Continuous Relative Phase Variability During an Exhaustive Run in Runners With a History of Iliotibial Band Syndrome

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Previous research has proposed that a lack of variability in lower extremity coupling during running is associated with pathology. The purpose of the study was to evaluate lower extremity coupling variability in runners with and without a history of iliotibial band syndrome (ITBS) during an exhaustive run. Sixteen runners ran to voluntary exhaustion on a motorized treadmill while a motion capture system recorded reflective marker locations. Eight runners had a history of ITBS. At the start and end of the run, continuous relative phase (CRP) angles and CRP variability between strides were calculated for key lower extremity kinematic couplings. The ITBS runners demonstrated less CRP variability than controls in several couplings between segments that have been associated with knee pain and ITBS symptoms, including tibia rotation–rearfoot motion and rearfoot motion–thigh ad/abduction, but more variability in knee flexion/extension–foot ad/abduction. The ITBS runners also demonstrated low variability at heel strike in coupling between rearfoot motion–tibia rotation. The results suggest that runners prone to ITBS use abnormal segmental coordination patterns, particularly in couplings involving thigh ad/abduction and tibia internal/external rotation. Implications for variability in injury etiology are suggested.

Keywords: running, variability, injury, dynamical systems, iliotibial band syndrome

Knowledge of system variability is essential for understanding the intrinsic behavior of a dynamical system. Between-stride variability during locomotion can play both beneficial and detrimental roles depending on the parameter under investigation. Increased variability in stride length (Nakamura et al., 1996) and stride time (Hausdorff et al., 2001) has been associated with increased risk of falling. Studies of segmental coordination patterns have suggested a beneficial role for variability in allowing flexibility to transition to more stable coordination patterns in response to perturbations (Van Emmerik & Van Wegen, 2000; Van Emmerik et al., 2004; Pollard et al., 2005).

While the relationship between variability and pathology in runners is poorly understood, variability in segmental coordination patterns may be an important etiological factor in running injuries (DeLeo et al., 2004). In the kinematic chain, motion of one segment must influence the motions of adjacent segments. Rather than focusing on the mechanics of single joints and segments, some researchers have considered the coupling, or coordination and relative timing, between segments (Hamill et al., 1992; Nigg et al., 1993; McClay & Manal, 1997; Hintermann & Nigg, 1998). In the dynamical systems approach to lower extremity coordination, continuous relative phase (CRP) provides a continuous measure of segmental coordination throughout the entire stride cycle, and allows an assessment of the flexibility in coordination (Hamill et al., 1999). Previous research using CRP and other coordination measures in runners has suggested that a lack of variability in lower extremity coordination is indicative of a pathological state, particularly in runners with patellofemoral pain (PFP). Hamill et al. (1999) found that runners with PFP were less variable across the entire stride cycle than healthy runners in couplings involving tibial rotation. Heiderscheit et al. (2002) found...
that runners with PFP displayed less variability in thigh rotation–tibia rotation coupling near heel strike compared with healthy controls. A certain degree of lower extremity coordination variability thus appears to be an important component of pain-free running.

The results of Hamill et al. (1999) and Heiderscheit et al. (2002) suggest that runners with pathology use a narrow range of coordination patterns. During the cyclic motions of running, repetitive coordination patterns could lead to repetitive local tissue stress, from which an injury may develop. However, interpretations of segmental coordination assessed by CRP must be made carefully. CRP is typically derived from sinusoidal oscillators (Kelso, 1995) that provide intuitive results. With the possible exception of hip flexion/extension, the time series of most running kinematics are predominantly nonsinusoidal. Interpretations of CRP for running kinematics are therefore limited to relationships between the signals’ phase planes and should not be used to describe relationships between the original kinematic time series (Peters et al., 2003).

Currently, the relationship between lower extremity coordination variability and iliotibial band syndrome (ITBS), a common overuse running injury, is unknown. ITBS is an overuse injury of the lateral knee believed to develop when the iliotibial band (ITB) becomes inflamed due to impingement (Fredericson & Wolf, 2005) or lateral compression (Fairclough et al., 2006) between the ITB and the lateral femoral epicondyle. Previous research has found kinematic discriminators between healthy runners and runners prone to ITBS. Runners with a history of ITBS have demonstrated greater foot inversion, foot adduction, and knee flexion at heel strike (Miller et al., 2007). Runners who prospectively developed ITBS demonstrated greater hip adduction and knee internal rotation before displaying symptoms (Noehren et al., 2007). In addition, runners with a history of ITBS have shown an increased likelihood of impingement with the lateral femoral epicondyle near the end of an exhaustive run and more strain in the ITB while running compared with healthy controls (Miller et al., 2007). If variability in the spatial and temporal coordination of these kinematics is related to pathology, then CRP variability in these couplings should discriminate between the groups.

Knowledge of lower extremity coordination variability in runners prone to ITBS, as well as the relationship between variability and fatigue, may be useful in treating and preventing ITBS from a clinical perspective. Dynamical systems theory predicts high variability during transitions (Schoner & Kelso, 1988), e.g., from swing to stance. Heiderscheit (2000) suggests that treatments of disordered movement may be most effective when variability is high. Based on these suggestions, it seems relevant to identify phases (stance, swing), instances (heel strike), or conditions (rested, fatigued) under which the locomotor system is or is not highly variable, and how this variability relates to the etiology of running injuries. However, these topics have not been investigated extensively.

The purpose of the study was to investigate the role of lower extremity coordination variability in runners with retrospective cases of ITBS during an exhaustive run. It was hypothesized that the ITBS runners would exhibit less variable coordination than control runners in couplings between kinematics previously associated with ITBS. Further, it was hypothesized that the ITBS runners would decrease their lower extremity coordination variability between the beginning and end of the run. A long-term goal of this research is to determine implications for variability in the etiology of ITBS. Suggestions for these implications are drawn from the present results.

Methods

Subjects

Sixteen recreational runners were recruited. Runners completed a self-report on their history of injuries and means of diagnoses. Eight runners who had been diagnosed by a physician or a physical therapist with ITBS comprised the ITBS group, mean (SD): age = 27.5 (9.0) years, height = 170.1 (6.9) cm, mass = 68.7 (15.9) kg. All runners in the ITBS group had experienced recurrent symptoms in one (two of eight) or both (six of eight) legs, with recurrence defined as losing at least a week of training time due to symptoms, but were symptom free for at least 4 months before data collection. Eight runners with no history of injuries were age matched within 4 years of an ITBS runner and comprised the control group, age = 26.4 (7.7) years, height = 172.8 (8.9) cm, mass = 71.3 (14.4) kg. No runner had a history of major lower extremity injury other than ITBS. The protocol was approved by the university’s institutional review board. Subjects gave informed written consent.

Experimental Setup

An eight-camera 120-Hz Peak Motus motion capture system (Vicon Peak, Centennial, CO) captured three-dimensional optical data while subjects ran on an adjustable speed Quinton treadmill (Stairmaster, Kirkland, WA).

Data Collection

Retroreflective markers were attached to both legs on the toe, heel, dorsifoot, medial and lateral malleoli, anterior calf, medial and lateral femoral epicondyles, anterior thigh, greater trochanter, anterior-superior iliac spines, and L5/S1. Subjects performed a standing calibration trial with their feet shoulder width apart while the cameras recorded marker positions for 1 s. Subjects ran on the treadmill at a level grade, with instructions to select a constant pace that would exhaust them within 20 min. Self-selected paces were allowed to better capture the subjects’ normal training kinematics. Subjects warmed up at a slower pace for 2 min before beginning the run. Marker positions were recorded every 2 min for 10 s until
the subject could no longer maintain the pace. Subjects wore black Spandex shirt and shorts and their own running shoes.

Data Reduction

Marker positions were smoothed by a fourth-order recursive Butterworth filter with a 15-Hz cutoff selected by residual analysis (Winter, 2004). A MATLAB program (MathWorks, Natick, MA) modeled the lower extremity as a rigid-segment linkage (pelvis, thigh, calf, foot), with three degrees of rotational freedom at each joint. Three-dimensional joint and segment angles were calculated by Cardan transformation matrices of three successive rotations (flexion/extension, adduction/abduction, internal/external rotation; Robertson et al., 2004). Angular velocities were calculated by the central difference method. Timings of heel strike and toe-off were determined using the zero-jerk algorithm (Hreljac & Marshall, 2000).

Phase plots (Figure 1) were constructed for thigh adduction/abduction (thigh AD/AB), tibia internal/external rotation (tibia IR/ER), foot adduction/abduction (foot AD/AB), foot inversion/eversion (foot IN/EV), knee flexion/extension (knee FL/EX), and knee adduction/abduction (knee AD/AB). Phase plots consisted of the angle on the horizontal axis and its respective angular velocity on the vertical axis. Phase plots were normalized by the following equations:

\[
\theta_{i,norm} = \frac{\theta_i - \min(\theta)}{\max(\theta) - \min(\theta)} - 1
\]

\[
\omega_{i,norm} = \frac{\omega_i}{\max[\max(\omega), \max(-\omega)]}
\]

where \( \theta \) is the angle, \( \omega \) is the angular velocity, and the subscript \( i \) indicates the data point within the stride. Normalization was performed to account for frequency and amplitude differences in the time series before computing phase angles and to allow comparisons with previous research on CRP in pathological running (Hamill et al., 1999). Equations 1 and 2 normalize the phase plot such that the origin corresponds to the midpoint of the angular range of motion and zero angular velocity. Equation 2 accounts for frequency differences in the signals by ensuring that CRP angles between signals of different frequencies provide intuitive results (Peters et al., 2003) and avoids losing information regarding zero velocity (Hamill et al., 2000). The phase angle \( \phi \) was defined as the angle between the right horizontal axis and a given data point \( (\theta_{i,norm}, \omega_{i,norm}) \):

\[
\phi = \tan^{-1}\left(\frac{\omega_{i,norm}}{\theta_{i,norm}}\right)
\]

CRP angles were calculated for five couplings of interest: thigh AD/AB–tibia IR/ER, thigh AD/AB–foot IN/EV, tibia IR/ER–foot IN/EV, knee FL/EX–foot AD/AB, and knee AD/AB–foot IN/EV. Couplings were selected based on their likelihood of imposing strain on the ITB, the importance of the kinematics in previous ITBS research (Miller et al., 2007; Noehren et al., 2007), and previous research on kinematic coupling in runners (Bates et al., 1978; Hamill et al., 1992, 1999; McClay & Manal, 1997). A CRP angle was defined as the proximal segment \( \phi \) minus the distal segment \( \phi \). CRP variability (VCRP) was calculated as the between-stride standard deviation in CRP for a single subject at each time step. VCRP was calculated between the first seven strides from the first, middle, and last 10-s data blocks. VCRP was averaged across the full stride, stance, or swing to obtain single-value representations of variability during these periods, and then averaged across subjects. VCRP at heel strike (0% of stance) was also assessed.

Statistical Analysis

VCRP were compared by a 2 × 2 factorial ANCOVA with group (ITBS or control) and time (start of the run or end of the run) as factors, with time as a repeated measure and running speed as a covariate. Post hoc comparisons were made by linear contrasts. Significant differences were reported at \( p < .05 \). Trends toward group differences were reported at \( p < .10 \).
**Results**

Runners reached voluntary exhaustion after an average of 16 (SD, 5) min, with no difference between groups. Average selected speeds were 9.5 (2.2) min/mile for the ITBS group and 7.8 (1.0) min/mile for the control group. Figure 2 shows exemplar CRP and VCRP data for both groups. There were no significant main effects for time and no significant interactions between group and time on VCRP.

*Figure 2* — CRP angles during the complete stride cycle for representative (a–e) ITBS subject and (f–j) control subject. Data are from the beginning of the subjects’ runs. 0% and 100% on the x-axis represent consecutive heel strikes. Vertical lines indicate toe-off. Dashed lines are CRP angles. Solid lines are plus or minus one between-stride standard deviation. Note the relatively lower variability in the ITBS subject in thigh AD/AB–tibia IR/ER, thigh AD/AB–foot IN/EV, and tibia IR/ER–foot IN/EV.
Figure 3 shows VCRP in couplings over the complete stride cycle. Compared with the control group, runners with a history of ITBS were more variable in knee FL/EX–foot AD/AB at the start of the run (18.6° for ITBS vs. 15.3° for control, \( p = .02 \)), less variable in thigh AD/AB–foot IN/EV at the end of the run (30.5° for ITBS vs. 33.1° for control, \( p = .03 \)), and tended to be less variable in thigh AD/AB–tibia IR/ER at the end of the run (31.4° for ITBS vs. 33.5° for control, \( p = .09 \)). VCRP in other couplings were not significantly different.

Table 1 summarizes the group differences in VCRP at heel strike. Among the five couplings analyzed, runners with a history of ITBS were less variable than controls in four couplings at the start and four couplings at the end of the run. Most of the differences were not significant due to large intersubject variance; however, the ITBS group was significantly less variable in thigh AD/AB–tibia IR/ER at the start of the run (13.3° for ITBS vs. 24.2° for control, \( p = .004 \)) and showed a trend to be less variable in thigh AD/AB–tibia IR/ER at the end of the run (19.3° for ITBS vs. 24.0° for control, \( p = .09 \)).

**Discussion**

In this study, lower extremity coordination variability assessed by continuous relative phase (CRP) in runners with a history of iliotibial band syndrome (ITBS) differed from age-matched control runners during a run to voluntary exhaustion, but only in particular segmental couplings and only at certain times during the run. Over the full stride cycle and during swing, the ITBS group was less variable in couplings between thigh AD/AB–foot IN/EV and thigh AD/AB–tibia IR/ER, although the only...
Figure 4 — CRP variability (VCRP) during swing. Data are for the start, middle, and end of the run. Circles are the ITBS group. Squares are the control group. † indicates a trend toward a difference in group means (p < .10).

Figure 5 — CRP variability (VCRP) during stance. Data are for the start, middle, and end of the run. Circles are the ITBS group. Squares are the control group. * indicates a significant difference in group means (p < .05).
between these segments. Stressing the ITB through a repetitive phasic relationship rotation, in conjunction with a lack of variability in tibia injured (Noehren et al., 2007). Greater peak knee internal rotation than runners who did not become runners who developed ITBS demonstrated greater peak knee internal rotation than controls (McClay & Manal, 1997). In a prospective study, increasing soft tissue strain at the knee (Bates et al., 1978; McClay & Manal, 1997). Excessive eversion is suspected to lead to excessive knee internal linked due to the anatomy of the ankle joint. Excessive heel strike. Tibia IR/ER and foot IN/EV are mechanically abnormal phasic relationship between these segments at the start of the run (Figure 3b), and showed a trend to be less variable in thigh AD/AB–tibia IR/ER at the end of the run, but not at the start of the run (Figure 3a). We hypothesize that these differences may be compensatory mechanisms used to avoid painful coordination patterns, or patterns that were painful in the past.

The findings of less variability in selected couplings for the retrospective ITBS group during the full stride cycle and during swing are similar to the results of previous studies on VCRP in injured runners (Hamill et al., 1999). The finding of less variability at heel strike in the injured group is also consistent with Hamill et al. (1999) and Heiderscheit et al. (2002), although their subjects were runners with PFP who were currently symptomatic. At heel strike, variability in tibia IR/ER–foot IN/EV was particularly low for runners with a history of ITBS. Although we cannot infer a direct relationship between the temporal synchrony of tibia IR/ER and foot IN/EV from this result, the lack of variability indicates an abnormal phasic relationship between these segments at heel strike. Tibia IR/ER and foot IN/EV are mechanically linked due to the anatomy of the ankle joint. Excessive inversion is suspected to lead to excessive knee internal rotation by internally rotating the tibia, potentially increasing soft tissue strain at the knee (Bates et al., 1978; McClay & Manal, 1997). In a prospective study, runners who developed ITBS demonstrated greater peak knee internal rotation than runners who did not become injured (Noehren et al., 2007). Greater peak knee internal rotation, in conjunction with a lack of variability in tibia IR–foot IN/EV coupling, could accumulate trauma by stressing the ITB through a repetitive phasic relationship between these segments.

Although couplings between other kinematics not considered in this study may also be significant discriminators between groups, couplings must be chosen by a rationale that relates to the functional mechanics of the system. For this study, couplings between kinematics that have been associated with ITBS (knee flexion, thigh adduction, rearfoot motion, tibia internal rotation; Miller et al., 2007; Noehren et al., 2007) were assessed. Along with lower tibia IR/ER–foot IN/EV variability at heel strike compared with controls, runners with a history of ITBS demonstrated lower thigh AD/AB–foot IN/EV variability during the full stride cycle at the end of the run (Figure 3), greater knee AD/AB–foot IN/EV variability at heel-strike at the start of the run, but lower knee AD/AB–foot IN/EV variability at heel-strike at the end of the run (Table 1). Thigh AD/AB–foot IN/EV and knee AD/AB–foot IN/EV are notable because both motions occur in the frontal plane, and could act to increase lateral compression of the ITB as proposed by Fairclough et al. (2006).

This study assessed five different kinematic couplings, but found significant differences only in some couplings. One possible explanation is that these couplings play different roles in the loading of the iliotibial tract. Functionally, the ITB stabilizes the lateral hip and resists hip adduction. At the end of the run, runners with a history of ITBS were less variable in thigh AD/AB–foot IN/EV (Figure 3b) and tended to be less variable in thigh AD/AB–tibia IR/ER (Figure 3a). Recent studies have suggested that abnormal hip muscle function (Fairclough et al., 2007) and weak hip abductors (Fredericson et al., 2000) are etiological factors in ITBS. Low variability in couplings involving thigh AD/AB could indicate dysfunctional hip abductors. Further research on hip muscle mechanics in healthy and pathological running is needed.

We hypothesized that runners with a history of ITBS would decrease VCRP between the start and end of the run. Statistical analysis indicated that neither group significantly changed VCRP in any coupling between the start and end of the run. There were also no interactions between group and time, indicating that time did not have a differential effect on VCRP between the groups. These findings suggest that fatigue did not have a large,

### Table 1: Group Differences in CRP Variability at Heel Strike

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Start of run</th>
<th>End of run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh AD/AB–tibia IR/ER</td>
<td>19.3 (8.7)</td>
<td>19.3 (10.3)</td>
</tr>
<tr>
<td>Thigh AD/AB–foot IN/EV</td>
<td>22.5 (7.0)</td>
<td>23.0 (11.9)</td>
</tr>
<tr>
<td>Tibia IR/ER–foot IN/EV</td>
<td>13.3 (8.2)*</td>
<td>20.2 (12.2)</td>
</tr>
<tr>
<td>Knee FL/EX–foot AD/AB</td>
<td>13.8 (6.7)</td>
<td>16.9 (10.4)</td>
</tr>
<tr>
<td>Knee AD/AB–foot IN/EV</td>
<td>22.9 (9.2)</td>
<td>24.5 (16.6)</td>
</tr>
</tbody>
</table>

**Note.** Values are means for all subjects in the group. * indicates significantly less variable than control (p < .05). † indicates a trend to be less variable than control (p < .10). Negative differences (Diff) indicate that the ITBS group’s average variability was smaller than the control group’s average variability. Units are in degrees.
consistent effect on variability in the five couplings analyzed. Previously, the runners with a history of ITBS demonstrated kinematic adjustments between the start and end of the run (increased knee flexion at heel strike, increased maximum foot inversion, increased maximum foot adduction) that may increase strain in the ITB (Miller et al., 2007). These combined findings suggest that the body can adjust the kinematics of individual joints and segments (possibly to attenuate impacts or reduce injury risks) without altering lower extremity coordination patterns. At this stage, the dynamical systems approach to running injury etiology is still relatively new, and the kinematic adjustments in individual segments during the run are probably more clinically meaningful than the lack of fatigue-induced changes in VCRP. More studies are needed to improve our understanding of the lower extremity as a dynamical system in healthy and pathological running.

An important question arises in regards to the present results: what are the physiological consequences of variability on running coordination, tissue trauma, and pathological states? Hamill et al. (1999) proposed that a lack of variability indicates a narrow range of relative segment actions that allow for pain-free running in runners with PFP. Low segmental coordination variability in couplings involving thigh AD/AB could limit the range of coordination patterns the runners with a history of ITBS used to successfully complete the movement, and could repeatedly stress the ITB through hip adduction as proposed by Noehren et al. (2007). In a previous study on the same group of runners, the runners with a history of ITBS demonstrated more strain than controls in a musculoskeletal model of the ITB (Miller et al., 2007). Unpublished results indicate similar findings in a prospective study of runners who developed ITBS (Hamill et al., 2007). Therefore, we propose that the ITBS group’s low variability in thigh AD/AB couplings limits the range of coordination patterns they use to successfully complete the movement task. Consequently, these runners performed repetitive segmental motion patterns that continually stressed the ITB, leading to pain and injury over time.

Runners with a history of ITBS were more variable in knee FL/EX–foot AD/AB during both stance and swing. Excessive variability in knee FL/EX–foot AD/AB may indicate a lack of stability in this coupling, both during weight-bearing (stance) and during recovery from and preparation for weight-bearing and impact (swing). In this context, the term stability must be used cautiously because the variability and stability of a dynamical system are not necessarily synonymous (Li et al., 2005). Messier et al. (1995) found that the knee extensors of runners with ITBS were weaker than healthy runners. In conjunction with the thigh AD/AB coupling results, these findings suggest three conclusions:

1. Muscular strength may play a role in VCRP.
2. A lack of coordinative flexibility (low variability) and a lack of consistent coupling control (high variability) should both be considered when investigating running injuries with a dynamical systems approach.
3. The swing phase should not be neglected when investigating running injuries.

The first conclusion is made cautiously because strength was not assessed for these particular runners. The second conclusion highlights the importance of careful data interpretation. Even if low variability is deemed “bad,” high variability is not necessarily “good.” Within any system, there is likely a midlevel of variability at which it performs optimally.

It is notable that in present study, as well as previous studies, pathological runners have failed to show less variability than the healthy group in couplings during the stance phase (Hamill et al., 1999; Heiderscheit et al., 2002). These findings seem counterintuitive to the theory that low variability is related to repetitive tissue stress. If pathological runners use a narrow range of coordination patterns that repeatedly stress the same tissues, they should be less variable during stance, when the actual pain and heavy tissue stress occurs for injuries such as ITBS and PFP. It is possible during recovery from their injuries (recall that the runners in the ITBS group were previously injured but symptom free during data collection), the ITBS group learned to select new coordination patterns that allowed pain-free running, leading to an increase in stance-phase variability. Low variability during swing in the runners with a history of ITBS may be an artifact of their earlier injured states that has remained due to the lack of weight bearing and lack of ITB pain during swing. However, runners currently experiencing PFP showed similar trends in variability (Hamill et al., 1999), and three of the eight runners in the ITBS group have experienced recurrent symptoms since data collection in late 2005/early 2006 (personal interviews). In any case, because variability in the runners with a history of ITBS may have been different before and after the injury, the present results cannot definitively confirm a causal or compensational role for variability in ITBS. Prospective studies observing variability before, during, and after recovery from injury would contribute significantly to our understanding of the interaction between variability, pain, and running injuries.

Although the statistical analysis accounted for running speed as a covariate, it could be argued that the study was limited by allowing subjects to run at self-selected paces and not a standardized pace. Although the group running times were statistically similar, the ITBS group tended to run slower. Since ITBS is an overuse injury likely developed during training, the decision to allow self-selected paces was made to better capture the runners’ normal training kinematics and coordination patterns.

In summary, during an exhaustive run, runners with a history of ITBS demonstrated less CRP variability than controls in thigh AD/AB–foot IN/EV, but were more variable in knee FL/EX–foot AD/AB. The same runners...
previously demonstrated more strain in a model of the iliotibial band. The results indicate that a history of ITBS is associated with altered variability in coupled segmental motions related to the injury, and suggest that variability in injury-prone runners may be indicative of abnormal segmental coordination patterns and the potential for repetitive tissue stress.

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References


