Original

The Correlation between Intersegmental Coordination Variability and Frontal Plane Hip Kinematics during Running in Persons with Patellofemoral Pain

Farzaneh Haghighat[1], Mohammadreza Rezaie[2], Samaneh Ebrahimi[3,4], Seyed Mohammadreza Shokuhian[5], Alireza Motealleh[3,4]*, Reza Salehi[6], Mohamad Parnianpour[7]

[1]PhD Candidate, Student Research Committee, Shiraz University of Medical Sciences, Shiraz, Iran
[2]MSc, Rehabilitation Sciences Research Center, Shiraz University of Medical Sciences, Shiraz, Iran
[3]PhD, Rehabilitation Sciences Research Center, Shiraz University of Medical Sciences, Shiraz, Iran
[4]PhD, Department of Physical Therapy, School of Rehabilitation Sciences, Shiraz University of Medical Sciences, Shiraz, Iran
[5]MSc, Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran
[6]PhD, Department of Physical Therapy, School of Rehabilitation Sciences, Iran University of Medical Sciences, Tehran, Iran
[7]PhD, Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

*Corresponding author: Alireza Motealleh
Department of Physical Therapy, School of Rehabilitation Sciences, Shiraz University of Medical Sciences, Shiraz, Iran
E-mail: motealleh@sums.ac.ir

Received: 16 January 2021
Accepted: 15 April 2021

ABSTRACT

Background: Despite the existing evidence indicating altered hip kinematics as well as the studies showing altered movement coordination variability in persons with patellofemoral pain (PFP), there is no study investigating the correlation between hip joint kinematic and movement coordination variability in persons with Patellofemoral pain (PFP).

Objective: This study aims to evaluate the correlation between peak hip adduction and variability of thigh frontal-shank transverse coordination during running in persons with PFP.

Material and Methods: In this cross-sectional correlational study, kinematic data were collected from 34 females (17 with and 17 without PFP) aged 18-35 years during treadmill running at preferred and fixed speeds, each for 30 s. The continuous relative phase method was used to calculate the coordination of thigh frontal-shank transverse. To calculate the deviation phase as the variability of intersegmental coordination, the standard deviation of the ensemble continuous relative phase curve points was averaged. The parameters of interest were peak hip adduction and coordination variability of thigh frontal-shank transverse. The Pearson Correlation Coefficient (r) was used to calculate the correlation between the variables.

Results: The Pearson correlation coefficient showed a significant negative correlation between the peak hip adduction angle and variability of thigh frontal– shank transverse during running at both fixed ($r= -0.553$, $P< 0.05$) and preferred ($r= -0.660$, $P< 0.01$) speeds in persons with PFP while the control group showed a small nonsignificant correlation ($r < 0.29$, $P > 0.05$).

Conclusion: The results indicated that greater adduction of the hip joint in persons with PFP during running is contributed to lesser variability of thigh frontal-shank transverse.

Keywords
Patellofemoral Pain Syndrome; Running; Kinematics; Dynamical System; Continuous Relative Phase; Variability; Hip Joint; Coordination

Introduction

Patellofemoral pain (PFP) is a common chronic musculoskeletal disorder [1] defined as anterior knee (around or behind patella) pain exacerbated by patellofemoral (PF) joint loading activities, such as stair ambulation, squatting, jumping, or running [1, 2]. Although PFP is considered as a multifactorial problem and its underlying mechanisms are not clearly diagnosed, pain is suggested to arise from elevated patellar contact stress resulting from abnormal patellar tracking [3, 4]. Considering that the patella articulates with the patellar surface of the femur, abnormal movements of the hip joint during weight-bearing tasks can affect the normal tracking of the patella [5]. An increasing number of studies have shown altered hip kinematics in the frontal and transverse planes during weight-bearing activities in persons with PFP compared to healthy individuals [6-8]. Since excessive quadriceps angle (Q-angle) predisposes the patella to laterally directed forces in the frontal plane, altered frontal-plane kinematics of the lower extremity, especially excessive knee valgus (induced by excessive hip adduction and or tibial abduction), can affect the PF joint negatively [5]. It has been suggested that hip adduction has the primary role in excessive dynamic knee valgus [9]. Two systematic reviews have also concluded a moderate association between PFP and hip adduction [10, 11]. Furthermore, excessive hip adduction predicted self-reported pain and function during a step-down task in this pathologic group [12]. Based on the prospective study conducted by Noehren et al. [13], female runners who develop PFP showed significantly greater hip adduction during running compared to healthy controls.

On the other hand, it is well known that functional tasks and goal-directed movements require coordination of numerous degrees of freedom (e.g. joints and segments) to convert them to a controllable system [14, 15]. Multiple degrees of freedom provide different solutions to the system to accomplish a task and optimize performance. In the presence of a large number of degrees of freedom, the variability of coordinative structures is unavoidable [16, 17]. Based on the dynamic system theory (DST), variations in coordinative patterns indicate the system's flexibility to adapt with internal and external perturbations, as opposed to the traditional view of variability, which is considered as noise [18]. For the first time, Hamill et al. [19] used the DST approach to investigate the variability of coordinative structures in individuals with an orthopedic injury and reported that patients with PFP displayed lesser coordination variability compared to healthy controls, probably in an attempt to avoid painful coordinative patterns. Reduced variability is proposed to cause the same area of the joint to be constantly exposed to pressure, resulting in excessive wear and tear of the articular structures and eventually overuse injuries [19]. Since then, more researches have been done based on this concept in different musculoskeletal injuries, including PFP [20-24].

Considering all the above mentioned, knowledge of the relationship between hip kinematics and lower extremity intersegmental coordination variability would help develop optimal preventive, diagnostic and rehabilitative strategies in patients with PFP. Although altered hip kinematics and altered coordination variability in persons with PFP have been reported in several studies, the relationship between hip kinematics and coordination variability has not been established to the best knowledge of the authors. Therefore, this study aimed at investigating the association between peak hip adduction angle and variability of thigh frontal-shank transverse in females with PFP during preferred speed running (PSR) and fixed speed running (FSR). It was hypothesized that greater peak hip adduction during running would be associated with lesser coordination variability in females with PFP.

Material and Methods

This cross-sectional correlational study was approved by the local Ethics Committee of Shiraz University of Medical Sciences (IR.SUMS.REHAB.REC.1397.006). All participants signed informed consent before their participation.

Participants

Thirty-four females (17 healthy and 17 with unilateral PFP) between the age of 18 to 35 years were enrolled in this study with the following eligibility criteria: 1) insidious onset of anterior knee pain persisted for at least 3 months [25], 2) pain evoked by at least 2 of the PF joint loading activities such as stair ambulation, running, squatting, kneeling, prolonged sitting, hopping and jumping, 3) pain evoked by palpation of patellar facets, isometric contraction of quadriceps muscle or applying a compressive force to the PF joint, 4) pain intensity of at least 3 in the 11-point (0-10) numerical rating scale (NRS): 0 implies no pain, and 10 implies maximum pain, 5) positive patellar apprehension test (sensitivity and specificity: 86.7%) [26], 6) score equal or less than 85/100 on the Kujala anterior knee pain score [27]. Exclusion criteria were: 1) any other knee injury or pathology except PFP, such as patellar tendonitis, meniscal pathology, ligamentous instability, osteoarthritis, bursitis, plica syndrome, and subluxation or dislocation of the patella, 2) visible lower extremity structural malalignment or other orthopedic disorders such as leg length discrepancy which affect the gait, 3) metabolic disease like diabetes, 4) cardiovascular disease, 5) neurological disorders, 6) pregnancy, 7) individuals who have received oral steroids, acupuncture, and physiotherapy within past six months, 8) professional athletes.

Data acquisition

A total of 13 retro-reflective markers were placed on the pelvis and lower limb anatomical landmarks as well as four rigid plates containing four markers, which were wrapped around thigh and shank segments to build a 6-degrees of freedom (DoF) model. The bony landmarks of interest were the bilateral anterior and posterior superior iliac spine (ASIS and PSIS), iliac crests, greater trochanters, medial and lateral knee condyles, medial and lateral ankle malleoli, and calcaneal tuberosity. The participants were asked to stand 3 s in an anatomical position as a static standing trial followed by running at two different speeds (each one for 30 seconds) on a treadmill (PROTEUS IMT-8000/8500, Philippines) with enough rest between the FSR (2.68 m/s) [21] and PSR. To determine the preferred speed for each individual, the speed decreased and increased between 2.2 to 3.3 m/s by the investigator until the participant reported a comfortable speed in this range while unaware of its amount. It should be noted that all participants wore standard shoes with the same brand. Eight Proreflex (Qualisys® Medical AB, Gothenburg, Sweden) cameras with a sampling rate of 200 HZ were used to track the marker trajectories.

Data analysis

The marker trajectories were imported into Visual3D software (C-Motion®, Rockville, MD, USA). The cubic spline and fourth-order Butterworth low-pass filter with a 9 HZ cutoff were applied to fill the gaps and reduce the noises, respectively. The static trial was used to calibrate the Visual3D 6 DoF model, and the pelvis, thigh, and shank segments were built according to the anatomical markers' position. Kinematic of the hip joint (thigh segment relative to pelvis segment), thigh and shank segments (relative to the lab) were computed using the Cardan sequence of X-Y-Z. Therefore, the X, Y, and Z were defined as the sagittal, frontal, and transverse planes where the flexion/extension, adduction/abduction, and internal/external rotation movements occur, respectively. As Visual3D follows the right-hand rule, the direction of positive rotation about the Y (anteroposterior) local axis (i.e., the direction of curl of the fingers) was considered as the direction of hip joint adduction. For individuals whose left limb was under evaluation, the negate function was used to make this parameter comparable among subjects.

A custom-written script in MATLAB software (version 2018a, The MathWorks Inc, Natick, MA) was utilized to extract the peak hip adduction angle as well as the coordination between thigh frontal and shank transverse in the stance phase of the running cycle. Also, the heel strike and toe-off events were computed based on the vertical displacement algorithm [28] using the heel marker's coordinates in each dynamic trial.

For measuring the intersegmental coordination, Continuous Relative Phase (CRP) technique was used, representing the difference in the phase angle of the two segments. In this study, each segment's phase angle was calculated using analytic signals extracted from the Hilbert transform. In the first step, the shank and thigh kinematics were interpolated to 101 points, and the range of the desired signal amplitudes was centered around zero [29]. The MATLAB built-in function for Hilbert Transform was used to transform the measured signal into a complex and analytic signal [29, 30]. The phase angle of each segment was calculated as:

$$\phi(t_i) = \tan^{-1}\left(\frac{H(t_i)}{x(t_i)}\right) \quad (1)$$

Where the $H(t_i)$ is the Hilbert transform of the real signal $x(t_i)$.

Then the CRP was calculated by subtracting the phase angle of the thigh segment signal in the frontal plane ($\phi_{thigh\ Y}$) from the phase angle of the shank segment signal in the transverse plane ($\phi_{shank\ Z}$) (Equation 2). To fix the discontinuities arising from the arctangent function, the absolute values of the CRP were calculated, and values more than 180 were subtracted from 360.

$$CRP(t_i) = \phi_{thigh\ Y}(t_i) - \phi_{shank\ Z}(t_i) \quad (2)$$

Finally, the deviation phase (DP) was calculated by averaging the standard deviation of the ensemble CRP curve points over the stance phase to quantify the coordination variability [31] (Equation 3) (Figure 1).

$$DP = \frac{1}{N}\sum_{i=1}^{N}|SD_i| \quad (3)$$

Where N is the number of points in the en-

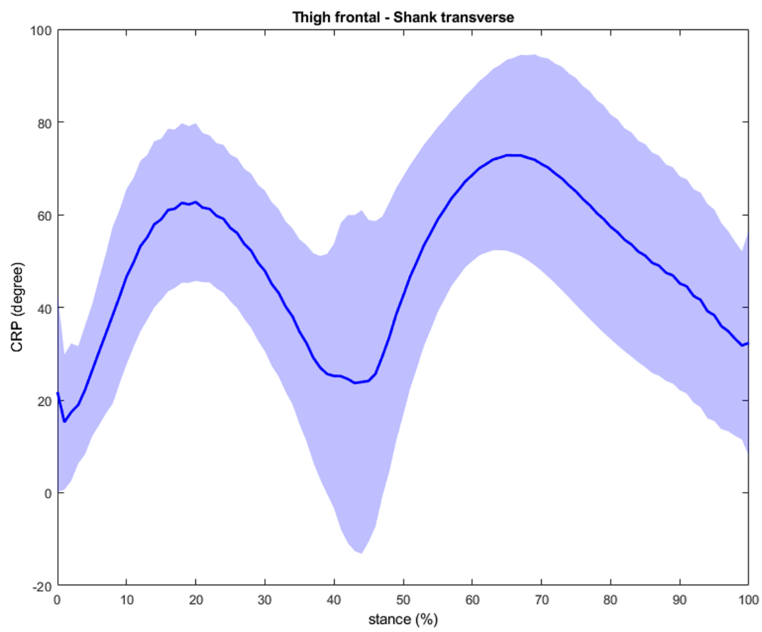

Figure 1: Continuous Relative Phase (CRP) (blue line) and variability of CRP (shaded area) for thigh frontal-shank transverse during the stance phase of a running cycle.

semble CRP curve and SD_i is the standard deviation of the ensemble CRP curve at each point (i). Lower DP values indicate less coordination variability and vice versa.

Statistical analysis

All statistical analyses were done by the SPSS software (version 26; SPSS Inc., Chicago, IL, USA). After ensuring that the data has a normal distribution by the Shapiro-Wilk test, the Pearson Correlation Coefficient (r) was used to investigate the correlation between the variables (peak hip adduction angle and intersegmental coordination variability). According to the commonly used guideline suggested by Cohen, r = 0.10 to 0.29, r = 0.30 to 0.49 and r = 0.5 to 1.0 denote small, medium and large correlation strength, respectively [32]. The significant level of 0.05 was selected for statistical analyses.

Results

Descriptive values for subject demographics and treadmill speeds during PSR are presented in Table 1. The Pearson correlation coefficient demonstrated a significant negative correlation between the peak hip adduction angle and DP of thigh frontal–shank transverse during the stance phase of FSR ($r = -0.553$, $P < 0.05$) and PSR ($r = -0.660$, $P < 0.01$) in the PFP group (Figures 2 and 3) while the control group showed a small nonsignificant correlation at both running speeds ($r < 0.29$, $P > 0.05$) (Table 2).

Table 1: Mean ± SD of demographics and preferred speed of running in patellofemoral pain (PFP) and control groups.

	PFP (Mean ± SD)	Control (Mean ± SD)	P-value
Age (year)	25.94 ± 3.99	24.12 ± 3.90	0.073
Height (m)	1.63 ± 0.05	1.61 ± 0.06	0.442
Weight (Kg)	59.70 ± 10.82	56.38 ± 5.70	0.275
Treadmill velocity during PSR (m/s)	2.10 ± 0.10	2.23 ± 0.24	0.057

SD: Standard deviation; PFP: Patellofemoral pain; PSR: Preferred speed running

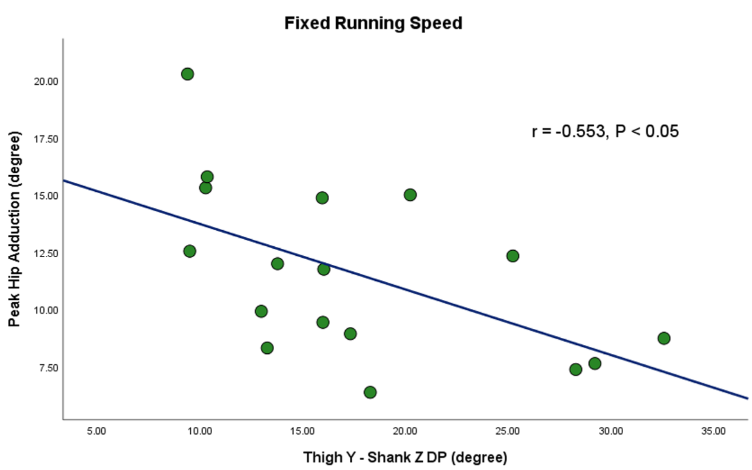

Figure 2: The correlation between peak hip adduction angle and deviation phase (DP) of thigh frontal – shank transverse in persons with patellofemoral pain during running at fixed speed.

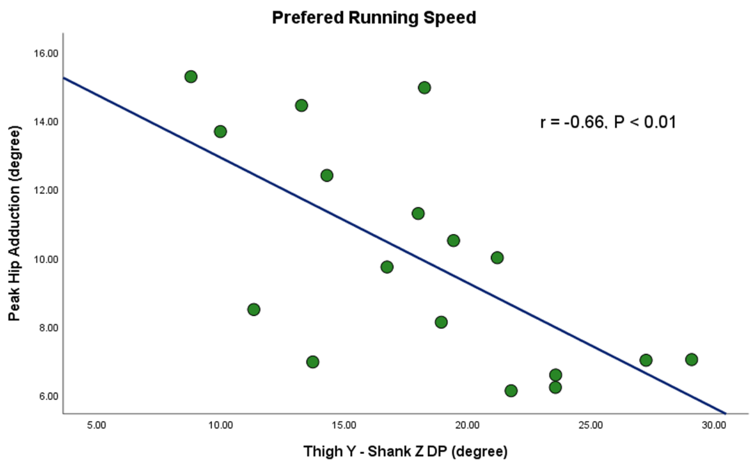

Figure 3: The correlation between peak hip adduction angle and deviation phase (DP) of thigh frontal – shank transverse in persons with patellofemoral pain during running at preferred speed.

Table 2: Pearson correlation coefficient (r) among peak hip adduction and thigh frontal-shank transverse deviation phase (DP) during running at fixed and preferred speeds.

		Peak hip adduction (FSR) r (P-value)	Peak hip adduction (PSR) r (P-value)
Thigh frontal-shank transverse DP (FSR)	PFP	-0.553 (0/021)	-
	Control	0.207 (0.425)	-
Thigh frontal-shank transverse DP (PSR)	PFP	-	-0.66 (0/004)
	Control	-	-0.022 (0.935)

DP: Deviation phase; PFP: Patellofemoral pain; FSR: Fixed speed running; PSR: Preferred speed running

Discussion

The results obtained in the present study showed that the variability of movement coordination (DP) between thigh frontal and shank transverse on the symptomatic side of patients with PFP during PSR and FSR was negatively correlated with peak hip adduction. This indicates that greater peak hip adduction during PSR and FSR was similarly associated with reduced variability of the coordination between the frontal plane motion of the thigh and transverse plane motion of the shank.

Excessive hip adduction and resultant dynamic knee valgus during weight-bearing tasks increase dynamic Q-angle. Excessive dynamic Q-angle, proposed to be largely attributed to hip adduction, potentially causes more lateral displacement and lateral tilt of the patella relative to the femur. Therefore, it can decrease PF joint contact area, increase joint stress, and over time results in PFP. Increased hip adduction would also strain the medial soft tissues that restrain knee joint valgus such as the medial collateral ligament, anterior cruciate ligament, and medial PF ligament [5].

In confirmation of the above hypothesis, several previous cross-sectional studies reported that persons with PFP demonstrated significantly greater hip adduction compared to asymptomatic individuals during running [33-36]. More importantly, a prospective study of PFP kinematic risk factors suggested that greater hip adduction during running was a significant predictor of individuals who later developed symptoms [13].

According to the theory proposed by Hamill et al. [19], reduced variability of lower limb intersegmental coordination is an indicator of the presence of PFP, probably as a protective mechanism to avoid exploring movement patterns that may induce pain, resulting in accomplishing the task without pain.

It is also suggested that the reduced variability of movement patterns causes the same joint structures to be exposed to continuous stress, which over time can result in PFP. Reduced variability is also suggested to limit the individual from responding to internal and external perturbations [18, 19, 23, 24, 37].

Since increased hip adduction has the potential to induce pain by putting stress on the PF joint in persons with PFP, the results of the present study (negative correlation between hip adduction and coordination variability) confirm the findings of those reporting reduced variability of coordinative patterns in the presence of PFP [19, 21-24]. After the theory proposed by Hamill [19], numerous biomechanical and motor control studies have suggested that coordination variability plays a functional role, and its absence indicates dysfunction in performing a task [14]. Hence, the current study results are also consistent with those of previous studies that associated higher degrees of hip adduction [12] or lower hip abductor strength [38] with decreased functional status and greater levels of pain in persons with PFP. Current results also confirm the findings of the previous studies that indicated improving hip kinematics leads to improved function and decreased pain in patients with PFP [39, 40].

Although a longitudinal prospective study is necessary to determine the causal relationship between hip kinematics and the variability of intersegmental coordination, the results of this study may indicate that increased peak hip adduction underlies the reduced intersegmental coordination variability. Therefore, the findings of the current study suggest that rehabilitative exercise programs in females with PFP can develop a wider range of movement patterns while improving hip kinematic.

The current study investigated the relationship between the frontal plane kinematic of the hip joint and the thigh frontal-shank transverse variability during PSR and FSR. Future studies are needed to investigate the correlation between other lower limb joints kinematics in different planes of motion and variability of different lower limb intersegmental couplings, which are important for patients with PFP. Further research is warranted to see whether improving hip frontal plane kinematic can induce an increase in the variability of thigh frontal-shank transverse in order to bring it closer to the normal values.

Conclusion

The results of the present study revealed that there is a significant negative relationship between peak hip adduction and coordination variability of thigh frontal -shank transverse on the symptomatic side of patients with PFP during PSR and FSR. Besides, this indicates that greater adduction of the hip joint in persons with PFP during running can contribute to lesser variability of thigh frontal- shank transverse coupling. Improving hip kinematics may warrant attention while attempting to optimize knee intersegmental coordination variability during the rehabilitative treatment of persons with PFP.

Acknowledgment

This study was extracted from the Ph.D. thesis by Farzaneh Haghighat, supported financially by Shiraz University of Medical Sciences (Grant number: 97-01-04-17431). We thank the Shiraz University of Medical Sciences, the Deputy for Research Affairs, and the School of Rehabilitation Sciences for their financial and scientific support. The authors wish to thank Mr. H. Argasi at the Research Consultation

Center (RCC) of Shiraz University of Medical Sciences for improving the use of English in the manuscript.

Conflict of Interest

None

References

1. Crossley KM, Van Middelkoop M, Callaghan MJ, et al. Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 2: recommended physical interventions (exercise, taping, bracing, foot orthoses and combined interventions). *Br J Sports Med*. 2016;**50**(14):844-52. doi: 10.1136/bjsports-2016-096268. PubMed PMID: 27247098. PubMed PMCID: PMC4975825.
2. Witvrouw E, Callaghan MJ, Stefanik JJ, Noehren B, et al. Patellofemoral pain: consensus statement from the 3rd International Patellofemoral Pain Research Retreat held in Vancouver, September 2013. *Br J Sports Med*. 2014;**48**(6):411-4. doi: 10.1136/bjsports-2014-093450. PubMed PMID: 24569145.
3. Draper CE, Fredericson M, Gold GE, Besier TF, et al. Patients with patellofemoral pain exhibit elevated bone metabolic activity at the patellofemoral joint. *J Orthop Res.* 2012;**30**(2):209-13. doi: 10.1002/jor.21523. PubMed PMID: 21812024. PubMed PMCID: PMC3219799.
4. Powers CM, Witvrouw E, Davis IS, Crossley KM. Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3. *Br J Sports Med*. 2017;51(24):1713-23. doi: 10.1136/bjsports-2017-098717. PubMed PMID: 29109118.
5. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther.* 2010;**40**(2):42-51. doi: 10.2519/jospt.2010.3337. PubMed PMID: 20118526.
6. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J Orthop Sports Phys Ther.* 2003;**33**(11):639-46. doi: 10.2519/jospt.2003.33.11.639. PubMed PMID: 14669959.
7. Huberti HH, Hayes WC. Patellofemoral contact pressures. The influence of q-angle and tendofemoral contact. *J Bone Joint Surg Am.* 1984;**66**(5):715-24. PubMed PMID: 6725318.
8. Lee TQ, Morris G, Csintalan RP. The influence of tibial and femoral rotation on patellofemoral contact area and pressure. *J Orthop Sports Phys Ther*. 2003;**33**(11):686-93. doi: 10.2519/jospt.2003.33.11.686. PubMed PMID: 14669964.
9. Clermont CA, Osis ST, Phinyomark A, Ferber R. Kinematic gait patterns in competitive and recreational runners. *J Appl Biomech.* 2017;**33**(4):268-76. doi: 10.1123/jab.2016-0218. PubMed PMID: 28253053.
10. Meira EP, Brumitt J. Influence of the hip on patients with patellofemoral pain syndrome: a systematic review. *Sports Health.* 2011;**3**(5):455-65. doi: 10.1177/1941738111415006. PubMed PMID: 23016043. PubMed PMCID: PMC3445210.
11. Neal BS, Barton CJ, Gallie R, O'Halloran P, Morrissey D. Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: a systematic review and meta-analysis. *Gait Posture.* 2016;**45**:69-82. doi: 10.1016/j.gaitpost.2015.11.018. PubMed PMID: 26979886.
12. Nakagawa T, Serrão F, Maciel C, Powers C. Hip and knee kinematics are associated with pain and self-reported functional status in males and females with patellofemoral pain. *Int J Sports Med.* 2013;**34**(11):997-1002. doi: 10.1055/s-0033-1334966. PubMed PMID: 23771827.
13. Noehren B, Hamill J, Davis I. Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc*. 2013;**45**(6):1120-4. doi: 10.1249/MSS.0b013e31828249d2. PubMed PMID: 23274607.
14. Hamill J, Palmer C, Van Emmerik RE. Coordinative variability and overuse injury. *Sports Med Arthrosc Rehabil Ther Technol.* 2012;**4**(1):45. doi: 10.1186/1758-2555-4-45. PubMed PMID: 23186012. PubMed PMCID: PMC3536567.
15. Turvey MT. Coordination. *Am Psychol.* 1990;**45**(8):938-53. doi: 10.1037//0003-066x.45.8.938. PubMed PMID: 2221565.
16. Bernshtein NA. The coordination and regulation of movements. Pergamon Press; 1967.
17. Latash ML, Scholz JP, Schöner G. Motor control strategies revealed in the structure of motor variability. *Exerc Sport Sci Rev.* 2002;**30**(1):26-31. doi: 10.1097/00003677-200201000-00006. PubMed PMID: 11800496.
18. Stergiou N. Innovative analyses of human movement. Human Kinetics Publishers; 2004.
19. 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. PubMed PMID: 10521606.

20. Cunningham TJ, Mullineaux DR, Noehren B, Shapiro R, Uhl TL. Coupling angle variability in healthy and patellofemoral pain runners. *Clin Biomech (Bristol, Avon)*. 2014;**29**(3):317-22. doi: 10.1016/j.clinbiomech.2013.12.008. PubMed PMID: 24411592.
21. Heiderscheit BC, Hamill J, Van Emmerik RE. Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *Journal of Applied Biomechanics.* 2002;**18**(2):110-21. doi: 10.1123/jab.18.2.110.
22. Jewell C, Weir G, Hamill J, Boyer KA. The influence of patellofemoral pain on coordination variability over a prolonged treadmill run. *ISBS Proceedings Archive.* 2018;**36**(1):634.
23. Haghighat F, Rezaie M, Ebrahimi S, Shokouhyan SM, et al. Coordination variability during walking and running in individuals with and without patellofemoral pain Part 1: Lower limb intersegmental coordination variability. *Journal of Medical and Biological Engineering.* 2021:1-10. doi: 10.1007/s40846-021-00603-5.
24. Haghighat F, Rezaie M, Ebrahimi S, Shokouhyan SM, Motealleh A, Parnianpour M. Coordination Variability During Walking and Running in Individuals With and Without Patellofemoral Pain Part 2: Proximal Segments Coordination Variability. *Journal of Medical and Biological Engineering.* 2021:1-9. doi: 10.1007/s40846-021-00598-z.
25. Biabanimoghadam M, Motealleh A, Cowan SM. Core muscle recruitment pattern during voluntary heel raises is different between patients with patellofemoral pain and healthy individuals. *Knee.* 2016;**23**(3):382-6. doi: 10.1016/j.knee.2016.01.008. PubMed PMID: 26873794.
26. Arjun R, Kishan R, Dhillon M, Chouhan D. Reliability of clinical methods in evaluating patellofemoral pain syndrome with malalignment. *International Journal of Research in Orthopaedics*. 2017;**3**(3):334-8. doi: 10.18203/issn.2455-4510.IntJResOrthop20170902.
27. Negahban H, Pouretezad M, Yazdi MJS, Sohani SM, Mazaheri M, Salavati M, et al. Persian translation and validation of the Kujala Patellofemoral Scale in patients with patellofemoral pain syndrome. *Disabil Rehabil.* 2012;**34**(26):2259-63. doi: 10.3109/09638288.2012.683480. PubMed PMID: 22630589.
28. Alvim F, Cerqueira L, Netto ADA, Leite G, Muniz A. Comparison of five kinematic-based identification methods of foot contact events during treadmill walking and running at different speeds. *J Appl Biomech*. 2015;**31**(5):383-8. doi: 10.1123/jab.2014-0178. PubMed PMID: 25950421.
29. Lamb PF, Stöckl M. On the use of continuous relative phase: Review of current approaches and outline for a new standard. *Clin Biomech (Bristol, Avon).* 2014;**29**(5):484-93. doi: 10.1016/j.clinbiomech.2014.03.008. PubMed PMID: 24726779.
30. Mehdizadeh S, Glazier PS. Order error in the calculation of continuous relative phase. *J Biomech.* 2018;**73**:243-8. doi: 10.1016/j.jbiomech.2018.03.032. PubMed PMID: 29628131.
31. 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. PubMed PMID: 11240056.
32. Cohen BJ, Cohen P, West SG, Aiken LS. Applied multiple regression/correlation analysis for the behavioral sciences. New York: Routledge; 2013.
33. Fox A, Ferber R, Saunders N, Osis S, Bonacci J. Gait kinematics in individuals with acute and chronic patellofemoral pain. *Med Sci Sports Exerc*. 2018;**50**(3):502-9. doi: 10.1249/MSS.0000000000001465. PubMed PMID: 29077638.
34. Noehren B, Pohl MB, Sanchez Z, Cunningham T, Lattermann C. Proximal and distal kinematics in female runners with patellofemoral pain. *Clin Biomech (Bristol, Avon).* 2012;**27**(4):366-71. doi: 10.1016/j.clinbiomech.2011.10.005. PubMed PMID: 22071426. PubMed PMCID: PMC3984468.
35. Noehren B, Sanchez Z, Cunningham T, McKeon PO. The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain. *Gait & Posture.* 2012;**36**(3):596-9. doi: 10.1016/j.gaitpost.2012.05.023. PubMed PMID: 22749951.
36. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clin Biomech (Bristol, Avon).* 2008;**23**(2):203-11. doi: 10.1016/j.clinbiomech.2007.08.025. PubMed PMID: 17942202.
37. Hamill J, Haddad JM, Heiderscheit BC, Van Emmerik RE, Li L. Clinical relevance of variability in coordination. *Movement System Variability*. 2006:153-65.
38. Dierks TA, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther.* 2008;**38**(8):448-56. doi: 10.2519/jospt.2008.2490. PubMed PMID: 18678957.

39. Mascal CL, Landel R, Powers C. Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *J Orthop Sports Phys Ther*. 2003;**33**(11):647-60. doi: 10.2519/jospt.2003.33.11.647. PubMed PMID: 14669960.

40. Noehren B, Scholz J, Davis I. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. *Br J Sports Med.* 2011;**45**(9):691-6. doi: 10.1136/bjsm.2009.069112. PubMed PMID: 20584755.