International Journal of Kinesiology & Sports Science
ISSN: 2202-946X
www.ijkss.aiac.org.au

Kinematic and Coordination Variability in Runners with and Without Patellofemoral Pain

Jessica A. Mutchler[1]*, Klarie Macias[1], Barry A. Munkasy[1], Samuel J. Wilson[1], John C. Garner[2], Li Li[1]
[1]*Department of Health Sciences and Kinesiology, Georgia Southern University Statesboro, GA*
[2]*Department of Kinesiology and Health Promotion, Troy University Troy, AL*
Corresponding Author: Jessica A. Mutchler, E-mail: jmutchler@georgiasouthern.edu

ARTICLE INFO

Article history
Received: April 13, 2020
Accepted: July 15, 2020
Published: July 31, 2020
Volume: 8 Issue: 3

Conflicts of interest: None
Funding: None

ABSTRACT

Background: Patellofemoral pain (PFP) is a common overuse injury that has been suggested to cause abnormal gait kinematics and variability in runners with PFP. Conflicting results have been presented as to the variability of joint kinematics and joint coordination. **Objective:** The purpose of this study was to examine the variability of lower extremity kinematics and joint coordination in the presence of PFP and exertion. **Methods:** Six female runners with PFP and matched controls (CON) ran at a self-selected pace on an instrumented treadmill until exertion or pain criteria was met. Sixteen anatomical retroreflective markers and seven tracking clusters were placed on the participants' lower extremities. Data collected for 20 steps from the beginning, middle, and end of the run were processed. Kinematic variability was assessed for each participant by calculating the standard deviation (SD) of peak knee flexion, internal rotation, and adduction angle and their velocities. Continuous relative phase (CRP) mean values were calculated from normalized phase plots for coordination relationships between knee horizontal plane motion and hip sagittal, frontal, and horizontal and ankle frontal plane motion. Coordination variability was calculated as the CRP coupling SD over 100% of stance for each time point for each participant. Statistical comparisons were assessed through a 2 (PFP vs. CON) x 3 (beginning, middle, end) repeated measures ANOVA. **Results:** There was an increase in variability for peak knee adduction angle, peak knee adduction velocity, hip flexion/knee rotation CRP, and knee rotation/rearfoot eversion CRP over time for the PFP group compared with CON ($P<0.05$). **Conclusion:** Pain and exertion increase the variability of joint kinematics and joint coordination reflecting decreased movement control towards the end of a run.

Key words: Physical Exertion, Joint Instability, Knee Joint, Running, Patellofemoral Joint, Female

INTRODUCTION

Patellofemoral pain (PFP) is a common overuse injury that may be defined as pain deep to, or around the patella (Crossley, Callaghan, & van Linschoten, 2016; Glaviano, Kew, Hart, & Saliba, 2015; Powers et al., 2012). In the general population 8 - 17% of all knee complaints are related to PFP in both athletes and non-athletes (Kannus, Aho, Järvinen, & Nttymäki, 1987; Van Middelkoop, Van Linschoten, Berger, Koes, & Bierma-Zeinstra, 2008; Wood, Muller, & Peat, 2011). It has been estimated that 1 in 6 adults going to general practice for a knee issue will present with a patellofemoral disorder, and rates of PFP development may be increasing (Glaviano et al., 2015; Wood et al., 2011). Although it is clear that PFP may develop due to ligament tears, arthritis, acute trauma, bone bruises, or stress fractures, more commonly individuals experience what may be called idiopathic PFP, where the actual source or cause of the pain is largely unknown (Powers et al., 2012). Abnormal gait kinematics, prolonged exertion, and lower extremity joint coordination in individuals with PFP may contribute to the pain development (Barton, Levinger, Menz, & Webster, 2009; Hamill, van Emmerik, Heiderscheit, & Li, 1999).

Previously both joint kinematics and joint coordination have been studied in regards to runners with PFP (Dierks, Manal, Hamill, & Davis, 2011; Hamill et al., 1999). Work in kinematics has predominantly focused on mean of peak angles, velocities, and excursions over a period of time between runners with and without PFP. Noehren, Pohl, Sanchez, Cunningham and Lattermann, in their 2012 study indicated that runners with PFP had altered hip kinematics compared to healthy, pain-free runners (Noehren, Pohl, Sanchez, Cunningham, & Lattermann, 2012). They demonstrated more constricted motion, which increases the repetitive stresses on the same soft tissue structures and may contribute to pain development (Noehren, Sanchez, Cunningham, & McKeon, 2012). Even in the absence of pain, running-induced fatigue may alter hip, knee, and ankle kinematics, which makes it critical to evaluate the effects of exertion on the kinematics of runners with PFP (Dierks, Davis, & Hamill, 2010; Koblbauer, van Schooten, Verhagen, & van Dieën, 2014). Joint coordination as calculated

Published by Australian International Academic Centre PTY.LTD.

http://dx.doi.org/10.7575/aiac.ijkss.v.8n.3p.58

by the average continuous relative phase (CRP), has not been reported to be significantly different between runners with PFP and healthy runners (Hamill et al., 1999). However, there are noticeable differences in the CRP variability in runners with and without PFP (Hamill et al., 1999).

Lower extremity joint coordination variability was shown to be decreased in runners with PFP compared to healthy runners (Hamill et al., 1999). Joint coordination refers to the movement of one joint with respect to the movement of another (Hamill et al., 1999; Silvernail, Boyer, Rohr, Brüggemann, & Hamill, 2015). This coordination is accomplished through the use of accessible degrees of freedom to create a specific movement pattern (Hamill et al., 1999; Silvernail et al., 2015). An optimal level of variability has been proposed in which an appropriate level of coordination variability may be indicative of a healthy state. A decrease in that variability may be more indicative of a rigid, confined state with poor adaptability (Hamill, Haddad, Heiderscheit, Emmerik, & Li, 2006; Silvernail et al., 2015; Stergiou, Harbourne, & Cavanaugh, 2006). Hamill, van Emmerick, Heiderscheit and Li, indicated that the decreased joint variability, as measured by CRP, reflected an injured running state (Hamill et al., 1999). The authors suggested that the decreased variability increased repetitive stress on the same soft tissue structure, increasing pain (Hamill et al., 1999). An increase above this optimal variability would also indicate an unhealthy state, as too much variability would make the system unstable, and unpredictable (Hamill et al., 2006).

Although the kinematics of runners with PFP has been extensively studied, the variability of these kinematics is not well understood. In a 2011 study conducted by Dierks, Manal, Hamill, and Davis, the authors sought to explore changes in hip, knee and ankle kinematics between runners with and without PFP during a prolonged run (Dierks et al., 2011). The authors highlighted the need to explore these variables in an exerted state of running due to the progressive nature of PFP when running, and runners commonly reporting a lack of knee pain at the beginning of a run (Dierks et al., 2011). The study observed that the PFP runners displayed less lower extremity joint motion in general compared to the healthy runners (Dierks et al., 2011). It was also observed that 30 of 44 standard deviations, of the various kinematics studied, were greater in the PFP group compared to the healthy runners (Dierks et al., 2011). Thus, individuals with PFP may display decreased joint motion but increased kinematic variability as a run progresses.

Considering the results of both increased kinematic variability and decreased CRP variability, it is a difficult task to compare the results of the two studies, especially as the two studies used different protocols, and participants (Li, 2011). To compare both the variability of joint kinematics and joint coordination, these measurements must be conducted on the same participants undergoing the same protocol. Therefore, the purpose of this study was to examine the variability of lower extremity kinematics and joint coordination in the presence of PFP and exertion.

We hypothesized that runners with PFP would exhibit altered patterns of kinematics and joint coordination indicative of decreased motor control and that exertion would exacerbate these differences. We expected that all differences detected between groups for the kinematic and CRP values to be the greatest at the end of the run when the runners are fatigued with increased pain.

METHODOLOGY

Participants and Study Design

The participants in this study included 6 female runners with PFP (PFP) (21.0 ± 0.6 years; 66.1 ± 7.9 kg; 1.62 ± 0.09 m), and a control group of 6 healthy female runners (CON) (21.2 ± 1.2 years; 61.5 ± 6.9 kg; 1.67 ± 0.11 m). This study used a case-control design with independent variables of group (PFP, CON) and time (beginning, middle end). Dependent variables included peak angle variability and peak velocity variability of the knee, and CRP variability of knee rotation relative to the hip and ankle. Inclusion criteria for all participants included running an average of ≥10 miles/week, having a heel strike running pattern, and answering "No" for all questions on the Physical Activity Readiness Questionnaire (Dierks et al., 2010). Exclusion criteria for all participants included any neurological injury or disease that could affect gait, any hip, ankle, or lower back injury within 6 months of the study, being an orthotic user, currently receiving physical therapy, or having knee pain that was caused by direct acute trauma (Dierks et al., 2011; Schwane et al., 2015). Additional inclusion criteria for the PFP group included anterior knee pain present during running for at least two months prior, knee pain present in at least two activities out of stair climbing or descending, hopping, running, kneeling, squatting or prolonged sitting, and insidious onset of knee pain unrelated to direct trauma (Dierks et al., 2011; Schwane et al., 2015). We received written informed consent from each participant after the protocol was thoroughly explained. The study was approved by the University Institutional Review Board. Prior to beginning the run, the participants were asked to fill out the Anterior Knee Pain Scale (AKPS) to evaluate their level of disability experienced due to knee pain, and the NASA Activity Scale (NAS) to evaluate their level of weekly physical activity. The AKPS is a 13-item likert type questionnaire that subjectively assesses PFP related to physical tasks (i.e. walking, running, squatting) and symptoms (i.e. swelling, atrophy of thigh) (Kujala et al., 1993). The composite score ranges from 0 to 100 with a higher score representing higher function and less symptom severity (Kujala et al., 1993). The NAS gives a participant 10 options for the selection of the best descriptor of level of physical activity from 0 (avoid walking or exertion) to 10 (run over 25 miles, walk over 34 miles or 12 hours of comparable activity per week) (Wier et al., 2001).

Procedures

Participants were fitted with the same model of neutral running shoes (Fitsole Lite Run, Nike, Beaverton, OR) provided by the lab and a heart rate monitor (T31-coded, Model

No: N2965; Polar Electro Inc., Lake Success, NY). Tracking clusters were placed on the participants' pelvis, right and left thighs, shanks, and calcanei. Participants were provided with a 4-minute warm-up to accustom themselves to the tracking clusters and the AMTI force-sensing instrumented treadmill (Watertown, MA, USA). Anatomical markers consisting of 16 retro-reflective markers were then placed on the left and right iliac crests, greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleoli, and the first and fifth metatarsal heads (Weinhandl, Joshi, & O'Connor, 2010). Joint movements were tracked using a 3-D motion capture system (Bonita 10 cameras; Nexus 2.3.0.88202; Vicon Motion Systems Ltd., Oxford Metrics, UK). Prior to the beginning of the run, a 3 s standing static trial was recorded. The anatomical markers were removed, and the clusters remained.

The participants self-selected their own running pace within the first minute of the run, and they were advised to select a pace that they could maintain for approximately 30 minutes. No changes in selected pace were allowed after the first minute of running. The Borg Ratings of Perceived Exertion (RPE) scale ranging from 6 (no exertion at all) to 20 (maximal exertion) was used to track RPE, and the Visual Analog Scale (VAS) using a 10cm line to indicate pain intensity, ranging from 0 (no pain) to 10 (worst pain possible) was used to track pain (Borg, 1998). Kinematic, kinetic, VAS scores, RPE, and heart rate (HR) data were taken at 5-minute intervals throughout the run. Kinematic and kinetic data were collected for 25s at the start of each time interval so that 20 footfalls were recorded (Dierks et al., 2011). The limb with PFP was selected for analysis for the PFP group, whereas the analyzed limb for the CON group was selected at random. If a participant had bilateral PFP, the leg with the greatest amount of knee pain was selected for analysis, however, this applied to only one participant. The run continued until one of the following conditions were met: 1) 85% of the participant's heart rate maximum (HR_{max}), 2) a score of 17 (very hard) on the Borg RPE scale, 3) a score of 7 (out of 10) on the VAS (for the knee pain group only), or 4) volitional fatigue (Borg, 1998; Dierks et al., 2010; Dierks et al., 2011). After the run, the participants performed a cool down until their heart rate fell below 120 beats per minute (Dierks et al., 2011). In order to be included for analysis, participants in the PFP group had to reach a minimum of 3 out of 10 on the VAS, by the end of the run.

Data Processing

Twenty footfalls of the first, middle, and last data trials, corresponding to the beginning, middle, and the end of the run, were analyzed. If there were an even number of intervals collected the later of the two middle trials were selected. For example, if there were eight intervals equal to 40 minutes, the fifth interval was selected as the middle trial. The three-dimensional marker coordinates were filtered with a 14 Hz low-pass, fourth-order 0 lag Butterworth filter using NEXUS software (VICON, Oxford, UK). Ground reaction force was captured through the force-sensing treadmill, sampled at 1,000 Hz. We defined the beginning of the stance phase as when the vertical ground reaction force exceeded 50 N, indicating foot-contact. We defined the end of stance phase as when the vertical ground reaction force fell below 50 N, indicating toe-off. Visual 3D (Visual3D, Version: 6.00.27, C-Motion Inc., Germantown, MD) was used to analyze the kinematic data.

The kinematic joint motions investigated in this study included the frontal plane motion of knee adduction, referenced as tibia relative to the femur. The transverse plane kinematic joint motion included knee internal rotation. Knee flexion was the only motion in the sagittal plane to be assessed. Peak angle (PA), and peak velocity (PV) were calculated for each kinematic variable. Peak angles and velocities were defined as the maximum value angle that occurred during stance. These kinematic variables were calculated for each step, and then the values were averaged across the 20 steps. Kinematic variability was calculated as the standard deviations (SD) within the 20 steps at each time point for each participant for each variable. This results in measures of peak angle SD (PASD), and peak velocity SD (PVSD). In this way, the SD was analyzed according to each individual rather than evaluating the SD of the group means.

The kinematic data was then used to calculate the CRP mean at each percent of stance according to the method described by Hamill et al., 1999 (Hamill et al., 1999). The kinematic data for each joint motion was first interpolated to 100 points to normalize data to 100% of stance (Visual 3D). CRP mean values were calculated from the normalized phase plots for coordination relationships of knee internal/external rotation and hip flexion/extension (KnRt_HiFlx), knee internal/external rotation and hip abduction/adduction (KnRt_HiADD), knee internal/external rotation and hip internal/external rotation (KnRt _HiRt), and knee internal/external rotation and rearfoot eversion/inversion (KnRt_FtEv). Variability was calculated as the SD of the CRP coupling over 100% of stance for each time point for each participant. The SD of each individual was then pooled for analysis. This resulted in the variables of KnRt_HiFlx_SD, KnRt_HiADD_SD, KnRt_HiRt_SD, and KnRt_FtEv_SD.

Statistical Analysis

Group means for age, height, body mass, weekly run distance, run time, NAS scores, and AKPS scores were compared using a one-way ANOVA to confirm the distinction of two groups and appropriate participant matching. The kinematic and CRP data were compared at the beginning, middle, and end of the run. Each variable was examined using a 2x3 repeated measures ANOVA using time as the repeated measure to determine if there was a significant interaction between group and time. Main effects were assessed and reported in the absence of a significant interaction. In the event of a significant result, post-hoc pairwise comparisons using Tukey's HSD were conducted. The significance level was set a priori to $p<0.05$. Cohen's D was used to calculate the effect size for all statistically significant results. Effect sizes were interpreted as follows: small $0.2 \leq d < 0.5$, medium $0.5 < d <$

0.8, and large d ≥ 0.8. Power was calculated retrospectively and it was calculated that for power to be sufficient at > .8, the calculated effect size must be ≥ 1.20 (Cohen, 2013).

RESULTS

The AKPS score for PFP group was significantly lower by 16 points compared to CON (PFP: 83 ± 8.20°, CON: 99.3 ± 1.63°; $F(1, 5) = 24.60$, $p < .05$; $d = 2.76$), which confirmed the PFP group experienced greater disability due to knee pain compared to CON (Crossley, Bennell, Cowan, & Green, 2004). Age, height, body mass, weekly run distance, NAS score, and run duration were not significantly different between groups (see Table 1 for details).

Data collected during the run for RPE, HR, and VAS scores are presented in Table 2 for both groups. The PFP group ran significantly slower compared to CON (PFP: 1.98 ± 0.11 m/s, CON: 2.14 ± 0.12 m/s; $F(1, 5) = 12.46$, $p < .05$; $d=1.24$) during the study.

Peak Angle Variability

There was a significant group by time interaction for knee adduction PASD. The PFP group had significantly more variability at the end of the run compared to CON (PFP: SD = 1.4°, CON: SD = 0.6°; $F(2, 10) = 4.14$, $p < .05$; $d = 1.27$). There were no significant differences observed for the PASD of knee internal rotation, or knee flexion. PASD values are shown in Table 3.

Peak Velocity Variability

There was a significant group by time interaction for knee adduction PVSD. The greatest difference occurred at the end of the run as the PFP group had nearly twice the variability of CON (PFP: SD = 30.7°*s^{-1}, CON: SD = 15.6°*s^{-1}; $F(2, 10) = 5.82$, $p < .05$; $d = 1.23$). There were no significant differences observed for the PVSD of knee internal rotation, or knee flexion. PVSD values are shown in Table 3.

Continuous Relative Phase Variability

There was a group by time interaction for both KnRt_HiFlx_SD (PFP: SD = 125.5, CON: SD = 57.3; $F(2, 10) = 6.23$, $p < .05$; $d = 1.20$) and KnRt_FtEv_SD (PFP: SD = 90.5, CON: SD = 25.1; $F(2, 10) = 5.52$, $p < .05$; $d = 1.49$). In both couplings at the end point of the run, PFP had twice the variability of CON, compared to the relatively similar group SD observed at the beginning of the run. CRP SD values are presented in Table 4. There were no significant differences observed for KnRt_HiADD_SD, or KnRt HiRt_SD.

Note: Data presented as the group means of the standard deviations; KnRT_HiFlx_SD = knee internal/external rotation and hip flexion/extension; KnRt_HiADD_SD = knee internal/external rotation and hip abduction/adduction; KnRt_HiRt_SD = knee internal/external rotation and hip internal/external rotation; KnRt_FtEv_SD = knee internal/external rotation and rearfoot inversion/eversion; * indicates significant group by time interaction, $P < 0.05$.

Table 1. Participant characteristics and demographic data

Variables	PFP	CON
Height (m)	1.62 (0.09)	1.67 (0.11)
Body mass (kg)	66.06 (7.90)	61.52 (6.89)
Age (years)	21.00 (0.55)	21.17 (1.17)
Weekly run distance (km)	12.33 (11.22)	17.83 (9.08)
NAS score	7.17 (1.30)	6.83 (1.17)
Run duration (min)	32.50 (10.84)	40.00 (13.78)

Data presented as mean (SD)

Table 2. RPE, HR, and VAS data collected during run

Criteria	Time	PFP	CON
RPE	Beg	8.2 (1.6)	8.7 (1.4)
	Mid	12.2 (1.3)	12.3 (2.0)
	End	15.6 (1.9)	14.7 (1.9)
HR	Beg	148.5 (10.4)	146.0 (15.3)
	Mid	175.0 (9.3)	160.0 (20.0)
	End	178.3 (10.5)	173.8 (13.6)
VAS	Beg	0.62 (0.86)	
	Mid	3.23 (2.22)	
	End	4.75 (1.99)	

Data presented as mean (SD); RPE = rating of perceived exertion; HR = heart rate; VAS = Visual analog scale; Beg = beginning interval; Mid = middle interval; End = end interval

Figure 1. A. Knee adduction variability reacted to running time differently between groups (significant Time X Group interaction, $p<.05$). B. Knee adduction velocity variability reacted to running time differently between groups (significant Time X Group interaction, $p<.05$). C. Knee rotation and hip flexion coupling (KnRt_HiFlx) variability reacted to running time differently between groups (significant Time X Group interaction, $p<.05$). D. Knee rotation and foot eversion coupling (KnRt_FtEv) variability reacted to running time differently between groups (significant Time X Group interaction, $p<.05$). For all graphs, mean and standard error of the mean (error bars) are presented. All increases of variability among the patella femoral pain group (PFP) at the end of the run were not observed with the control group (CON).

DISCUSSION

The primary goal of this project was to investigate the effect of pain and exertion on the variability of joint kinematics and joint coordination. Our initial hypothesis of altered motor control in the presence of pain and exertion was supported by the significant differences in the variability of PASD and PVSD for knee adduction, as well as the SD for the CRP couplings of KnRt_HiFlx_SD and KnRt_FtEv_SD for PFP group. In each of these instances, the variability of the PFP group was significantly greater than that of the CON group by the end of the run. The increased variability at the end may indicate a decreased ability to control movement with increased exertion and pain. While the authors expected to see changes in CRP variability for the PFP group, the in-

Table 3. Variability of kinematic variables at beginning, middle, and end of run

Variables	Knee adduction			Knee flexion			Knee internal rotation		
	Beg	Mid	End	Beg	Mid	End	Beg	Mid	End
Angle (°) PFP	0.6	0.6	1.4*	1.2	1.2	2.1	0.9	1.1	1.4
Angle (°) CON	0.5	0.9	0.6*	1.2	1.0	1.1	0.9	0.7	0.9
Vel (°*s^{-1}) PFP	13.1	14.7	30.7*	25.3	62.5	30.7	27.3	35.4	53.5
Vel (°*s^{-1}) CON	20.4	13.1	15.6*	32.6	25.6	27.4	48.4	33.7	34.3

Data presented as the group means of the standard deviations; Beg = beginning interval; Mid = middle interval; End = end interval; * indicates significant group by time interaction, P < 0.05

Table 4. Variability of continuous relative phase for four couplings

Group	KnRT_HiFlx_SD			KnRt_HiADD_SD			KnRT_HiRt_SD			KnRT_FtEV_SD		
	Beg	Mid	End	Beg	Mid	End	Beg	Mid	End	Beg	Mid	End
PFP	73.2	56.7	125.5*	39.8	57.1	86.5	52.5	77.2	97.4	35.4	47.2	90.5*
CON	70.2	70.0	57.3*	40.1	38.8	38.1	107.3	86.4	86.2	30.7	27.6	25.1*

Data presented as the group means of the standard deviations; KnRT_HiFlx_SD = knee internal/external rotation and hip flexion/extension; KnRt_HiADD_SD = knee internal/external rotation and hip abduction/adduction; KnRt_HiRt_SD = knee internal/external rotation and hip internal/external rotation; KnRt_FtEv_SD = knee internal/external rotation and rearfoot inversion/eversion; * indicates significant group by time interaction, P < 0.05

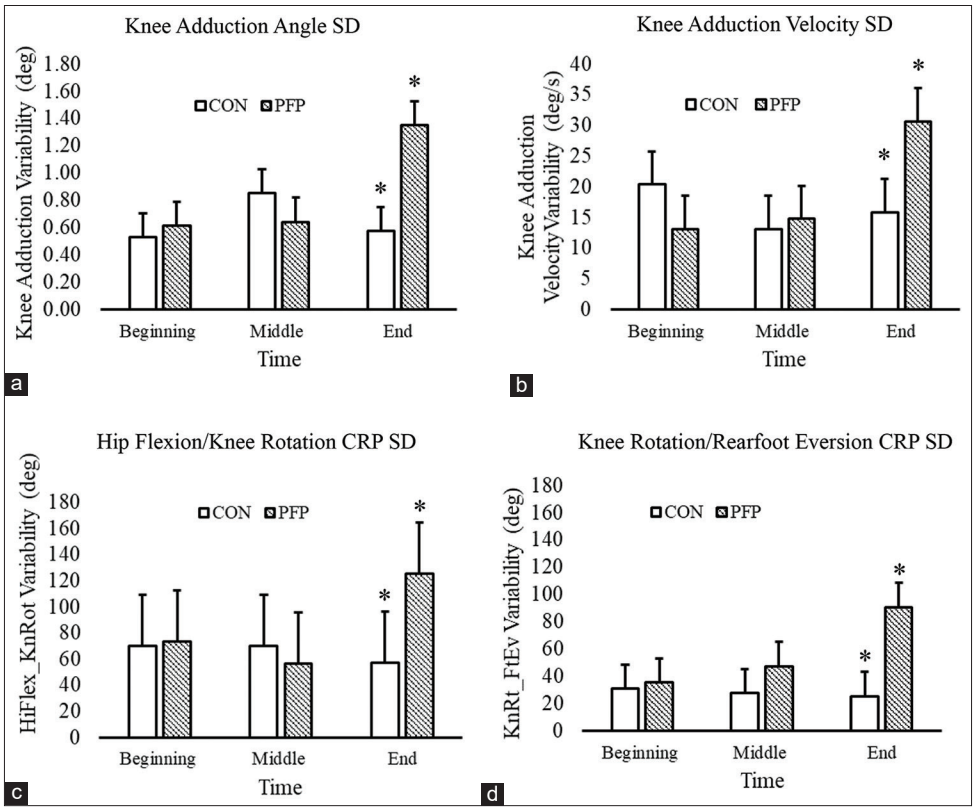

Figure 1. a. Knee adduction variability reacted to running time differently between groups (significant Time X Group interaction, p<.05). b. Knee adduction velocity variability reacted to running time differently between groups (significant Time X Group interaction, p<.05). c. Knee rotation and hip flexion coupling (KnRt_HiFlx) variability reacted to running time differently between groups (significant Time X Group interaction, p<.05). d. Knee rotation and foot eversion coupling (KnRt_FtEv) variability reacted to running time differently between groups (significant Time X Group interaction, p<.05). For all graphs, mean and standard error of the mean (error bars) are presented. All increases of variability among the patella femoral pain group (PFP) at the end of the run were not observed with the control group (CON).

crease in CRP variability for the PFP group at the end of the run was contradictory to the reduced variability observed in previous literature (Hamill et al., 1999). Although our sample size was small, all of the statistically significant differ-

ences have large effect sizes of 1.20 or greater, reaching the statistical power of >0.80.

The variability of the angles and angular velocities of knee internal rotation and knee flexion were also investigated; we have failed to detect significant differences among these measures. Knee flexion is generally decreased in runners with PFP, as a method of decreasing pain (Dierks et al., 2011). As knee flexion increases, the stress at the patellofemoral joint also increases, which could increase pain (Wallace, Salem, Salinas, & Powers, 2002). When examining the variability of the knee flexion angle, there were no significant differences between the two groups in our study. This may have resulted from the lack of disability the PFP group reported according to the AKPS scale given the mean was 83 ± 6.58 out of a possible 100. Greater disability and pain may have resulted in significant differences in knee flexion angle between the two groups. The same reasoning may apply to the lack of significant differences in regards to knee internal rotation values. It is also unclear whether or not there are differences in knee internal rotation values in runners with and without PFP. There is evidence to suggest that female runners with PFP have greater knee internal rotation, but in a study of both sexes there was a trend towards greater external rotation as well (Noehren, Pohl, et al., 2012; Willson & Davis, 2008). It should be noted that the mean of knee flexion PVSD for PFP at the middle of the run (SD = 62.5°*s^{-1}) was the highest among all PVSD means across group and time yet did not result in a statistically significant difference. This may be explained by the low sample size and individual variability within the PFP group. Data from the middle trial of the run showed that three of the six PFP runners experienced a spike in knee flexion PVSD, that was not observed in the other three runners or in any runner within the CON group.

The average knee adduction variability indicated that the two groups changed differently with running time. The greatest differences in SD are seen at the end of the run, in which the PFP group (SD = 1.4°) exhibited much greater variability compared to CON (SD = 0.6°). Despite the fact that we examined variability as the average of each individual person's standard deviation across 20 steps, and Dierks et al., examined the standard deviation of the group means, their results show a similar trend to ours when exploring the measures in an exerted state (Dierks et al., 2011). The runners with PFP (SD = 5.6) in their study had a greater standard deviation compared to healthy runners (SD = 4.4) for knee adduction at the end of the run (Dierks et al., 2011). The greater standard deviation in the PFP group indicates a decreased joint motion control (Dierks et al., 2011). The results of our study indicate that the PFP group's variability increases significantly more with prolonged exertion compared to CON.

In general, the results of our study would suggest that with increasing running time, the variability in peak velocity of PFP runners is more susceptible to the effects of exertion compared to CON. Although the PFP runners in our study began the run with less variability, the PFP group finished the run with 15.1°*s^{-1} greater variability compared to CON. Dierks et al., had similar results in which their runners with PFP had more PV variability than healthy runners at the beginning (5.9°*s^{-1}) and at the end of the run (4.1°*s^{-1}) (Dierks et al., 2011). The result of the increased variability in regards to knee adduction may indicate that the PFP runners had decreased control over knee adduction PVSD with increased exertion and pain, compared to CON.

The significant results observed in this study indicate that knee adduction variability may be a critical component of PFP in runners. Greater knee adduction could create greater lateral forces and subsequently greater stress at the patellofemoral joint (Powers et al., 2012). The increased variability of both the knee adduction angle and angular velocity may indicate decreased control of this motion which could increase the potential for increased patellofemoral joint stress. There is little evidence to suggest that knee adduction angles themselves differ between those with PFP and healthy runners. Both Noehren et al., and Dierks et al., reported no significant differences in knee adduction angles between runners with and without PFP (Dierks et al., 2011; Noehren, Pohl, et al., 2012). The increased variability seen in this study may, therefore, be more informative than peak angles or velocities alone.

The CRP variability for both KnRt_HiFlx and KnRT_FtEv exhibited a significant change in which the PFP group finished the run with significantly more variability compared to CON. Hamill et al., compared CRP variability in individuals with PFP and observed that the individuals with PFP exhibited decreased coupling variability compared to healthy runners (Hamill et al., 1999). This result would seem to present the opposite conclusion from the results of the current study. However, Hamill et al., compared runners only at the beginning of the run prior to fatigue (Hamill et al., 1999). Comparing only the beginning of the run, the SD of CRP coupling KnRt_HiRt in the current investigation for the PFP is less than the CON, which may agree with the observations of Hamill et al. (1999). Furthermore, Hamill, Haddad, Heiderscheit, and Li, noted that there is an optimal range of variability indicating that too little variability creates too strict a system for optimal variability, but too much variability creates a system that is too unstable to properly adapt to the situation (Hamill et al., 2006). Therefore, even with differing results between studies, both observations support that variability less or greater than the optimal level would be indicative of an unhealthy state (Hamill et al., 2006). As the greatest differences in CRP variability occurred at the end of the run, the PFP group may have been unable to cope with the increase in pain or increase in exertion creating a more varied, less controlled coupling state.

Decreased movement control may be the unifying theme between the variability of kinematics and joint coordination. Although we expected the joint coordination to respond with less variability, it may be that both too little and too much CRP variability indicate decreased control. That being said, for runners with PFP, both the outcome goal (kinematics), and the method of execution (joint coordination), were highly variable in the presence of exertion and pain. Within

the current study we cannot make conclusions on whether the variability was more influenced by the increase in exertion or increase in pain experienced by the runners with PFP. The average run time was 32.5 ± 10.9 minutes for the PFP group, and 40.0 ± 13.8 minutes for CON. In the PFP group, two participants reached 17 on the RPE scale, one reached 85% HR_{max}, one reached 7/10 pain on VAS, and two stopped from volitional fatigue. For CON, one participant reached 17 on the RPE scale, three reached 85% HR_{max}, and two stopped from volitional fatigue. All participants in the PFP group reached a minimum of 3/10 pain by the end of the run, which indicates that all PFP participants were running with at least mild pain during the last trial.

A study published by Hafer, Brown, and Boyer in 2017 investigated lower extremity segment coordination variability in runners with and without iliotibial band syndrome (ITBS) during a run to exertion (Hafer, Brown, & Boyer, 2017). Participants in the study ran to volitional exertion unless they first reached stopping criteria that was similar to the current investigation, based on the Borg RPE scale and pain. The results of their study showed no statistically significant differences for group or time for any of the segment couplings (Hafer et al., 2017). Although statistical significance was not reached, they did report a trend towards the significance of increased coordination variability of thigh and knee couplings at the end of the run in the ITBS group that experienced pain during the run ($p = 0.06$) (Hafer et al., 2017). The groups without ITBS, as well as the group with ITBS but without pain during the run, did not show a change in their segment coordination variability from beginning to end of the run (Hafer et al., 2017). Run time for their study was on average 25.13 minutes for all groups, which was less than the run time for either group in this current study. ITBS does differ from PFP, but both are chronic and have been reported to cause changes in runners' movement patterns. The trend reported in their study may have reached significance had the run time been longer, and lends support that additional studies exploring the effects of chronic pain syndromes that cause progressive pain at the knee in the presence of increased exertion are warranted.

There were a couple of limitations to the current investigation that should be addressed. In order to continuously collected both kinematic and kinetic data throughout the run, the prolonged run occurred on a force-sensing treadmill located in a research laboratory with minimal distractions. This may differ from the normal running surface of our participants, so it is important to point out that one study has investigated the difference in segment coordination between overground and treadmill running at different speeds (Abbasi et al., 2020). The study showed that although CRP measures did differ between treadmill and overground running and at different speeds, CRP variability did not statistically differ between overground and treadmill running (Abbasi et al., 2020). This may help improve confidence that the patterns in CRP variability observed while testing on a treadmill are likely to be present in overground running as well.

One additional limitation of the study was the inclusion of only female participants and the low number of participants ($n = 12$). The inclusion of only female participants may limit generalizability and comparison to other studies including Dierks et al., which included both sexes (Dierks et al., 2011). Currently, research does not suggest that males and females respond differently specific to reported exertion and pain. To combat the low number of participants, and in an effort to give an idea of the meaningfulness of the results, we included the effect sizes for all statistically significant differences. All significant differences reached statistical power of >0.80, with effect sizes of 1.20 or greater.

The significant results of the current study add to previous literature and lends support to the theory that unhealthy patterns of joint and coordination variability exist in runners with PFP as pain and exertion are increased. In the beginning of a run, runners with PFP may be more at risk of damaging repetitive stress on soft tissue structures from restricted movement patterns seen through lower joint and coordination variability. Then as pain and exertion increase, runners with PFP are more likely to experience higher joint and coordination variability than runners without PFP, identifying a breakdown in dynamic movement control that could cause an increase in injury risk. Based on these potentially harmful patterns, future research should focus on interventions to address both limited and excessive variability in joint motion and coordination when in an exerted state of running. One intervention to be explored further is the valgus control instruction (VCI) exercise program explored by Emamvirdi, Letafatkar, and Khaleghi Tazji, for the prevention and rehabilitation of female athletes with PFP (Emamvirdi, Letafatkar, & Khaleghi Tazji, 2019). Emamvirdi et al., reported that participants who completed the specific 6-week VCI program experienced a decrease in pain, increase in performance of several hopping tests, decrease in valgus knee angle when performing a single-leg squat, and increased hip strength from pre to post test and compared to the control group (Emamvirdi et al., 2019). Runners who present with restricted movement at the beginning of their run and instability in their movement at the end of their run may benefit from this VCI program. A decrease in valgus knee angle may help to reduce medial tensile forces and lateral compressive forces, which could help to reduce pain experienced by runners with PFP. Furthermore, the increase in eccentric torque that participants were observed to gain through the VCI program may be beneficial for runners with PFP to help improve movement control when experiencing increasing levels of exertion. It is recommended that future research be done to explore the effects of the VCI program on joint and coordination variability in runners with PFP.

CONCLUSIONS

When examining runners with PFP during a prolonged run, it would seem that pain and exertion increase the variability of joint kinematics and joint coordination. The increased variability may reflect a decrease in movement control creating an unstable state towards the end of the run. This would suggest that runners with PFP have decreased ability for the

lower extremity to adapt to the demands of a prolonged run when compared to a runner without PFP.

REFERENCES

Abbasi, A., Yazdanbakhsh, F., Tazji, M. K., Aghaei, P., Svoda, Z., Nazarpour, K., & Vieira, M. F. (2020). A comparison of coordination and its variability in lower extremity segments during treadmill and overground running at different speeds. *Gait & posture*, 79, 139-144 doi: 10.1016/j.gaitpost.2020.04.022

Barton, C. J., Levinger, P., Menz, H. B., & Webster, K. E. (2009). Kinematic gait characteristics associated with patellofemoral pain syndrome: a systematic review. *Gait & posture, 30*(4), 405-416. doi: 10.1016/j.gaitpost.2009.07.109

Borg, G. (1998). Borg's perceived exertion and pain scales. Champaign (IL): Human Kinetics. doi: 10.1097/00005768-199809000-00018

Cohen, J. (2013). Statistical power analysis for the behavioral sciences. (2nd ed.). New York: Routledge. doi: 10.4324/9780203771587

Crossley, K. M., Bennell, K. L., Cowan, S. M., & Green, S. (2004). Analysis of outcome measures for persons with patellofemoral pain: which are reliable and valid? *Archives of physical medicine and rehabilitation, 85*(5), 815-822. doi: 10.1016/S0003-9993(03)00613-0

Crossley, K. M., Callaghan, M. J., & van Linschoten, R. (2016). Patellofemoral pain. *British journal of sports medicine, 50*(4), 247-250. doi: 10.1136/bjsports-2015-h3939rep

Dierks, T. A., Davis, I. S., & Hamill, J. (2010). The effects of running in an exerted state on lower extremity kinematics and joint timing. *Journal of biomechanics, 43*(15), 2993-2998. doi: 10.1016/j.jbiomech.2010.07.001

Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. (2011). Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. *Medicine & Science in Sports & Exercise, 43*(4), 693-700. doi: 10.1249/MSS.0b013e3181f744f5

Emamvirdi, M., Letafatkar, A., & Khaleghi Tazji, M. (2019). The effect of valgus control instruction exercises on pain, strength, and functionality in active females with patellofemoral pain syndrome. *Sports health, 11*(3), 223-237. doi: 10.1177/1941738119837622

Glaviano, N. R., Kew, M., Hart, J. M., & Saliba, S. (2015). Demographic and epidemiological trends in patellofemoral pain. *International journal of sports physical therapy, 10*(3), 281. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4458915/

Hafer, J. F., Brown, A. M., & Boyer, K. A. (2017). Exertion and pain do not alter coordination variability in runners with iliotibial band syndrome. *Clinical Biomechanics, 47(Aug)*, 73-78. doi: 10.1016/j.clinbiomech.2017.06.006

Hamill, J., Haddad, J. M., Heiderscheit, B. C., Emmerik, R., & Li, L. (2006). Clinical relevance of variability in coordination. In K. Davids, S. Bennett & K. Newell (Eds), *Movement system variability* (pp. 153-165). doi: 10.5040/9781492596851.ch-008

Hamill, J., van Emmerik, R. E., Heiderscheit, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14*(5), 297-308. doi: 10.1016/S0268-0033(98)90092-4

Kannus, P., Aho, H., Järvinen, M., & Nttymäki, S. (1987). Computerized recording of visits to an outpatient sports clinic. *The American Journal of Sports Medicine, 15*(1), 79-85. doi: 10.1177%2F036354658701500112

Koblbauer, I. F., van Schooten, K. S., Verhagen, E. A., & van Dieën, J. H. (2014). Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *Journal of Science and Medicine in Sport, 17*(4), 419-424. doi: 10.1016/j.jsams.2013.05.013

Kujala, U. M., Jaakkola, L. H., Koskinen, S. K., Taimela, S., Hurme, M., & Nelimarkka, O. (1993). Scoring of patellofemoral disorders. *Arthroscopy, 9*(2), 159-163. doi: 10.1016/S0749-8063(05)80366-4

Li, L. (2011). Motion and variability control during prolonged running with patellofemoral pain. *Medicine and science in sports and exercise, 43*(10), 2013; author reply 2014. doi: 10.1249/mss.0b013e3182297e21

Noehren, B., Pohl, M. B., Sanchez, Z., Cunningham, T., & Lattermann, C. (2012). Proximal and distal kinematics in female runners with patellofemoral pain. *Clinical Biomechanics, 27*(4), 366-371. doi: 10.1016/j.clinbiomech.2011.10.005

Noehren, B., Sanchez, Z., Cunningham, T., & McKeon, P. O. (2012). The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain. *Gait & posture, 36*(3), 596-599. doi: 10.1016/j.gaitpost.2012.05.023

Powers, C. M., Bolgla, L. A., Callaghan, M. J., Collins, N., & Sheehan, F. T. (2012). Patellofemoral pain: proximal, distal, and local factors—second international research retreat, August 31–September 2, 2011, Ghent, belgium. Journal of orthopaedic & sports physical therapy, 42(6), A1-A54. doi: 10.2519/jospt.2012.0301

Schwane, B. G., Goerger, B. M., Goto, S., Blackburn, J. T., Aguilar, A. J., & Padua, D. A. (2015). Trunk and lower extremity kinematics during stair descent in women with or without patellofemoral pain. *Journal of athletic training, 50*(7), 704-712. doi: 10.4085/1062-6050-49.3.100

Silvernail, J. F., Boyer, K., Rohr, E., Brüggemann, G.-P., & Hamill, J. (2015). Running mechanics and variability with aging. *Medicine & Science in Sports & Exercise, 47*(10), 2175-2180. doi: 10.1249/MSS.0000000000000633

Stergiou, N., Harbourne, R. T., & Cavanaugh, J. T. (2006). Optimal movement variability: a new theoretical perspective for neurologic physical therapy. *Journal of Neurologic Physical Therapy, 30*(3), 120-129. doi: 10.1097/01.NPT.0000281949.48193.d9

Van Middelkoop, M., Van Linschoten, R., Berger, M. Y., Koes, B. W., & Bierma-Zeinstra, S. M. (2008). Knee complaints seen in general practice: active sport participants versus non-sport participants. *BMC musculoskeletal disorders, 9*(1), 36. doi: 10.1186/1471-2474-9-36

Wallace, D. A., Salem, G. J., Salinas, R., & Powers, C. M. (2002). Patellofemoral joint kinetics while squatting with and without an external load. *journal of ortho-*

paedic & sports physical therapy, 32(4), 141-148. doi: 10.2519/jospt.2002.32.4.141

Weinhandl, J. T., Joshi, M., & O'Connor, K. M. (2010). Gender comparisons between unilateral and bilateral landings. *Journal of applied biomechanics, 26*(4), 444-453. doi: 10.1123/jab.26.4.444

Wier, L., Ayers, G., Jackson, A., Rossum, A., Poston, W. C., & Foreyt, J. (2001). Determining the amount of physical activity needed for long-term weight control. *International journal of obesity, 25*(5), 613-621. doi: 10.1038/sj.ijo.0801586

Willson, J. D., & Davis, I. S. (2008). Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clinical Biomechanics, 23*(2), 203-211. doi: 10.1016/j.clinbiomech.2007.08.025

Wood, L., Muller, S., & Peat, G. (2011). The epidemiology of patellofemoral disorders in adulthood: a review of routine general practice morbidity recording. *Primary health care research & development, 12*(2), 157-164. doi: 10.1017/S1463423610000460