Introduction
The knee and subtalar joint actions are related by the internal/external rotation motion of the tibia during the support phase of running. It has been suggested that maximum knee flexion should occur at the same time as maximum subtalar eversion during which time the tibia undergoes internal rotation (Bates et al., 1978). Asynchronous timing between knee joint flexion and ankle joint eversion maxima has been related to knee pain in runners (Hamill et al., 1992; McClay and Manal, 1997).

Hamill et al. (1999) suggested using a dynamical system analysis in the investigation of lower extremity joint couplings. Using preliminary data, they assessed the use of the continuous relative phase (CRP) and the variability of the CRP of various lower extremity couplings in subjects with knee pain and those with no knee pain. They suggested that greater variability, indicating a much looser coupling between lower extremity joint actions, would be the norm in healthy individuals while less variability, indicating a much tighter coupling, would be evident in individuals with knee pain. The purpose of this study was, therefore, to assess joint coupling variability from a dynamical systems perspective in individuals with patellofemoral pain (PFP) and those without a history of knee pain.

Methods
Sixteen female, volunteer subjects (19-36 years) provided informed consent to participate in this study in accordance with University policy. Eight of the subjects were diagnosed with symptomatic, unilateral PFP. In accordance with previously established criteria (Powers et al., 1997), the PFP subjects were admitted to the study if they had reproducible pain with at least two exercises associated with exacerbating PFP. Subjects were excluded if the presence of ligamentous instability or prior knee surgery was established during the pre-participation screening. The other eight subjects served in the non-impaired control group. They had no history of pathology or surgery and were free of any knee pain. Knee pain was assessed prior to the data collection session using a visual analog scale (VAS). The scale consisted of a 10 cm horizontal line with ends indicating “no pain” (0) and “extreme pain” (10). Subjects marked a vertical line on the scale to indicate the intensity of their perceived pain during the experimental procedure.

Kinematic data were collected using seven high-speed digital cameras (240 Hz) interfaced to a microcomputer. Triads of markers fixed to rigid structures were placed on the thigh and leg segments while three markers were placed on anatomical locations on the foot segment. Prior to the running trials, a standing calibration trial was collected for each subject. Data were collected for 20 s while the subjects ran on a motorized treadmill at their preferred running speed (mean = 2.40 m•s⁻¹) and at a fixed running speed (2.68 m•s⁻¹). Three-dimensional coordinates of each marker were low pass filtered at 9 Hz. Joint angles were calculated using a joint coordinate system analysis (Grood and Suntay, 1983). In this paper, CRP variability was determined for the same couplings as reported in Hamill et al. (1999).

CRP is generally determined from the difference in phase angles of the respective motions that constitute the coupling. In Hamill et al. (1999) paper, phase angles were calculated from the coordinates \( \hat{\theta}, \hat{\epsilon} \) for each joint angle of the coupling. These phase angles typically require normalization to scale for amplitude differences (Hamill, et al., 2000). Artifacts in this type of phase angle calculation can result when determining relative phase from position-velocity phase plots (Fuchs et al., 1996). Recently, the Hilbert Transform has been used to eliminate such problems and thus was used in this study (Rosenblum et al., 2000). The Hilbert Transform is an analytic signal calculated by phase shifting all frequency components of the original time series by \( \pi \) radians. The analytic signal contains both real and imaginary components where
the real component is the original signal and the imaginary component is the iFFT of the phase-shifted frequencies. In lieu of the position-velocity state space, CRP is calculated from the analytic state space as follows:

\[ \varphi_1(t) - \varphi_2(t) = \tan^{-1} \frac{\tilde{s}_1(t) - \tilde{s}_2(t)}{s_1(t) - s_2(t)} \]

where \( \tilde{s}_1(t) \) and \( \tilde{s}_2(t) \) are the imaginary components of the Hilbert Transform of the two joint angles and \( s_1(t) \) and \( s_2(t) \) are the original joint angles. The variability of the CRP was then assessed over 10 strides cycles for each coupling in each locomotor speed condition.

**Results and Discussion**

Using the VAS pain results, the non-PFP group reported no pain while running at either speed while the PFP group reported an average pain value of 2.4 at the fixed speed and 1.9 at the preferred speed. There were no statistically significant differences between the groups (p>0.05). Figure 1 is a representative illustration of the phase planes of a single subject for a single joint coupling (tibial rotation-foot inversion/eversion) at the fixed running speed. These data represent 13 continuous strides.

![Figure 1: Representative phase planes where the real component (ℜ) of the Hilbert transform is plotted against the imaginary component (ℑ). CRP is later assessed as the difference between the phase angles calculated from the phase plots. Shown above are the phase plots for a) tibial rotation and b) foot inversion / eversion.](image)

Figure 2 illustrates the ensemble CRP variability for each group for the tibial rotation - foot inversion / eversion coupling over the complete running stride at the fixed running speed.

![Figure 2: Ensemble group CRP variability for the tibial rotation-foot inversion/eversion coupling.](image)
Statistically, there were no significant differences in the variability of continuous relative phase between the non-PFP group and the PFP group in any of the couplings examined (p>0.05). In addition, no significant differences were found between the involved and non-involved limbs (p>0.05). There were no differences in the analyses between the preferred and fixed running speeds (p>0.05). These results are illustrated in Figure 3.

The presence of unilateral PFP was previously hypothesized by Hamill et al. (1999) to be characterized by a reduced CRP variability in lower extremity joint couplings related to the involved knee. In this study, the PFP group displayed similar CRP variability for all couplings compared to the non-PFP group. These results do not appear to support the hypotheses of Hamill et al. (1999). However, it should be noted that the pain level reported by the PFP group was very low and not different from the non-PFP group. Therefore, we cannot conclude that CRP variability is a poor discriminator of those with and without PFP because the pain level may not have been great enough to produce an observable decrease in CRP variability. It may also be that decreased CRP variability is a product of the level of pain and not the cause of the injury. Although there were no differences at the within-limb couplings, there may be possible differences in the between-limb couplings.

References