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The Role of Vertical Stiffness in Predicting the Incidence of Patellofemoral Pain Syndrome: A Prospective Cohort Study

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Original Article

Abstract

Introduction: Patellofemoral pain syndrome (PFPS) is one of the most common overuse injuries of the lower extremity, particularly prevalent among active individuals. Despite numerous studies, the biomechanical risk factors associated with its incidence have not yet been fully identified. Vertical stiffness, as a modifiable variable that reflects both kinetic and kinematic components of the movement system, may play an important role in identifying individuals at risk. This study aimed to investigate the role of vertical stiffness in predicting PFPS incidence.

Materials and Methods: In this prospective cohort study, 80 first-year physical education students (50 women and 30 men) who met the inclusion criteria were selected using convenience sampling. Vertical stiffness of both lower limbs was measured during running at the beginning of the academic semester. Participants were monitored for 16 weeks, and lower extremity injuries were recorded and confirmed by an orthopedic physician. At the end of the follow-up period, participants were divided into two groups: those with PFPS and those without injury. Differences in vertical stiffness between groups were analyzed using an independent t-test, and the predictive role of vertical stiffness was examined using binary logistic regression.

Results: The mean pre-injury vertical stiffness in the PFPS group was significantly higher than that in the uninjured group ($P \leq 0.05$). Logistic regression analysis showed that higher vertical stiffness was significantly associated with an increased risk of developing PFPS [odds ratio (OR) = 2.078, 95% confidence interval (CI): 1.026–4.207, $P \leq 0.05$].

Conclusion: High vertical stiffness is a significant predictor of PFPS incidence. These findings suggest that assessing vertical stiffness may help identify individuals at risk and support the design of prevention strategies targeting biomechanical factors.

Keywords: Patellofemoral pain syndrome; Vertical stiffness; Running; Risk factors; Biomechanics

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Introduction

Patellofemoral pain syndrome (PFPS) is recognized as one of the most prevalent musculoskeletal disorders affecting the lower extremity, with an estimated prevalence of approximately 22.7% in the general population (1, 2). Furthermore, this syndrome is estimated to account for 25% to 40% of all knee-related injuries (1). It is characterized by peripatellar or retropatellar pain exacerbated during weight-bearing activities such as running, jumping, landing,

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and stair climbing (3). The clinical significance of PFPS is underscored by the fact that approximately 70% to 90% of patients experience recurrent or persistent symptoms, which may ultimately progress to patellofemoral osteoarthritis (4, 5). Despite substantial efforts to prevent and treat PFPS, its high prevalence persists, indicating that its underlying risk factors and pathomechanisms remain incompletely understood (3, 6). PFPS is currently recognized as a multifactorial disorder, and previous studies have identified biomechanical factors, including both kinematic and kinetic variables, as important risk factors for its development (7). Evidence indicates a direct relationship between patellofemoral joint contact force and variables such as the knee extensor moment, knee flexion angle, and knee joint power, whereby increases in these parameters elevate the stress imposed on the patellofemoral joint (8).

Furthermore, elevated ground reaction forces, altered lower-extremity kinematics, and increased loading rates have also been identified as key contributors to increased mechanical loading on the patellofemoral joint (9, 10). Most previous studies have investigated kinetic and kinematic factors in isolation; however, the actual function of the musculoskeletal system arises from the dynamic, simultaneous interaction between these two components. Therefore, investigating variables that integrate kinematic and kinetic characteristics into a single, unified index may provide a more comprehensive understanding of the mechanisms underlying injury development (11, 12).

Stiffness is defined as the ratio of force to deformation and describes a structure's resistance to deformation. As a biomechanical index, stiffness represents the net interaction between kinetic and kinematic variables, reflecting the musculoskeletal system’s capacity to resist deformation under externally applied forces or moments (13). Stiffness plays a crucial role in regulating the mechanical behavior of the musculoskeletal system and in storing and returning mechanical energy during movement. Within this framework, it influences the transmission and distribution of forces throughout the lower extremity and serves as a key determinant of movement efficiency (13, 14). Moreover, because stiffness simultaneously reflects both the external forces applied to the body and the musculoskeletal system's response to those forces, it is considered a valuable biomechanical index for investigating the mechanisms underlying musculoskeletal injuries (13, 15). Existing evidence suggests a non-linear, U-shaped relationship between stiffness and injury risk. Excessively high stiffness increases mechanical loading on the musculoskeletal system, thereby elevating the likelihood of hard-tissue injuries.

In contrast, excessively low stiffness permits excessive joint motion, consequently increasing the risk of soft-tissue injuries (15, 16). Stiffness can be quantified at various levels, including joint, limb, and whole-body stiffness. Whole-body stiffness, also known as vertical stiffness, is a functional index defined as the ratio of the change in vertical ground reaction force to the vertical displacement of the body's center of mass during locomotor activities (17).

Despite this theoretical framework, findings regarding the relationship between stiffness and injury remain inconsistent, and no definitive conclusion has yet been reached. For example, Watsford et al. reported that football players who sustained hamstring injuries during the competitive season exhibited higher lower-extremity vertical stiffness than uninjured players (18). In contrast, by increasing the assessment frequency to monthly intervals, Pruyn et al. and Spörri et al. reported that absolute pre-injury vertical stiffness was not associated with the occurrence of soft tissue injuries; instead, bilateral asymmetry in vertical stiffness between the dominant and non-dominant limbs appeared to contribute to injury occurrence (19, 20). Another study also reported no significant association between vertical stiffness and hamstring injuries (21).

Given the contradictory reports on the stiffness-injury relationship, it appears that part of this heterogeneity stems from evaluating this index globally, without accounting for the specific mechanical properties of different injuries. From a theoretical perspective, elevated stiffness is primarily associated with increased mechanical loading and hard tissue injuries (15, 16). However, previous investigations have primarily focused on the association between stiffness and soft tissue injuries, such as muscle strains and tendinopathies. This discrepancy suggests that evaluating the role of stiffness without accounting for the mechanical properties and loading characteristics of specific injuries may yield inconsistent findings. Therefore, investigating stiffness in load-dependent overuse injuries, such as patellofemoral pain syndrome, may provide a more accurate understanding of its role in injury development. Furthermore, because stiffness is a modifiable biomechanical factor, identifying its contribution to injury development represents an important step toward recognizing injury risk factors and developing effective prevention strategies. Accordingly, given that no prospective study has specifically investigated the role of vertical stiffness in the development of patellofemoral pain syndrome, the present study aimed to determine whether pre-injury vertical stiffness, as an index of the musculoskeletal system's mechanical response, could predict subsequent patellofemoral pain syndrome.

Materials and Methods

This study used a quasi-experimental, prospective cohort design. Eighty first-year physical education students from the University of Mazandaran (30 males and 50 females) participated in this study and were selected through convenience sampling. The sample size was estimated based on previous studies in this field (18, 20, 22). All stages of the research were conducted in the biomechanics laboratory at the University of Mazandaran. Prior to the study, research objectives were explained to participants, and all provided written informed consent. This study was conducted in accordance with the ethical principles for human research and the Declaration of Helsinki and was approved by the Ethics Committee of the University of Mazandaran. Inclusion criteria comprised being a first-semester physical education student, being between 19 and 25 years old, and having a body mass index (BMI) between 18.5 and 29.9 kg/m². Exclusion criteria were classified into two categories. The first category included the presence of any musculoskeletal disorders or postural abnormalities, such as chronic ankle sprains, lower extremity fractures, joint injuries, stress fractures, osteoarthritis, shin splints, or leg pain within the six months preceding the test, as well as structural abnormalities of the lower extremity, such as pes planus or pes cavus (14, 16, 23, 24).

To ensure the participants' health, all individuals were evaluated by an orthopedic specialist prior to study entry. To assess the medial longitudinal arch, the navicular drop test was performed using Brody's method, and only individuals with a normal navicular drop (5–9 mm) were included in the study (25). The second exclusion criterion pertained to participants' physical activity history. Given the effect of training history on the stiffness index, only individuals who had not participated in any regular training program during the year preceding the test and who had relatively similar levels of physical activity were included (26, 27). Throughout the study period, participants followed an identical academic curriculum comprising physical fitness, volleyball, and track and field courses (Table 1). Extracurricular physical activities were also recorded, and none of the participants engaged in any regular off-campus training program during the study period. All participants used their own footwear throughout the study period and during the assessment sessions. Prior to testing, the type of footwear used was recorded to ensure that all participants wore standard, commercially available sports shoes without specialized biomechanical design features (e.g., minimalist shoes).

Biomechanical assessments were conducted prior to the start of the academic semester, when all participants were injury-free. To measure vertical stiffness, participants were evaluated in the biomechanics laboratory under controlled conditions. Three-dimensional kinetic and kinematic data were collected using a motion analysis system (Simi Reality Motion, Unterschleissheim, Germany), six cameras (JVC-9X0, Yokohama, Japan), a force plate (Kistler, Winterthur, Switzerland), reflective markers, and cluster markers (Qualisys, Gothenburg, Sweden). Reflective markers were attached to anatomical landmarks, including the anterior and posterior superior iliac spines, greater trochanters, femoral epicondyles, malleoli, calcaneus, and metatarsal heads. Additionally, rigid cluster markers were placed on the thigh and shank. A static trial was recorded first to define the anatomical coordinate system; subsequently, anatomical markers were removed, leaving only the tracking clusters to record dynamic trials.

The running trials were conducted at a controlled speed of 4.0 ± 0.2 m/s. To control the running speed, a 4 m distance was set between the starting point and the center of the force plate. The time required to traverse this distance was recorded simultaneously by two evaluators using digital stopwatches (Q&Q, Tokyo, Japan). If the discrepancy between the two measurements exceeded 0.05 s, the trial was repeated. Running speed was calculated as the distance covered divided by the transit time, and only trials within the predetermined speed range were included in the analysis. Each participant completed three successful trials for each lower extremity, and the mean value of these trials was used for statistical analysis (24).

Table 1. Physical Activity Characteristics and Training Session Structures of the Participants over the Academic Semester

Physical Activity Type	Session Duration (hours)	Weekly Frequency (sessions/week)	Total Sessions per Semester
Physical Fitness	2	2	32
Volleyball	2	2	32
Track and Field	2	2	32

Prior to testing, participants performed only light jogging as a warm-up, and stretching was avoided due to its potential to increase stiffness. A 3-minute rest interval was provided between trials. Raw kinematic and kinetic data were smoothed using a fourth-order Butterworth low-pass filter with cutoff frequencies of 10 Hz for kinematic data and 50 Hz for kinetic data. All computations were performed using MATLAB software (MATLAB R2020, MathWorks, Natick, MA, USA). Vertical stiffness was calculated as the ratio of the maximum vertical ground reaction force to the maximum vertical displacement of the body's center of mass (28).

The vertical displacement of the center of mass was derived by double integration of the vertical acceleration obtained from the ground reaction force. To enable comparisons among individuals with different anthropometric characteristics, vertical stiffness values were normalized to body mass. In addition to the variables required to calculate vertical stiffness, several supplementary biomechanical variables were extracted and analyzed based on the existing literature. These variables, which are indirectly related to vertical stiffness, were examined to facilitate a more precise interpretation of the findings and to identify potential factors influencing differences in vertical stiffness between the two groups. These variables included ground contact time, loading rate, and the angular range of motion of the knee and ankle joints (16, 17, 29). Ground contact time was defined as the time interval between the initial contact of the foot with the force plate and toe-off of the same foot (22). The loading rate was calculated from the slope of the initial portion of the vertical ground reaction force–time curve, corresponding to the time interval between 20% and 80% of its first peak (30).

Injury surveillance was conducted throughout the academic semester by monitoring symptoms such as pain, swelling, or reduced function following each training session. Upon the observation of any symptoms, the individual was referred to an orthopedic specialist. The diagnosis of patellofemoral pain syndrome was confirmed by the orthopedic physician following the requisite clinical examinations, and all information regarding symptoms, history, and injury type was recorded. Individuals who sustained injuries other than patellofemoral pain syndrome were excluded from the final analysis. At the end of the follow-up period, participants were divided into two groups: those diagnosed with patellofemoral pain syndrome and those who remained uninjured. Statistical analyses were performed using SPSS software (Version 26, SPSS Inc., Chicago, IL, USA). The normality of the data distribution was evaluated using the Shapiro–Wilk test, and the homogeneity of variances was assessed using Levene's test. Data were reported as mean ± standard deviation, and the significance level for all tests was set at $P \leq 0.05$. An independent-samples t-test was used to compare anthropometric variables between the injured and uninjured groups.

Furthermore, within the uninjured group, a paired-samples t-test was used to compare vertical stiffness between the right and left limbs. Comparisons of vertical stiffness and the other biomechanical variables between the two groups were also performed using an independent-samples t-test. Finally, binary logistic regression was performed to determine whether vertical stiffness was associated with patellofemoral pain syndrome, and the OR and 95% CI were reported.

Results

Injury surveillance revealed that, of the 80 participants monitored during the follow-up period, 12 developed patellofemoral pain syndrome (PFPS), whereas 46 remained uninjured. The remaining participants were excluded from the final analysis because they sustained injuries other than patellofemoral pain syndrome. Table 2 presents the anthropometric characteristics of the participants in the two groups. Prior to performing the parametric analyses, the data distribution was assessed using the Shapiro–Wilk test. The results indicated that all variables were normally distributed. An independent-samples t-test was used to compare the variables between the two groups. The results demonstrated no significant differences in the anthropometric variables between the groups. Therefore, these findings confirmed the homogeneity of the two groups with respect to their anthropometric characteristics.

Table 2. Demographic characteristics of the participants in the PFPS and uninjured groups

Variable	PFPS group (n = 12)	Uninjured group (n = 46)	P value
Age (years)	20.17 ± 1.11	19.8 ± 0.8	0.557
Height (m)	1.65 ± 0.05	1.69 ± 0.08	0.124
Body mass (kg)	61.88 ± 5.75	64.81 ± 10.33	0.346
Body mass index (kg/m²)	22.16 ± 2.29	22 ± 2.96	0.887

Values are expressed as mean ± SD. Statistical significance was set at $P \leq 0.05$.

Table 3. Results of the Shapiro–Wilk and Levene's Tests in the Control, Hopping, and TheraBand Groups

Variable	Time	Group	Normality (Shapiro-Wilk)	Homogeneity of Variance (Levene's Test)
Proprioception	Pretest	Control	0.341	0.515
		Hopping	0.898	
		TheraBand	0.657	
	Post-test	Control	0.995	0.067
		Hopping	0.531	
		TheraBand	0.379	
Time to Stabilization	Pretest	Control	0.718	0.600
		Hopping	0.244	
		TheraBand	0.693	
	Post-test	Control	0.956	0.415
		Hopping	0.368	
		TheraBand	0.367	

To compare vertical stiffness between the left and right limbs in the uninjured participants, a paired-samples t-test was conducted. The results indicated no statistically significant difference in vertical stiffness between the left and right limbs (Table 3). Accordingly, to obtain a representative index for the uninjured group, the mean vertical stiffness of the left and right limbs was calculated for each participant and used in the between-group comparative analyses. In contrast, the statistical analyses for the PFPS group were performed using the pre-injury vertical stiffness of the affected limb.

To better elucidate the observed differences in the vertical stiffness index, several biomechanical variables related to the components of vertical stiffness were also compared between the two groups, along with the primary study variable. The results of these comparisons are presented in Table 4. The independent-samples t-test showed that vertical stiffness was significantly greater in the patellofemoral pain syndrome group than in the uninjured group (P = 0.034). In addition, a significant between-group difference was observed in the vertical displacement of the body's center of mass (P = 0.018), with the uninjured group exhibiting greater values than the patellofemoral pain syndrome group. In contrast, no significant between-group differences were observed in the maximum vertical ground reaction force (P = 0.177), ground contact time (P = 0.171), or mean loading rate (P = 0.682).

Binary logistic regression was performed to assess the predictive value of vertical stiffness for PFPS. Prior to the analysis, all vertical stiffness values were standardized as Z scores to improve model stability and facilitate comparison of the regression coefficients. The results indicated that pre-injury vertical stiffness was a significant predictor of PFPS occurrence (B = 0.731, SE = 0.360, P = 0.042). Based on the results, a one-standard-deviation increase in vertical stiffness was associated with a 2.078-fold increase in the likelihood of developing PFPS. Overall, the findings of this study indicate that higher pre-injury vertical stiffness may be associated with a greater likelihood of developing patellofemoral pain syndrome.

Discussion

This prospective study aimed to determine whether pre-injury vertical stiffness could predict the future development of patellofemoral pain syndrome (PFPS). Unlike retrospective research examining biomechanical changes after injury onset and symptom progression (31, 32), the prospective design allowed evaluation of whole-body vertical stiffness as a potential predictor of injury risk. Our findings showed that higher pre-injury vertical stiffness was associated with a significantly increased risk of developing PFPS. Specifically, a one-standard-deviation increase in vertical stiffness was associated with a 2.08-fold increase in the likelihood of developing PFPS. These results indicate that elevated vertical stiffness may be a risk factor for PFPS. Consistent with previous reports (15–17, 22), vertical stiffness appears to be associated with PFPS. However, these results conflict with those reported by Spörri et al. (20). A plausible explanation for this discrepancy is that Spörri et al. investigated a broad range of soft-tissue injuries rather than a single specific pathology.

Table 4. Comparison of vertical stiffness between the left and right limbs in the uninjured group

Variable	Uninjured (Left limb) (n = 46)	Uninjured (Right limb) (n = 46)	t	df	P value
Vertical stiffness (kN/m/kg)	0.355 ± 0.054	0.359 ± 0.059	-0.537	45	0.594

Values are expressed as mean ± SD. Statistical significance was set at P≤≤0.05.

Table 5. Comparison of vertical stiffness and associated biomechanical variables between the uninjured and PFPS groups

Variable	Uninjured group	PFPS group	t	P value
Vertical stiffness (kN/m/kg)	0.357 ± 0.05	0.394 ± 0.061	-2.170	0.034*
Peak vertical ground reaction force (body weight)	2.103 ± 0.141	2.163 ± 0.11	-1.368	0.177
Ground contact time (s)	0.261 ± 0.025	0.273 ± 0.023	-1.385	0.171
Vertical displacement of the center of mass (m)	0.081 ± 0.011	0.071 ± 0.012	2.445	0.018*
Average loading rate (N/kg/s)	83.68 ± 14.65	85.59 ± 12.6	-0.412	0.682
Knee joint angular displacement (degrees)	27.98 ± 5.68	28.69 ± 3.4	-0.833	0.408
Ankle joint angular displacement (degrees)	17.3 ± 0.62	16.67 ± 0.76	2.57	0.013*

Values are presented as mean ± SD. Statistical significance was set at p≤0.05.
*Indicates a statistically significant between-group difference.

As previously discussed, stiffness regulation may play distinct roles depending on the nature of the injury. Nonetheless, Spörri et al. concluded that further research is required before definitively ruling out a relationship between stiffness and injury. Vertical stiffness reflects how the lower-extremity system interacts with vertical ground reaction forces during running and directly relates to the musculoskeletal capacity to attenuate mechanical energy (17). Our findings indicate that individuals who later developed PFPS adopted a stiffer stance-phase movement pattern, as evidenced by significantly reduced vertical center-of-mass displacement compared with the uninjured group. Because vertical stiffness is largely determined by joint range of motion (ROM) (33), and given the significant reduction in ankle sagittal-plane ROM observed in the future-injured group, this restriction likely limits the capacity to gradually attenuate impact forces, thereby increasing load transfer to proximal joints (33).

Furthermore, restricted ankle dorsiflexion during ground contact can trigger compensatory mechanisms, such as excessive foot pronation and tibial internal rotation, which increase mechanical loading on the patellofemoral joint (34). Consequently, the combination of reduced ΔyCoM and restricted ankle mobility reflects an altered shock-absorption strategy that shifts mechanical loading to the knee. These findings are consistent with previous research showing that limited ankle dorsiflexion alters the kinetic and kinematic profiles of proximal segments, thereby elevating injury risk (34, 35). Conversely, pre-injury knee joint angular displacement was greater in the PFPS group than in the uninjured cohort, though this difference was not statistically significant. While increased knee flexion is traditionally linked to greater ΔyCoM and a subsequent reduction in Kvert (33), this relationship is non-linear. Indeed, CoM vertical displacement is governed by a complex interplay of biomechanical parameters, including ground reaction force profiles, contact time, spring-mass compression dynamics, and coordinated kinematics among the hip, knee, and ankle joints (36).

Thus, while alterations in knee ROM may increase vertical displacement under certain conditions, this effect can be offset by compensatory adjustments at other joints along the kinetic chain or by variations in spatiotemporal running patterns. Supporting this non-linear interpretation, individuals with lower vertical displacement in our study exhibited greater knee flexion, though this difference was not statistically significant. This suggests that variations in vertical stiffness and CoM displacement reflect a multifactorial, adaptive movement strategy rather than a simple consequence of isolated kinematic changes such as knee flexion. From a patellofemoral pathology perspective, greater knee flexion during running has been linked to an elevated risk of PFPS due to increased contact forces between the patella and the femoral trochlea (12). Conversely, other studies report that individuals with PFPS exhibit reduced knee flexion angles during running compared to healthy controls (9, 37). These authors suggest that limited knee flexion decreases the patellofemoral joint contact area, thereby increasing joint stress concentration despite lower net contact forces. This mechanism contrasts with the former paradigm. Based on our findings, the greater knee angular displacement observed in the future-injured group likely represents a compensatory shock-absorption mechanism secondary to restricted ankle mobility. When ankle dorsiflexion is limited, the forward progression of the tibia over the foot is constrained. To compensate for this restriction, facilitate forward progression, and control body weight during stance, runners may increase knee flexion. Under conditions of restricted ankle ROM, the ankle's capacity to attenuate mechanical energy is compromised, forcing the musculoskeletal system to rely more heavily on the knee during the loading phase. Consequently, the knee must accommodate a larger share of the impact energy, resulting in greater joint excursion and elevated eccentric muscular demand. This compensatory increase in knee motion during weight-bearing heightens patellofemoral joint reaction forces and concentrates compressive stress on the patellofemoral articular cartilage. Therefore, this movement pattern reflects a proximal shift in the shock-absorption strategy from the ankle to the knee, ultimately increasing the risk of PFPS.

Limitations

One limitation of the present study is that vertical stiffness was calculated from only a single running step. Given that biomechanical variables may fluctuate across consecutive steps, analyzing multiple sequential strides might have provided a more stable estimate of vertical stiffness and enhanced the explanatory power of the findings. Another limitation concerns the type of footwear participants wore. Although efforts were made to ensure that the footwear worn during testing matched that used during training, individual variations in mechanical properties—such as shock absorption and midsole stiffness—may have influenced the biomechanical profile and the estimation of vertical stiffness. Utilizing standardized footwear for all participants could have minimized the influence of this confounding variable. Furthermore, the volume and intensity of the training programs undertaken by the male and female participants were not fully controlled. Despite similar planning in terms of activity type, Frequency, and objectives, potential differences in program implementation (e.g., training intensity) may have acted as confounding variables, influencing biomechanical characteristics and the resulting findings.

Recommendations

Because vertical stiffness was assessed from a single step in this study, future research should analyze multiple consecutive strides to yield more reliable estimates of lower-extremity stiffness. Furthermore, examining how vertical stiffness relates to injury incidence across varying conditions, such as different running speeds or surfaces, would provide a more comprehensive understanding of its role in running-related injuries. Additionally, interventional studies are recommended to design and evaluate training programs that modulate vertical stiffness. Investigating the effects of resistance training, plyometric exercises, and neuromuscular control training on vertical stiffness could help develop effective strategies to reduce the risk of patellofemoral pain syndrome.

Conclusion

The findings of this study demonstrate that higher vertical stiffness is associated with an increased risk of developing patellofemoral pain syndrome in physically active individuals and may serve as a biomechanical marker for identifying those at risk. Given that vertical stiffness is a modifiable variable, targeted training interventions appear to be a promising approach for preventing PFPS. However, further prospective and interventional studies are necessary to confirm this relationship and determine the effectiveness of such interventions.

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Authors' Contribution

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Conflict of Interest

The authors did not have a conflict of interest.

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