb injuries are prevalent among young and adolescent athletes, making up around 40% of all injuries. As part of the kinetic chain, the knee is directly affected by movements and forces from the foot, heel, and lower leg. The knee must transmit these forces to the proximal joints, including the hip, pelvis, and spine [1]. Any abnormal forces that cannot be effectively distributed along this pathway must be absorbed by the surrounding tissues. In a Closed Kinetic Chain (CKC), these forces must either be transferred proximally or absorbed by the most distal joint [2]. Structural damage often arises when the system fails to distribute these forces adequately, especially at the knee, which is particularly susceptible due to its pivotal role in the movement chain. Hence, the knee joint stability heavily relies on the ligaments, joint capsule, and surrounding muscles [1]. While the knee is structurally intended to ensure stability and mobility under weight-bearing conditions, its medial compartment is somewhat unstable [3, 4].

Patello Femoral Pain Syndrome (PFPS) refers to a range of conditions or anatomical issues that cause pain in the front of the knee. It ranks among the leading causes of anterior knee pain [5]. PFPS is ubiquitous in athletes, often resulting in considerable pain and disability [6]. Alarmingly, the incidence rate is high, with roughly 22 out of every 1,000 individuals diagnosed with PFPS each year [7, 8]. Additionally, women are 2.23 times more likely than men to suffer from this condition [7]. Patellofemoral Pain Syndrome is a frequent

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musculoskeletal disorder of the lower limb, impacting 15–33% of adults and 21–45% of adolescents, with a notably higher occurrence in females within both groups [9]. This syndrome often affects military personnel, runners, and athletes involved in jumping sports [10].

Multiple studies reveal that 50–94% of individuals with patellofemoral pain syndrome (PFPS) experience ongoing pain for years following the initial symptom onset. Despite management attempts, in a previous study [11], only 22% of participants recovered after being monitored for 14–20 years. They also estimated that roughly half of PFPS cases resolve within four years, while the other half may take up to 12 years to resolve. Some researchers indicate that PFPS often starts in adolescence and can persist or recur in adulthood. Additionally, optimal knee joint functioning relies on intricate and coordinated muscle interactions. Effective knee movement depends on the synchronized actions of various lower limb muscles, which serve as agonists, antagonists, synergists, stabilizers, and neutralizers to generate and modulate forces, ensuring dynamic joint stability. Disruption of these interactions can hinder neuromuscular control.

A study tracked a group for 14 to 20 years, revealing that only about a quarter (22%) of participants experienced recovery. It was estimated that roughly 50% of PFPS cases resolve within four years, while the rest may take up to 12 years. Some researchers propose that PFPS often begins in adolescence and either persists or recurs in adulthood. Additionally, optimal knee joint function necessitates intricate and coordinated interactions between muscles. Effective knee movement depends on the synchronized actions of various lower limb muscles, which must function as agonists, antagonists, synergists, stabilizers, and neutralizers to generate and modulate forces while providing dynamic joint stability effectively. Any disruption in these interactions can hinder neuromuscular control.

The muscle synergy hypothesis, first introduced by Bernstein, is a prominent method for comprehending, preventing, and addressing muscular dysfunctions [12]. Analyzing muscle synergy offers valuable insights into the neural strategies that facilitate movement and the outcomes of muscular activity [13]. In clinical settings, 'synergy' has classically referred to abnormal muscle activation, as seen in patellofemoral pain syndrome (PFPS), which results in poor joint coordination in the lower limbs [14]. Additionally, it has been proposed that muscle synergy in healthy individuals represents the coordinated activation patterns necessary for executing functional motor tasks, possibly signifying a foundational principle of neural control. Therefore, examining muscle synergy can lead to a more explicit recognition of motor impairments or compensations and a more precise evaluation of the adaptability and flexibility of motor patterns. Gaining insight into flexibility in muscle coordination may help design more focused rehabilitation strategies, ultimately enhancing therapeutic results [15].

Recent research into neuromuscular control mechanisms bolsters the muscle synergy hypothesis. For instance, studies reveal that individuals utilize similar synergy structures across different sports activities, such as walking, jumping, swimming, and kicking. These findings demonstrate that muscle synergy patterns are adaptable and inherent, potentially accounting for the observed similarities in motor execution among different individuals [16]. From a biomechanical modeling perspective, studies have shown that muscle synergy models can effectively replicate complex motor behaviors [17, 18]. Research involving individuals with Parkinson’s disease [19], cerebral palsy [16], spinal cord injuries [20], and PFPS [21]. Reveals that their muscle synergies differ from those of healthy individuals during certain activities, such as walking. Consequently, this study aims first to extract the muscle synergies of individuals with and without PFPS while walking, and then to analyze and compare their synergy patterns and activation coefficients throughout the gait cycle.

Method and Materials

This study adopts a quasi-experimental

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design, focusing on adults aged 25 to 35. Participants were selected through convenience sampling. Using G*Power software, we calculated the necessary sample size for two groups based on an effect size of 0.5, a significance level of 0.05, and a statistical power of 0.80, which resulted in a sample size of 21 participants. These participants were then allocated into two groups: a healthy group (n = 12) and a PFPS group (n = 9). The Research Ethics Committee of Allameh Tabataba'i University granted ethical approval for the study (Ethics Code: IR.ATU.REC.1401.087). Inclusion criteria were: ages 25–35 years; a positive Clarke's test; anterior knee pain lasting a minimum of three months; no history of lower limb fractures or surgeries in the last six months; increased pain during at least two activities (such as climbing or descending stairs, squatting, or prolonged sitting); and pain upon palpation of the medial or lateral patella [4]. The exclusion criteria included: refusal to participate, inability to undergo tests, pain during testing, joint swelling [22], a history of lower limb surgery, pregnancy, and menstruation.

After screening, we thoroughly explained the study procedures to the participants using the inclusion and exclusion criteria. Participants were required to provide their written informed consent before enrollment. Upon arrival, we collected baseline measurements, including age, height, weight, dominant leg, sports history, and physical activity level. Subsequently, participants were assigned to their respective groups. The study utilized the following instruments: an 8-camera motion analysis system (Vicon, UK) operating with Nexus software at a sampling frequency of 100 Hz. Additionally, ground reaction forces and joint kinetics were recorded using a 60 cm × 40 cm Bertec force plate, sampling at 1000 Hz. This device features four piezoelectric force sensors, one embedded in each corner. The force plate was synchronized with the motion analysis system, and data were captured using Nexus software.

Accurate extraction of kinematic and kinetic data requires proper system calibration. Therefore, the calibration procedure was conducted by established standards. In Vicon systems, calibration is performed using the Active Wand device. This tool defines the Global Coordinate System (GCS) and establishes spatial position and orientation in three-dimensional space. The calibration involves two essential stages.

1. Establishing the origin of the coordinate system (static calibration): In this step, the wand is placed on the force plate. The axes of the laboratory coordinate system are defined as follows: the Y-axis indicates the anterior–posterior direction (i.e., the movement direction); the X-axis represents the medio–lateral direction; and the Z-axis denotes the vertical direction.

2. Dynamic calibration: To conduct this procedure, maneuver the wand throughout the entire capture volume for an adequate duration, ensuring that all cameras can effectively track the calibration object. For successful calibration, the imaging error for each camera must be 0.2 mm or less. If the error exceeds this limit, the calibration process must be repeated. Additionally, it is essential to note that both static and dynamic calibrations were performed before each testing session.

Reflective marker application: Before testing, we used double-sided adhesive tape to attach 14 mm reflective markers to specific anatomical points on the participants' lower limbs. The exact landmarks included the Anterior Superior Iliac Spine (ASIS), Posterior Superior Iliac Spine (PSIS), marker clusters on the mid-thigh and mid-shank areas, medial and lateral femoral condyles, medial and lateral malleoli, first, second, and fifth metatarsals, and the heel. In total, 36 reflective markers were arranged for static analysis, as outlined below:

Anterior superior iliac spine (ASIS) – 2 markers; posterior superior iliac spine (PSIS) – 2 markers; medial and lateral femoral condyle – 4 markers; medial and lateral malleolus – 4 markers; first, second, and fifth metatarsal – 6 markers; heel – 2 markers; and four clusters – 16 markers.

Before the static trials began, participants were instructed to stand on the force plate so that all cameras could capture the markers

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effectively. Additionally, three non-collinear markers were used to define the position of each segment accurately. The procedures for the analysis of this study included the following methods.

a) Muscle synergy count: Muscle synergies were evaluated through ElectroMyoGraphy (EMG) signal recordings using the Hierarchical Alternating Least Squares (HALS) algorithm. This method enhances Non-negative Matrix Factorization (NMF) by optimizing variable updates for improved efficiency. HALS consists of five main steps: 1. Random initialization or recursive use of the Perron–Frobenius theorem for SVD. 2. Estimating the matrix X. 3. Setting all harmful elements in X to zero or a small positive value. 4. Estimating matrix A. 5. Setting all harmful elements in matrix A to zero or a small positive value. In the above equations, Y represents the input data matrix, A denotes the basis matrix composed of non-negative vectors, X represents the matrix of unknown non-negative components, and E signifies error or noise.

b) Muscle response time to perturbation: The onset of muscle response was defined as when EMG activity exceeded three standard deviations above the baseline average before the onset of perturbation. The response time was recorded as the interval between the initiation of perturbation and the start of muscle activation.

c) Median and mean frequency of EMG signals (physiological work): EMG data collected at the beginning and end of the gait initiation protocol were analyzed. The median frequency, which indicates motor unit recruitment speed, was obtained from wavelet transform analysis performed in MATLAB. Furthermore, the Root Mean Square (RMS) of EMG activity per stride was calculated by dividing the total RMS by the number of strides.

To analyze the data, descriptive statistics, including the mean and standard deviation, were used to summarize the data. We applied the Kolmogorov–Smirnov (KS) test to assess the normality of the data distribution. All statistical analyses were carried out using SPSS software. An independent t-test was conducted to evaluate the study hypotheses and investigate differences between variables. The threshold for statistical significance across all analyses was set at $p < 0.05$.

Findings

In this study, 12 participants with a mean age of 22.81 ± 4.18 and 9 participants in the intervention group with a mean age of 23.40 ± 4.72 completed the study. Table 1 shows the demographic features of study participants, organized by group. This table shows that there are no significant differences between the two groups at the initial stage of this study.

Table 2 indicates no significant difference in the number of muscle synergies or the contribution of each lower limb muscle to the extracted synergies between the control and affected groups ($p \leq 0.05$). Consequently, this supports the null hypothesis and refutes the alternative hypothesis.

Table 1) Demographic characteristics of participants

Variable	Group	N	Mean ± SD	p-value (Sig.)
Age (years)	Control	12	22.81 ± 4.18	0.164
	PFPS	9	23.40 ± 4.72	
Height (m)	Control	12	1.66 ± 4.89	0.406
	PFPS	9	1.67 ± 5.45	
Weight (kg)	Control	12	61.10 ± 3.11	0.314
	PFPS	9	60.30 ± 2.56	
Body Mass Index (kg/m^2)	Control	12	22.18 ± 3.56	0.186
	PFPS	9	21.70 ± 3.87	

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Table 2) Results of the independent t-test for the number of lower limb muscle synergies during walking in the two

Variable	Group	N	df	t	p-value (Sig.)
Number of Muscle Synergies	Control	12	19	5.44	0.74
	PFPS	9			
Tibialis Anterior Muscle	Control	12	19	7.52	0.94
	PFPS	9			
Vastus Lateralis Muscle	Control	12	19	5.23	0.33
	PFPS	9			
Vastus Medialis Muscle	Control	12	19	5.75	0.16
	PFPS	9			
Soleus Muscle	Control	12	19	8.52	0.75
	PFPS	9			
Gastrocnemius Muscle	Control	12	19	6.43	0.40
	PFPS	9			
Gluteus Medius Muscle	Control	12	19	4.63	—
	PFPS	9			

Discussion

This study indicated no significant difference in lower limb muscle synergies between individuals with PFPS and healthy individuals during walking. In other words, those with PFPS exhibited no greater synergies than their healthy counterparts. Various studies have explored biomechanical abnormalities believed to contribute to PFPS, focusing on these in injury prevention and intervention programs. These abnormalities include knee valgus, increased hip adduction, internal pelvic rotation, foot deviation, reduced hip abductors and external rotators, and lower knee extensors [23, 24].

The findings of this study align with those of Kleiss et al. Their research, 'The Effect of Kinesio Taping on Pain and Walking in Patients with Patellofemoral Pain Syndrome' examined ten subjects, both with and without Patellofemoral Pain Syndrome (PFPS). Their results indicated no significant differences in walking speed between participants with PFPS and those without [25]. Additionally, Earl et al. identified a link between decreased knee flexion angles and PFPS during descent; similar trends have been observed in stair walking among individuals with PFPS [26, 27]. Moreover, Tijs et al. conducted a study that supports these findings, demonstrating no notable differences in the strength of any hip muscle groups between runners with PFPS and those without the condition. They concluded that variations in strength among hip muscle groups do not serve as risk factors for PFPS [28].

One potential explanation for the lack of impact of the number of lower limb muscle synergies on walking for those with PFPS compared to healthy individuals is the differences in variables and measurement techniques employed. Numerous kinematic investigations of the lower limb have been carried out during various screening tasks [29-36]. Dynamic abnormalities, such as increased hip adduction and internal rotation while walking and running, heighten the risk of injury [34, 35]. These activities contribute to knee valgus and diminish the patellofemoral joint's contact surface area, increasing the forces acting on it. Dynamic knee valgus during movement is a key indicator for identifying people at risk for PFPS [37-39]. Two prospective studies have assessed movement variations, particularly hip joint movements, between participants experiencing increases in PFP and those without. Noehren et al. (2013) explored the link between hip adduction and PFP in 400 female runners through three-dimensional gait analysis, observing that 15 participants with heightened PFP exhibited significantly larger hip adduction angles. Supporting studies include Noehren et al.'s research titled Proximal and Distal Kinematics in Female Runners with Patellofemoral Pain, which determined that there were no significant differences in peak rear foot inversion, forefoot flexion, or forefoot abduction across groups. Furthermore, there was no notable variation in peak pelvic drop between the two populations [40].

Decreased flexibility in the gastrocnemius muscle can limit the range of motion (ROM) of

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dorsiflexion. The foot may undergo pronation to meet the necessary dorsiflexion ROM during walking and other activities [41]. Individuals with patellofemoral pain show a significant reduction in the length of the gastrocnemius and soleus muscles compared to healthy individuals [41]. This reduction in dorsiflexion ROM has been linked to increased knee valgus as a compensatory response [42]. A study was conducted on the dorsiflexion range of motion (ROM). They reported a significant rise in gastrocnemius stiffness among participants who later developed PFP, in contrast to the healthy control group [43]. Therefore, it is suggested that an increase in gastrocnemius stiffness may affect ankle and foot kinematics during walking.

One possible explanation for the minimal differences in lower limb muscle synergies during walking between individuals with PFPS and healthy individuals may be the restricted number of variables that can be combined in a meta-analysis, along with the necessity to detail various risk factors separately in each study.

Conclusion

This study marks the first exploration of how muscle synergy influences walking in patients with patellofemoral pain syndrome in Iran. It can be inferred that environmental factors influence this injury, as neither the contribution nor the number of muscle synergies changed. Although the results were not statistically significant, the average contributions of muscles to these synergies show variance, suggesting different neural patterns among affected individuals. The lack of substantial findings may stem from the small sample size of participants with patellofemoral pain syndrome compared to healthy participants, as well as variability in measurement techniques. This condition impacts balance and postural control, interfering with everyday activities. Consequently, focusing on rehabilitating this injury and the factors that affect it could play a crucial role in effective treatment.

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Authors' Contribution

Each author engaged in various facets of the research. They assisted in drafting the manuscript and sanctioned the final version.

Conflicts of Interest

This study had no conflicts of interest.

Ethical approval

The Research Ethics Committee of Allameh Tabataba'i University granted ethical approval for the study (Ethics Code: IR.ATU.REC.1401.087).

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