

Variability of Stride Characteristics and Joint Coordination Among Individuals With Unilateral Patellofemoral Pain

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The purpose of this investigation was to determine whether individuals with patellofemoral pain (PFP) display a reduction in intralimb joint coordination variability compared to nonimpaired persons. In addition, it was hypothesized that the variability of the stride characteristics would be similar between groups. Eight individuals with unilateral PFP and 8 nonimpaired participants ran on a treadmill at a fixed ($2.68 \text{ m}\cdot\text{s}^{-1}$) and preferred speed while stride characteristics and 3-D kinematics of the bilateral lower extremities were recorded. Intralimb coordination variability was measured using a vector coding technique applied to relative motion plots of various joint couplings. The PFP group displayed greater stride length variability during running at the preferred speed. However, this was not the case during running at the fixed speed. When averaging across the entire stride cycle, coordination variability for all joint couplings was consistent between the two groups. However, further analysis about heel-strike revealed reduced joint coordination variability for the thigh rotation/leg rotation coupling of the PFP group's injured limb compared to that of the nonimpaired group. With the exception of the transverse plane rotations at heel-strike, it would appear that the level of pain experienced by the PFP participants may not be great enough to produce a change in the intralimb coordination patterns during running.

Key Words: anterior knee pain, relative motion, locomotion variability

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Introduction

Variability in human locomotion has been interpreted to be both detrimental and beneficial to overall performance, depending on the parameter of interest. Studies involving stride characteristics (i.e., stride duration, stride length) have concluded that variability increases the risk of falling (Gabell & Nayak, 1984; Hausdorff, Cudkowicz, Firtion, Wei, & Goldberger, 1997). However, studies addressing joint coordination have hypothesized that variability offers flexibility to adapt to perturbations (Holt, Jeng, Ratcliffe, & Hamill, 1995) and is essential to the changing coordination patterns during locomotion (van Emmerik, Wagenaar, Winogrodzka, & Wolters, 1999).

Movement coordination has been defined as the mastering of redundant degrees of freedom to produce a controllable system (Bernstein, 1967). The formation of coordinative structures (functional synergies) between neurons, muscles, and joints allows a reduction in the functional degrees of freedom to a more controllable level. While capable of performing independently, each component of the synergy can become functionally linked to behave as a task-specific unit. In view of such a large number of degrees of freedom, variability in the formation of these coordinative structures would appear to be inevitable. It has been argued that this variability provides a level of flexibility in task execution (Holt et al., 1995; Turvey, 1990).

The combination of joint coordination variability and task outcome consistency has been frequently demonstrated. While exhibiting low variability in the task criterion, expert marksmen displayed a variety of joint motion coordination patterns (Arutyunyan, Gurfinkel, & Mirskii, 1969). Similar movement variability was observed during point-to-point reaching tasks (Morasso, 1981). The hand trajectories displayed common features across a variety of reaching locations, while the joint trajectories varied substantially. Similar differences in variability between the joint coordination and resultant task outcome were observed with the coordination of pelvic and trunk transverse rotation during locomotion (van Emmerik et al., 1999).

Among individuals with pathology, stride parameter variability has been shown to increase compared to nonimpaired individuals (Hausdorff et al., 1998; Nakamura, Meguro, & Sasaki, 1996). However, additional research has demonstrated that the variability of joint coordination patterns decreases with pathology. Individuals with Parkinson's disease displayed reduced variability in movement pattern between the trunk and pelvis (van Emmerik et al., 1999). With the observed stride duration and its variability among these patients being similar to that of healthy aged-matched participants, van Emmerik et al. concluded that stride characteristics (i.e., stride duration) were not sensitive enough to detect these coordination changes.

Similar reductions in joint coordination variability have been identified among persons with orthopaedic injury. Hamill, van Emmerik, Heiderscheit, and Li (1999) observed individuals with patellofemoral pain (PFP) displaying reduced coordination variability among joint couplings of the painful limb. Reduced variability without any neurological disease led Hamill et al. to suggest that the knee pain diminished the variability of the PFP group by constraining the available movement patterns. That is, the individuals would avoid painful coordination patterns.

An additional mechanism suggested as minimizing pain among persons with

PFP is reduced stride length (Powers, Heino, Rao, & Perry, 1999). The stride-to-stride variability of stride length, however, has not been documented in individuals with PFP. Based on Morasso (1981) and van Emmerik et al. (1999), the resulting variability of stride length need not be influenced by changes in the variability of lower extremity joint couplings. Further, since individuals with PFP do not generally display an unsteady gait, alterations in the variability of stride length or duration would not be anticipated.

In addition to pathology, the speed of locomotion has been shown to influence the level of movement variability. Speeds near the walk-run and run-walk transition region ($2.0\text{--}2.2\text{ m}\cdot\text{s}^{-1}$), as well as during slow walking ($0.2\text{--}0.6\text{ m}\cdot\text{s}^{-1}$), display an accompanying increase in the variability of stride characteristics and joint coordination patterns (Brisswalter & Mottet, 1996; van Emmerik et al., 1999). Thus, locomotion speed must be considered when comparing the variability of movement parameters between individuals.

The purpose of this investigation, therefore, was to compare the variability of stride characteristics and joint coordination between persons with and without PFP. The variability of stride duration and length were compared for group and limb (injured vs. noninjured) differences as well as across running speeds. It was hypothesized that variability in stride parameter would be similar between individuals with and without PFP. It was also hypothesized, based on Hamill et al. (1999), that the injured limb of individuals with unilateral PFP would display reduced variability in intralimb joint coordination compared to their noninjured limb or to either limb of nonimpaired persons. Variability of intralimb joint coordination was observed and compared during two running speeds.

Methods

Eight women, ages 19 to 36 years (mean age 24 ± 6 yrs) with a diagnosis of unilateral PFP, were recruited from the University of Massachusetts community as well as from local physical therapy clinics. Mean body mass was 70.1 ± 11.4 kg and mean height was 1.71 ± 0.047 m. In accordance with previously established criteria (Powers, Landel, & Perry, 1996), symptomatic individuals were admitted to the study if they had reproducible pain with at least two exercises associated with exacerbating PFP (i.e., squatting, stair-climbing, kneeling, prolonged sitting). Individuals were excluded if the presence of ligamentous instability or internal derangement was established during a preparticipation screening, or if they reported prior knee surgery.

Eight asymptomatic women ages 21 to 38 (mean age 27 ± 6 yrs) comprised the nonimpaired or control group. Mean body mass was 57.9 ± 7.2 kg and mean height was 1.70 ± 0.069 m. These participants had no history of knee surgery or pathology and were free of any current knee pain. Women reporting discomfort with the activities used as criteria for the PFP group were dismissed. Using data from the literature, sample size was estimated for a minimum statistical power of 80% (Cohen, 1988). Prior to participation, all the women were required to sign an informed consent form approved by the human subjects review committee of the UMass School of Public Health and Health Sciences.

During treadmill running, kinematic data were collected using a seven-camera (240 Hz) Qualisys ProReflex™ system (Qualisys, Inc., Glastonbury, CT). The room coordinate system was right-handed and fixed in space, with right-handed

orthogonal segment coordinate systems defined for the bilateral thigh, leg, and foot. Running was conducted on a StarTrac 3000 treadmill (Unisen, Inc., Irvine, CA) with zero inclination. The treadmill belt was 50.8 cm wide and 152.4 cm long.

Based on a three-segment rigid body model, reflective marker triads composed of three noncollinear hollow polypropylene spheres fastened to a polypropylene base were secured to the lateral surface of the thigh and leg near midsegment. To measure foot motion, reflective markers were placed on the shoe at the heel, the head of the fifth metatarsal, and anterior to the lateral malleolus. In view of the differences in gait pattern between shod and barefoot running (De Wit, De Clercq, & Aerts, 2000), shod running was deemed necessary, preventing marker attachment directly to the foot. A fourth marker was secured to the anterior tip of the shoe for toe-off detection. All participants wore running shoes with a standardized midsole to prevent variations in segment movement due to different midsole durometers (Hamill, Bates, & Holt, 1992).

Bilateral three-dimensional (3-D) kinematic data were recorded for 20 s while the participants ran on the treadmill at fixed and preferred speeds. The order of speeds was balanced across participants to prevent a presentation effect. In addition to the running conditions, a 3-s static stance trial was recorded to establish the baseline orientations for the lower extremity segments. The participant stood erect with the longitudinal axis of the foot aligned to the anteroposterior axis of the room coordinate system.

To obtain the preferred running speed, a treadmill speed within the range of 0.5 to 8.0 $\text{m}\cdot\text{s}^{-1}$ was randomly selected. While blinded to the treadmill speed, the participant increased or decreased the treadmill speed until she obtained a comfortable and preferred speed. This was repeated three times and the average of the three was used as the preferred speed for data collection. To examine the possible confounding effects of different preferred speeds, a fixed speed condition was included. The fixed speed was established at 2.68 $\text{m}\cdot\text{s}^{-1}$ (6.0 mph) to avoid the walk/run or run/walk transition speed region (1.8–2.2 $\text{m}\cdot\text{s}^{-1}$) previously reported (Thorstensson & Roberthson, 1987). Prior to the recording of each condition, the participant was given time to accommodate to the running speed. Knee pain was assessed following each running speed using a visual analog pain scale (Chesworth, Culham, Tata, & Peat, 1989).

Three-dimensional Cartesian coordinates for each marker were determined at the time of recording using a nonlinear transformation technique with ProReflex software (Qualisys, Inc.). Markers were sorted and identified from the recordings using Track3D commercial software (Qualisys, Inc.). Absent marker position data secondary to temporarily occluded markers were interpolated using a cubic spline. Coordinate data were low-pass filtered using a fourth-order Butterworth recursive filter with cutoff frequency of 9 Hz. The cutoff frequency was selected using Winter's (1990) residual analysis technique.

The frames associated with initial foot contact and toe-off were determined for each stride based on the vertical jerk of the heel marker and vertical acceleration of the toe marker, respectively.¹ Within-subject means and standard deviation

¹A peak vertical acceleration of the toe marker coincided with toe-off. Due to some participants having a midfoot strike running pattern, the vertical jerk of the heel marker was required to detect initial foot contact.

tions of stride length and duration were calculated from the initial 15 strides for each condition. Custom software was used to calculate 3-D segment and joint angles consistent with Areblad et al. (Areblad, Nigg, Ekstrand, Olsson, & Ekstrom, 1990). The angle data were linearly interpolated with heel-strike at 0% and terminal swing at 100% of stride.

Consistent with Hamill et al. (1999), within-limb couplings were created for thigh rotation/leg rotation and thigh flexion/leg flexion. Based on the reduction in maximal knee flexion among participants with PFP (Dillon, Updyke, & Allen, 1983), additional joint couplings were considered (i.e., knee rotation/ankle inversion, knee flexion/ankle inversion, and knee flexion/ankle dorsiflexion). Relative motion diagrams, or angle-angle plots, were created for each coupling with the proximal segment comprising the abscissa and the distal segment comprising the ordinate. Each plot displayed the relative motion, or coordination, between the two components of the coupling.

Contrary to Hamill et al. (1999), joint coordination was not assessed using continuous relative phase due to its limitations with non-sinusoidal time series (Diedrich & Warren, 1995). With the exception of the sagittal plane motion at the hip, the remaining joint motions of the lower extremity during running are largely non-sinusoidal. Thus, the use of continuous relative phase for assessing the variability of intralimb lower extremity coordination during running may produce inaccurate results.

Using the relative motion plots, quantification of joint coordination was obtained using a modification of a vector coding technique suggested by Sparrow, Donovan, van Emmerik, and Barry (1987). The orientation to the right horizontal of the resultant vector between two adjacent data points in the stride cycle was calculated as follows:

$$\phi_{i,i} = \tan^{-1} \left(\frac{y_{i+1} - y_i}{x_{i+1} - x_i} \right), \text{ where } i = 1, 2, \dots, n \quad (1)$$

Following conversion from radians to degrees, the resulting range of values for ϕ , or coupling angle, was 0–360°. The mean vector and standard deviation between trials were calculated for each time interval from the initial 15 strides. Because directional data are classified as a circular variable, the between-trial mean and standard deviation were determined using circular statistics (Batschelet, 1981). The average standard deviation across the entire stride cycle served as the measure of the variability of the joint coordination between the components of each coupling. These procedures were repeated for each participant, providing a measure of the between-trial, within-subject variability.

Due to changing functional demands of the lower extremities across the stride cycle (i.e., weight acceptance, propulsion, and limb advancement), averaging the variability within specific regions of the stride rather than across the entire stride may provide a more sensitive analysis for detecting between-group differences. Therefore, the statistical analyses were repeated for the averages of each of five stride regions (11–30%, 31–50%, 51–70%, 71–90%, and 91–10%), with each region containing a functional event of the running stride (midstance, toe-off, swing acceleration, swing deceleration, and heel-strike, respectively).

Preferred speed was compared between groups using an independent *t*-test, with pain values for the PFP group compared across speeds using a paired *t*-test. Coefficients of variation (CV) for stride duration and length were calculated based on the standard deviation and mean of each parameter. The mean stride characteristics, as well as the coefficients of variation, were each compared using a three-factor (group by limb by speed) ANOVA with repeated measures (speed). The joint coordination variability was also compared using a three-factor (group by limb by speed) ANOVA with repeated measures (speed) for each coupling.

The factor "limb" consisted of two levels, injured and noninjured for the PFP group. Although absent of injury, the right and left limbs of the control group were randomly distributed into injured and noninjured categories to allow for statistical comparison. Effect size (ES) calculations, based on partial- η^2 values (Cohen, 1973), were performed for all measures. While Cohen (1988) has provided estimates of what constitutes a small (0.01), medium (0.06), and large (0.14) effect for partial- η^2 , effect sizes from the present study were interpreted relative to each other.

Results

With the exception of stride length variability, the stride characteristic parameters were similar across groups (Table 1 and Figure 1). The coefficient of variation of stride length displayed a significant group-by-speed interaction ($p = 0.03$, ES = 0.30), indicating that at the preferred running speed the PFP group had greater stride length variability than the controls (Figure 1). The effect size of 0.30 indicates that 30% of the variance in stride length variability was attributable to the group-by-speed interaction. The coefficient of variation of stride duration did not display a group effect ($p = 0.29$, ES = 0.08) or limb effect ($p = 0.49$, ES = 0.03) (Figure 1). The mean values of stride length and stride duration were consistent between groups ($p = 0.67$, ES = 0.01, and $p = 0.57$, ES = 0.02, respectively) and limbs ($p = 0.22$, ES = 0.10, and $p = 0.24$, ES = 0.10, respectively), regardless of speed.

The injured limb of the PFP group displayed a similar level of average coordination variability across the stride cycle compared to the noninjured limb or to either limb of the control group (Table 1 and Figure 2). Minimal interaction between group and limb was observed for all couplings ($p > 0.42$, ES < 0.05), indicating that the coordination variability across limbs was similar between groups. Further, when compared across limbs and speed, the groups displayed similar values of joint variability for all couplings ($p > 0.21$, ES < 0.11) (Table 1).

Analysis of the specific stride regions revealed the injured limb of the PFP group to have less variability near heel-strike for the thigh rotation/leg rotation coupling than the noninjured limb of the PFP group during preferred-speed running ($p < 0.02$, ES = 0.38) (Figure 3). In addition, the injured limb of the PFP group displayed less variability than for the control group, while the noninjured limb of the PFP group displayed greater variability than for the control group. No group differences were detected among the other regions or couplings ($p < 0.17$, ES = 0.13).

The PFP group reported a similar average pain score during running at the fixed speed (2.4 ± 1.0) compared to the preferred speed (1.9 ± 0.9) ($p = 0.14$). The participants in the control group did not experience any pain (0). The mean preferred running speed between the controls ($2.72 \text{ m}\cdot\text{s}^{-1}$, $SD = 0.15$) and those with PFP ($2.57 \text{ m}\cdot\text{s}^{-1}$, $SD = 0.29$) was similar ($p = 0.22$).

Table 1 Average Stride Characteristics and the Variability of Intralimb Joint Coordination (°) Across the Stride Cycle^a

| | PFP | | Control | |
|---------------------------------|---------------|---------------|---------------|---------------|
| | Injured | Noninjured | Injured | Noninjured |
| Stride duration (s) | | | | |
| Fixed | 0.736 ± 0.034 | 0.736 ± 0.033 | 0.731 ± 0.040 | 0.731 ± 0.039 |
| Preferred | 0.743 ± 0.030 | 0.742 ± 0.030 | 0.728 ± 0.039 | 0.727 ± 0.039 |
| Stride length (m) | | | | |
| Fixed | 1.98 ± 0.091 | 1.98 ± 0.090 | 1.97 ± 0.12 | 1.97 ± 0.12 |
| Preferred | 1.92 ± 0.22 | 1.91 ± 0.22 | 1.98 ± 0.17 | 1.98 ± 0.17 |
| Thigh rotation/Leg rotation | | | | |
| Fixed | 22.2 ± 5.8 | 24.7 ± 5.4 | 23.9 ± 5.6 | 23.5 ± 5.6 |
| Preferred | 22.4 ± 6.0 | 25.4 ± 5.5 | 23.2 ± 6.2 | 23.5 ± 4.5 |
| Thigh flexion/Leg flexion | | | | |
| Fixed | 4.6 ± 0.7 | 4.0 ± 0.7 | 4.2 ± 0.7 | 3.8 ± 0.7 |
| Preferred | 4.5 ± 1.0 | 4.4 ± 0.9 | 4.5 ± 1.7 | 3.8 ± 0.8 |
| Knee rotation/Ankle inversion | | | | |
| Fixed | 21.6 ± 3.5 | 22.4 ± 4.7 | 19.3 ± 3.8 | 19.0 ± 4.8 |
| Preferred | 20.5 ± 5.3 | 20.9 ± 3.8 | 19.3 ± 3.7 | 20.2 ± 4.7 |
| Knee flexion/Ankle inversion | | | | |
| Fixed | 9.7 ± 2.0 | 9.1 ± 1.6 | 8.6 ± 1.3 | 7.8 ± 1.6 |
| Preferred | 9.0 ± 1.9 | 9.1 ± 2.1 | 8.9 ± 2.6 | 8.4 ± 2.5 |
| Knee flexion/Ankle dorsiflexion | | | | |
| Fixed | 5.3 ± 1.0 | 5.2 ± 0.6 | 5.2 ± 0.9 | 5.3 ± 0.6 |
| Preferred | 5.7 ± 1.6 | 5.7 ± 0.7 | 5.7 ± 1.6 | 5.7 ± 0.7 |

^a PFP = patellofemoral pain, fixed and preferred running speed, group mean ± between-participant standard deviation.

Discussion

The purpose of this study was to compare the variability of joint coordination, as well as stride characteristics, between persons with and without PFP. It was hypothesized that individuals with PFP would display a reduction in intralimb joint coordination variability compared to nonimpaired persons but that their stride characteristics would be similar. Based on our results, differences in stride length variability were apparent between groups. When averaged across the stride cycle, the joint coordination variability was consistent between groups. However, further analysis revealed that group differences were evident at heel-strike in the coordination variability of the thigh rotation/leg rotation coupling.

Increased variability in stride length among the PFP group refutes our hypothesis that stride characteristic variability would be similar between groups. This observation is in agreement with the research on stride characteristic variability among individuals at risk for falling (Hausdorff, Edelberg, Mitchell, Goldberger,

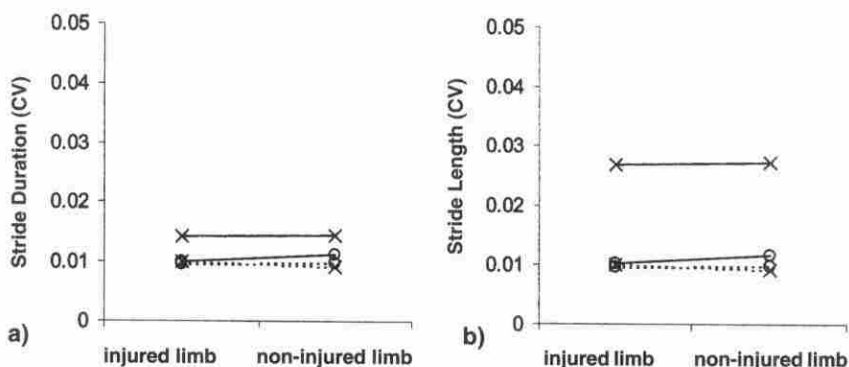


Figure 1 — Variability of stride characteristics. Coefficient of variation (CV) of: (a) stride duration, and (b) length for the control and patellofemoral (PFP) groups. The PFP group had greater variability in the stride length of both limbs at the preferred vs. fixed speed. Control group (O); PFP group (X); Fixed speed (---); Preferred speed (—).

& Wei, 1997; Nakamura et al., 1996), as well as individuals with Parkinson's disease (Hausdorff et al., 1998). However, individuals with PFP are generally healthy persons void of any significant neuromuscular disease. The pain, muscular weakness, and altered contraction timing of the quadriceps among individuals with PFP (Powers et al., 1996; Suter, Herzog, & De Souza, 1998) may be enough to alter the stride-to-stride consistency of stride length. The generalizability of this result should be viewed with caution, however, as there was no apparent increase in stride length variability of the PFP group during running at the fixed speed.

When averaged across the stride cycle, the variability of the coordination patterns of the intralimb couplings did not reveal any differences between the PFP and control groups or between the injured and noninjured limbs at either the fixed or preferred running speeds. Dividing the stride cycle into five regions provided a more sensitive analysis than the average variability of the entire stride cycle, yet a group difference was revealed only for the thigh rotation/leg rotation coupling during the region corresponding to heel-strike.

Considering the increased error associated with kinematic recording of transverse plane rotation, this result may simply be coincidence. However, the presence of variability in this coupling at heel-strike may serve an important adaptability role. Intralimb coordination pattern variability has been suggested to permit the flexibility required to ambulate in uncertain environments (Clark & Phillips, 1993). While running on a treadmill may not be regarded as an uncertain environment, there is likely a degree of uncertainty in every running stride before physical contact is achieved between the foot and the ground. Thus, greater joint pattern variability would likely be observed prior to and at the instant of heel-strike, providing the flexibility to adapt to unanticipated perturbations.

The reduced thigh rotation/leg rotation variability at heel-strike of the injured limb coincides with the observations of Hamill et al. (1999). The reduced thigh rotation/leg rotation variability among individuals with PFP was suggested

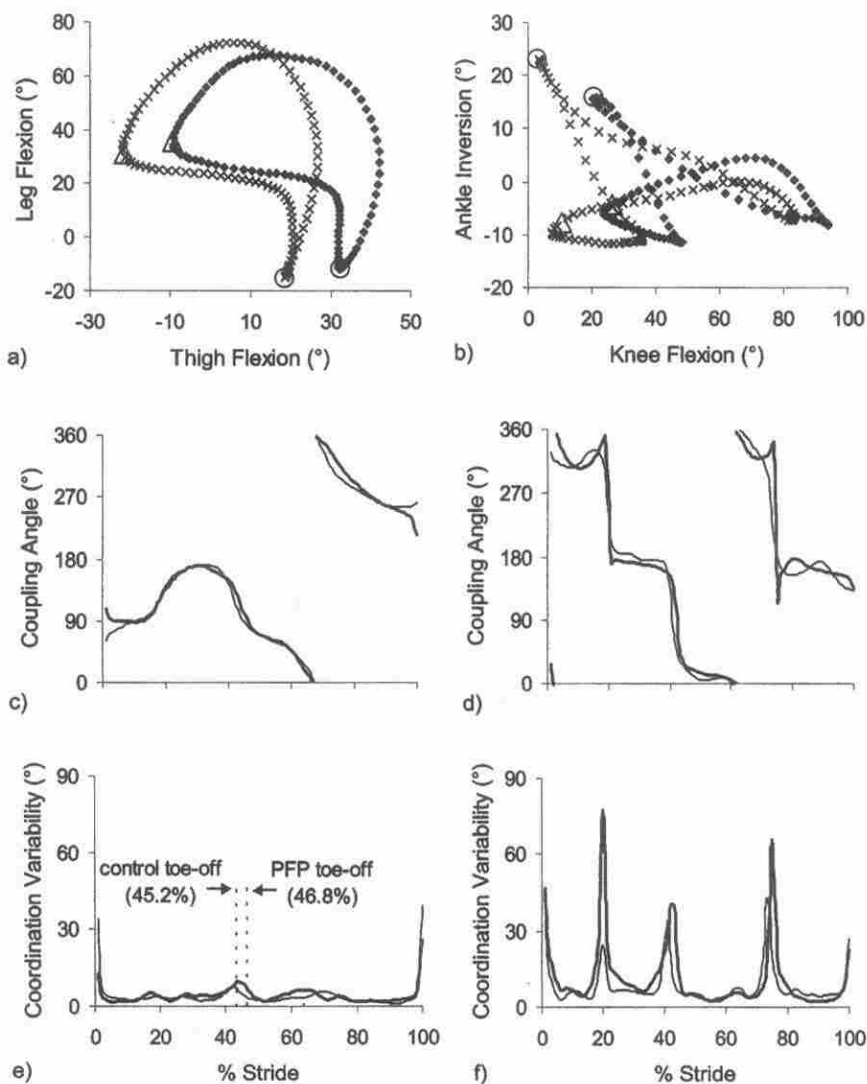


Figure 2 — Mean relative motion plots of a representative participant from each group (PFP = ♦; Control = ×) for: (a) thigh flexion/leg flexion, and (b) knee flexion/ankle inversion of the injured limbs during running at $2.68 \text{ m}\cdot\text{s}^{-1}$ (heel-strike = O; toe-off = Δ). Mean coupling angles (c, d) and coordination pattern variability (e, f) for the respective couplings. The difference in toe-off between the participant with patellofemoral pain and the control can account for the time shift in the occurrence of increased variability during swing. PFP (—); Control (—). Representative participants are shown rather than group ensemble averages due to between-participant variation.

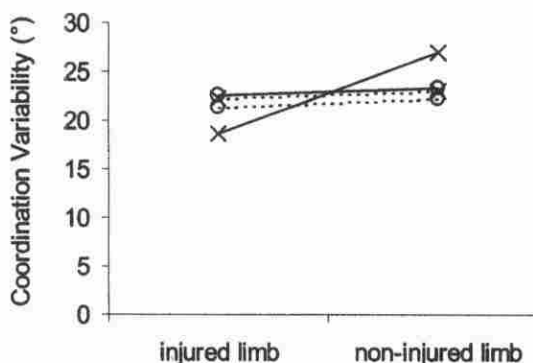


Figure 3 — Coordination pattern variability between thigh rotation and leg rotation at heel-strike $\pm 10\%$. During the preferred running speed, the injured limb of the patellofemoral group (PFP) showed a decrease in variability relative to the fixed speed and relative to the controls. The noninjured limb showed an increase in variability. Control group (O); PFP group (X); Fixed speed (- - -); Preferred speed (—).

to be a mechanism compensating for the pain. However, it may be equally as plausible that there was a reduction in variability prior to the onset of pain. Further research may determine whether the joint coordination variability would increase following a reduction in pain.

An increase in the thigh rotation/leg rotation variability of the noninjured limb during preferred running was concurrent with the decreased variability of the injured limb. This suggests that the intralimb joint coordination of one limb is influenced by the intralimb coordination of the other. Similar differences in variability were observed between the affected and nonaffected limbs of children with spastic hemiplegic cerebral palsy (Jeng, Holt, Fетters, & Certo, 1996). The increased variability of the noninjured limb may have provided a source of flexibility and adaptability to compensate for the more constrained patterns of the injured limb. Assessment of the interlimb coordination of homologous joints and the accompanying variability may shed light on this relationship.

The lack of further differences in joint coordination variability between groups may have resulted from the limited symptoms (i.e., pain) in the PFP group. Based on the perceived pain scores, the average pain reported by the PFP participants was 2.4 (range = 0.9–3.9) at the fixed speed and 1.9 (range = 0.0–2.7) at the preferred speed. It should be noted that while all those with PFP sought treatment for their symptoms due to activity limitations, running was not consistently limited. That is, some participants with PFP had minimal pain while running, whereas activities such as stair climbing or squatting were more severely affected. Studies of joint coordination variability during these tasks may have revealed greater differences.

Periods of increased joint coordination variability were observed for both groups during the stride cycle. The increased variability corresponds to changes in the joint coordination (Figures 2e, 2f). Prior to each increase in variability, the couplings maintain a coordinative state for a period of time. As it transitions to a new coordinative state, variability is increased. Transitions from one coordinative

state of the coupling to another are indicated by a reversal of direction of one or both joints. The reversal of direction of motion in joints has been hypothesized to be a critical event in investigating movement coordination (Clark & Phillips, 1993).

Ghez and Sainburg (1995) observed joint coordination variability upon a reversal of direction to be greater than the variability observed when the joints maintained a constant direction of motion. Further, individuals with reduced proprioception have the most difficulty reversing direction during a movement task, as indicated by increased variability. Therefore, the greater variability observed at direction reversals in the present study would be anticipated based on the neuromuscular complexity of the task.

However, it should be noted that regions of minimal joint displacement during running are present when the joint's direction of motion is reversed. Minimal joint displacement will influence the calculation of the coupling angle due to proximity of the data points. The greater the proximity of consecutive data points, the greater the coupling angle sensitivity to slight changes in displacement. Thus, minimal displacement of either joint in a coupling between data points of close proximity would have a greater impact on the resulting coupling angle than if the same displacement occurred between two data points farther apart. Ultimately, this can influence the level of variability in joint coordination.

During running at preferred speed, the participants with PFP displayed greater variability in stride length relative to the control group. When averaged across the entire stride cycle, those with unilateral PFP did not display a reduction in the variability of joint coordination compared to their noninjured limb or to either limb of the control group. Thus it would appear that the level of pain experienced by the PFP participants may not be enough to produce a change in the intralimb coordination patterns during running. A more detailed analysis of heel-strike, however, revealed a decrease in the variability of the thigh rotation/leg rotation coupling for the injured limb of the PFP group. Whether this observation occurred as a result of pain or possibly existed prior to the onset of pain is left to further study.

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