Influence of Custom Foot Orthotic Intervention on Lower Extremity Intralimb Coupling During a 30-Minute Run

Christopher L. MacLean, Richard van Emmerik, and Joseph Hamill

The purpose of this study was to analyze the influence of a custom foot orthotic (CFO) intervention on lower extremity intralimb coupling during a 30-min run in a group of injured runners and to compare the results to a control group of healthy runners. Three-dimensional kinematic data were collected during a 30-min run on healthy female runners (Shoe-only) and a group of female runners who had a recent history of overuse injury (Shoe-only and Shoe with custom foot orthoses). Results from the study revealed that the coordination variability and pattern for the some couplings were influenced by history of injury, foot orthotic intervention and the duration of the run. These data suggest that custom foot orthoses worn by injured runners may play a role in the maintenance of coordination variability of the tibia (transverse plane) and calcaneus (frontal plane) coupling during the Early Stance phase. In addition, it appears that the coupling angle between the knee (transverse plane) and rearfoot (frontal plane) joints becomes more symmetrical in the late stance phase as a run progresses.

Keywords: kinematics, coordination variability, foot orthoses, running

Lower extremity coordination has been of interest to movement scientists studying mechanism of running injury for many years (Bates et al., 1979). In vivo, coordination (defined as intersegmental coupling) has been analyzed by a number of discrete methods including the analysis of the relative timing of discrete events during the stance phase (McClay & Manal, 1997) and by evaluating the coupling coefficient (Nigg et al., 1993). The coupling coefficient has been defined as the ratio of calcaneal eversion excursion to tibial internal rotation excursion from heel strike to their respective maxima (Nigg et al., 1993; McClay & Manal, 1997). More recently, methods have been employed to analyze the coordination patterns and variability through continuous relative phase (Hamill et al., 1999) and vector-coding techniques (Heiderscheit et al., 2002; Pollard et al., 2005; Ferber et al., 2005). Specific to foot and ankle coordination, the effects of shoe characteristics (Hamill et al., 1992; Van Woensel & Cavanagh, 1992; Kurz & Stergiou, 2004); arch height (Nigg et al., 1993; Nawoczenski et al., 1998); varying running speed, stride length and obstacle height (Stergiou et al., 1999, 2003); and degree of pronation (McClay & Manal, 1997) have been investigated.

Bates and colleagues (1979) suggested that healthy running dynamics may involve a synchrony between subtalar joint, tibial and knee angular rotations. The authors suggested that a decoupling of this mechanism precipitated by either the subtalar joint reaching maximum pronation prematurely before midstance or following midstance may be deleterious. Several studies have investigated the influence of shoe construction on lower extremity coupling. Hamill et al. (1992) and Van Woensel and Cavanagh (1992) both evaluated the relative timing of maximum rearfoot eversion and maximum knee flexion events. Hamill et al. (1992) reported that a soft midsole running shoe intervention led to a decoupling of rearfoot eversion and knee flexion, and described this as potentially being a series of antagonistic counter rotations. Similarly, Van Woensel and Cavanagh (1992) reported that lower extremity coupling could be altered with varus and valgus posted running shoes.

Of particular interest to the current study is the effect of a custom foot orthotic intervention on the coupling characteristics of the lower extremity. Nawoczenski et al. (1995) analyzed the influence of custom foot orthotic intervention on the coupling coefficient in a group of high and a group of low arched subjects. These authors reported that the ratio significantly increased when the intervention was worn by subjects in both groups. It should be noted that Nawoczenski et al. (1995) defined
the coupling coefficient as the tibial adduction excursion relative to the tibial internal rotation excursion.

Ferber et al. (2005) analyzed coordination patterns and variability in a group of runners who had been treated with custom foot orthotic therapy. These authors primarily focused on the coupling of rearfoot frontal plane rotation with tibial transverse plane motion. The authors reported that there were no significant differences between the groups for the Shod condition and no significant differences when comparing orthotic conditions in the Treatment group. Thus, the authors concluded that the pattern and variability of coordination for the tibial rotation (transverse plane) relative to the calcaneus rotation (frontal plane) coupling were not different between groups or between orthotic conditions within the injured runner group.

In human locomotion studies, increased movement variability has been viewed as detrimental (Hausdorff et al., 1997) and beneficial (Holt et al., 1995; Hamill et al., 1999; Van Emmerik & Van Wegen, 2000). It has been suggested that increased coordination variability may be beneficial and essential during locomotion to provide flexibility to perturbations and uncertain environments (Holt et al., 1995), and facilitate changes in coordination patterns (Van Emmerik & Van Wegen, 2000). Several researchers have compared intralimb coordination variability in a group of healthy subjects and a group of subjects with patellofemoral pain syndrome (Hamill et al., 1999; Heiderscheit et al., 2002) and iliotibial band syndrome (Miller et al., 2008).

The studies on patellofemoral pain syndrome revealed significant decreases in coordination variability for some of the couplings of interest when injured subjects were compared with a group of healthy controls. In light of this, Hamill et al. (1999) suggested that a reduction in coordination variability may be an indication of a greater repeatability of action between joint and segment couplings that eventually could lead to constant stress to biological tissues and eventual overuse injury. More recently, Miller et al. (2008) investigated the role of coordination variability over the course of an exhaustive run in runners with a history of iliotibial band syndrome and a group of healthy runners. These authors reported that the runners with a history of injury exhibited significantly lesser coordination variability than controls for a number of the couplings. What remains unclear is whether a decrease in coordination variability is the cause of injury or representative of an injury state.

With this in mind and given that custom foot orthotic therapy is often a clinical intervention for these and other overuse running injuries, we were interested to investigate what, if any, role custom foot orthoses play in influencing coordination variability over the course of a 30-min run. Therefore, the purpose of the current study was to analyze the influence of a custom foot orthotic intervention on lower extremity intralimb coupling during a 30-min run in a group of runners with an overuse knee injury (Injured group) and to compare the results to a group of healthy runners (Control group). It was hypothesized that coordination variability would be increased by custom foot orthotic intervention in the Injured group, that coordination variability would be decreased in the Injured group compared with the Control group when running in the shoe-only (Shod) condition, that there would be no significant differences between the coordination variability when comparing the Injured group in the custom foot orthotic condition to the Control group in the Shod condition, and that coordination pattern (phase angles) would be significantly different between groups and conditions and throughout the course of the run.

Methods

Subject Selection

An a priori sample size prediction was performed using SAS v.8.2 and data from the literature (Heiderscheit et al., 2002). A sample size of nine subjects per group was estimated for a minimal statistical power $\geq 0.80$ and $\alpha = 0.05$. This study included two groups: (1) a Control group ($n = 9$) of healthy female runners who had not sustained an overuse running injury in the 6 months leading up to the study and (2) an Injured group ($n = 9$) of female runners that had sustained an overuse knee running injury in the 6 months leading up to the study. The Injured group had worn a custom foot orthotic intervention for all running activities in the six weeks leading up to the study. All Injured group subjects were diagnosed by a sports medicine physician (University Health Services, University of Massachusetts–Amherst) with either iliotibial band friction syndrome or patellofemoral pain syndrome in the 6 months leading up to the custom foot orthotic intervention. Approval for the participation of human subjects in this investigation was obtained from the University Human Subjects Review Committee.

Experimental Setup

Three-dimensional kinematic data were collected using an eight-camera Qualisys QTM system (Qualisys, Inc., Gothenburg, Sweden). A right-handed global coordinate system (GCS) was employed with the origin of the GCS positioned on the treadmill. The right-handed, GCS was oriented so that the $z$-axis was vertical, the $y$-axis was in the anteroposterior direction and in the direction of motion, and the $x$-axis was in the mediolateral direction.

The sampling frequency for all running trials was 240 Hz. The cameras were interfaced to a microcomputer and positioned around the treadmill. The treadmill was positioned over an embedded AMTI force platform (600 mm $\times$ 900 mm) so that heel strike and toe-off could be identified. Signals from the force platform were interfaced with a microcomputer and synchronized with the kinematic data.

Protocol

Before data collection, markers were positioned on each subject. These markers included both calibration and
tracking markers. Calibration markers were positioned on the left and right greater trochanters, right-side medial and lateral femoral condyles, right-side medial and lateral maleoli, and the 1st and 5th metatarsal heads. Tracking markers were securely positioned to define the pelvis (L5/S1 joint line, ASIS, iliac crest), thigh (rigid array of four markers), leg (rigid array of four markers) and calcaneus (rigid array of three markers). Calibration markers were left on for the initial stance trial and then removed. The tracking markers remained in position for all running trials. Following the calibration stance trial, each subject performed a 30-min treadmill run at a treadmill velocity of 3.0 m·s⁻¹ (± 5%). It was felt that a run duration of 30 min was a better indication of what occurs ecologically.

The Injured group performed the 30-min run once with custom foot orthoses (CFO) and once without (Shod). All testing sessions were performed in Bite OS Xtension running sandals (Bite Shoes, Redmond, WA). This particular running sandal has a removable manufacturer insole which allowed for skin mounted marker placement directly on the calcaneus. The order of the CFO and Shod conditions was randomly assigned for each subject. Testing sessions were separated by 2–4 days to allow for rest. The Control group performed the run only one time for the Shod condition. Kinematic data were collected for 10-s intervals, at 0, 15 and 30 min of the run. The custom foot orthotic design was a semirigid, functional foot orthosis with a thermoplastic (3 mm copolymer or polypropylene) orthotic shell. Thermoplastic orthotic shells were vacuum pressed and finished at Paris Orthotics Laboratory. Orthotic shell material selections were based on subject body weight. The device was intrinsically posted to calcaneal vertical and inverted an additional 5 degrees. Personalizing each device to meet the specific needs of the subject was accomplished by adjusting orthotic shell material thickness based on body weight and posting to calcaneal vertical. Posting methods employed by various health care professionals can vary substantially so a laboratory standard approach was taken. Foot orthoses also included an extrinsic ethyl vinyl acetate rearfoot stabilizer with nylon strike plate. The heel cup depth was 18 mm and a minimum cast dressing was used. Lastly, a full-length, Microcel Puff top cover was added for additional cushioning. Following the 30-min run, each subject was asked to complete a Visual Analog Scale (Mundermann et al., 2002) to ensure that the run was executed, pain-free. During the 30-min run, there were no changes in Visual Analog Scale scores for any of the subjects or conditions.

**Data Reduction**

Kinematic data for the stance phase of each treadmill running trial were digitized using QTM software (Qualisys, Inc., Gothenburg, Sweden). Synchronized raw kinematic and vertical force platform signals were processed using Visual 3D software (C-Motion, Inc., Rockville, MD). Raw kinematic data were low-pass filtered using a fourth order, zero lag Butterworth digital filter with a cut-off frequency of 12 Hz. Right-handed local coordinate systems for the pelvis, thigh, leg and foot were calculated.

Three-dimensional segment and joint angles were calculated during the stance phase, which was identified by heel strike and toe-off from the vertical force platform signal. Joint kinematic data are reported about anatomically oriented axes. Three-dimensional segment and joint angles were calculated using an x (flexion/extension) – y (abduction/adduction) – z (longitudinal rotation) Cardan rotation sequence (Cole et al., 1993). Joint angles are reported as movement of the distal segment relative to the proximal segment. Segment angles are reported relative to the laboratory coordinate system. Kinematic data were interpolated to 101 data points, with each data point representing 1% of the stance phase.

The intralimb couplings that were investigated included the (1) tibia (transverse plane) and calcaneus (frontal plane) (TibTP/CalFP), (2) knee (sagittal plane) and rearfoot (frontal plane) (KnTP/RFFP), (3) knee (frontal plane) and rearfoot (frontal plane) (KnTP/RFFP), and (4) knee (transverse plane) and rearfoot (frontal plane) (KnTP/FlPP). These couplings were included because the coupling between the foot and tibia has been implicated in the mechanism underlying patellofemoral pain (Heiderscheit et al., 2002). Relative motion plots were created for each of the intralimb couplings of interest. In the plots, the proximal joint or segment angle was positioned on the horizontal axis (abscissa) and the distal joint or segment on the vertical axis (ordinate).

A modified vector coding technique, employed by Sparrow et al. (1987) and Heiderscheit et al. (2002), was used to quantify coupling between the segments or joints of interest. The phase or coupling angle is a modality that quantifies the pattern of coupling or coordination throughout the stance phase (Hamill et al., 2000). The phase angle was calculated as

$$\gamma_i = \arctan(\frac{(y_i - y_{i+1})}{(x_i + 1 - x_i)})$$

where $i$ is the percent stance (1, 2, ..., $n$), and $x$ and $y$ are the vector coordinates for each respective data point on the relative motion plot.

The resulting phase angle was converted from radians to degrees. Converted phase angles ranged from 0° to 360° and the interpretation of the phase angle ($\gamma$) is as follows (Hamill et al., 2000):

- 0°, 90°, 180°, or 270°: indicates movement of one joint or segment
- 0° or 180°: indicates movement of proximal segment or joint, distal segment or joint is fixed
- 90° or 270°: indicates movement of the distal segment or joint, proximal segment or joint is fixed
- 45° or 225°: indicates equal relative movement of both segments or joints in the same direction
- 135° or 315°: indicates equal relative motions but in opposite directions
The phase angle is directional and thus the between trial mean values and standard deviations were calculated using circular statistics (Batschelet, 1981, Hamill et al., 2000). The mean direction of the vector (coordinates \((\bar{x}, \bar{y})\) of the vector) for each instant in time during the movement sequence is determined by calculating the mean cosine and sine of each directional component of the phase angle (\(\gamma\)):

\[
\bar{x} = 1 / n \sum (\cos \gamma_i)
\]
\[
\bar{y} = 1 / n \sum (\sin \gamma_i)
\]

The mean direction of \(\gamma\) is then calculated:

If \(\bar{y} > 0\), \(\gamma = \arctan (\bar{y} / \bar{x})\)

If \(\bar{y} > 0\), \(\gamma = 180 + \arctan (\bar{y} / \bar{x})\)

The second measure of interest is the coordination variability. The measure for coordination variability used by Heiderscheit et al. (2002) is the standard deviation of the vector magnitude and is calculated as

\[
s^2 = 2(1-r)
\]

where \(s^2\) is coordination variability (in degrees) and

\[
r = (\bar{x}^2 + \bar{y}^2)^{1/2}
\]

In a method similar to that employed by Hamill et al. (1999), each of the intralimb couplings were analyzed across the entire stance phase (0–100%) and with the stance phase partitioned into three phases: Early Stance (0–20%), Mid Stance (21–60%), and Late Stance (61–100%). This method was employed to ensure a more symmetrical manner or in phase as the duration progressed, indicating that the joints were functioning in a more symmetrical manner or in phase as the duration of the run increased.

**Results**

**Treatment Group (Shod vs. CFO Condition)**

For the TibTP/CalFP coordination variability, there was a significant Condition \(\times\) Time interaction \((p = .001; ES = 0.58)\) during the early stance phase (Table 1; Figure 1). Coordination variability significantly decreased throughout the course of the run when the Injured Group performed in the Shod condition \((p = .01; ES = 0.42)\) but went unchanged while running in the CFO condition \((p = .30; ES = 0.14)\).

For the KnTP/RFP coupling, there were significant Condition \(\times\) Time interactions for the coordination variability during early stance \((p = .02; ES = 0.40)\) and throughout the entire stance phase \((p = .001; ES = 0.56)\). During the early stance phase, the coordination variability for the KnTP/RFP coupling was significantly decreased for the Shod condition \((p = .02; ES = 0.36)\) throughout the course of the run. Conversely, coordination variability did not change significantly throughout the course of the run for the CFO condition.

Lastly, phase angle analyses revealed that there was a significant Time main effect during the late stance phase for the KnTP/RFP \((p = .009; ES = 0.44)\) intralimb coupling. Phase angles were closer to 45° as the run progressed, indicating that the joints were functioning in a more symmetrical manner or in phase as the duration of the run increased.

**Control Group (Shod Condition) vs. Treatment Group (Shod Condition)**

For the TibTP/CalFP coupling variability, there was a significant Group \(\times\) Time interaction \((p = .004; ES = 0.30)\).

**Table 1** Coordination variability (degrees) means and SDs for the TibTP/CalFP coupling

<table>
<thead>
<tr>
<th>Coupling (Phase)</th>
<th>0 min</th>
<th>15 min</th>
<th>30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>TibTP/CalFP (AS)</td>
<td>TGS 22.07 ± 5.23</td>
<td>19.18 ± 4.71</td>
<td>17.56 ± 4.00</td>
</tr>
<tr>
<td></td>
<td>TGO 19.44 ± 4.78</td>
<td>20.62 ± 5.10</td>
<td>20.02 ± 4.74</td>
</tr>
<tr>
<td>TibTP/CalFP (ES)</td>
<td>TGS 27.70 ± 9.81</td>
<td>19.84 ± 5.54</td>
<td>16.72 ± 6.26</td>
</tr>
<tr>
<td></td>
<td>TGO 19.66 ± 7.96</td>
<td>21.84 ± 4.01</td>
<td>24.56 ± 10.55</td>
</tr>
<tr>
<td>TibTP/CalFP (MS)</td>
<td>TGS 23.63 ± 5.64</td>
<td>21.55 ± 5.63</td>
<td>20.07 ± 5.22</td>
</tr>
<tr>
<td></td>
<td>TGO 22.49 ± 5.20</td>
<td>24.28 ± 9.32</td>
<td>23.02 ± 6.23</td>
</tr>
</tbody>
</table>

*Note. TGS, Treatment Group shoe-only condition; TGO, Treatment Group shoe + custom foot orthotic condition; AS, entire stance phase; ES, early stance phase; MS, midstance phase; LS, late stance phase.*
Figure 1 — Condition means for the Tib\textsubscript{TP}/Cal\textsubscript{TP} coupling coordination variability (CV) for the Treatment Group at 0 (A), 15 (B) and 30 (C) of the run. The two conditions are the Shod (thin line) and CFO (thick line) conditions measured during the Early Stance phase.

A) Treatment Group: CFO vs Shod
Condition Comparison at 0-min

B) Treatment Group: CFO vs Shod
Condition Comparison at 15-min

C) Treatment Group: CFO vs Shod
Condition Comparison at 30-min

Figure 2 — Ensemble average of the Tib\textsubscript{TP}/Cal\textsubscript{TP} coupling coordination variability (CV) for the Treatment Group at 0 (A), 15 (B) and 30 (C) of the run. The two conditions are the Shod (thin line) and CFO (thick line) conditions measured across the stance phase.
during the early stance phase (Table 2; Figure 3 and 4). Coordination variability remained unchanged throughout the run for the Control group ($p = .08; ES = 0.27$) while it significantly decreased as the run progressed in the Injured group ($p = .01; ES = 0.42$). There were no other significant interactions or main effects revealed for any of the other intralimb couplings.

The phase angles for the knee and rearfoot couplings were influenced by the 30-min run. For the KnTP/RFP coupling, there was a significant Time main effect ($p < .001; ES = 0.45$) for the late stance phase. The phase angles approached 45° as the run progressed indicating that the knee and rearfoot rotations became increasingly symmetrical as the duration of the 30-min run increased.

### Control Group (Shod Condition) vs. Treatment Group (CFO Condition)

There were no significant interactions or main effects for the TibTP/CalFP or KnTP/RFP couplings for coordination variability (shown later in Figure 5) or phase angle variables. However, there was a significant Time main effect ($p = .01; ES = 0.25$) throughout the entire stance phase for the KnTP/RFP coordination variability. Coordination variability was significantly increased as the run progressed.

Lastly, analysis of the phase angles for the KnTP/RFP coupling revealed significant Time main effect during the late stance phase ($p < .001; ES = 0.49$) and throughout the entire stance phase ($p < .001; ES = 0.38$). Once again, phase angles became closer to 45° (increased symmetry) as the run progressed.

### Discussion

The purpose of the current study was to determine the influence of a CFO intervention on the intralimb coordination patterns and coordination variability during a 30-min run. A Visual Analog Scale was used to ensure that runners were able to perform the 30-min run, pain-free. The first hypothesis predicted that coordination variability exhibited by the Injured group would be significantly greater for the CFO condition compared with the Shod condition. This hypothesis was not completely supported. Interestingly, for the TibTP/CalFP (Figures 1 and 2) and KnTP/RFP couplings during the early stance phase, as the duration of the run increased coordination variability remained unchanged throughout the run in

### Table 2 Coordination variability (degrees) means and SDs for the TibTP/CalFP coupling

<table>
<thead>
<tr>
<th>Coupling (Phase)</th>
<th>0 min</th>
<th>15 min</th>
<th>30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>TibTP/CalFP (AS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGS</td>
<td>22.07 ± 5.23</td>
<td>19.18 ± 4.71</td>
<td>17.56 ± 4.00</td>
</tr>
<tr>
<td>CGS</td>
<td>17.77 ± 5.81</td>
<td>19.99 ± 2.98</td>
<td>19.55 ± 4.07</td>
</tr>
<tr>
<td>TibTP/CalFP (ES)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGS</td>
<td>27.70 ± 9.81</td>
<td>19.84 ± 5.54</td>
<td>16.72 ± 6.26</td>
</tr>
<tr>
<td>CGS</td>
<td>17.39 ± 6.52</td>
<td>16.19 ± 5.97</td>
<td>20.13 ± 9.56</td>
</tr>
<tr>
<td>TibTP/CalFP (MS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGS</td>
<td>23.63 ± 5.64</td>
<td>21.55 ± 5.63</td>
<td>20.07 ± 5.22</td>
</tr>
<tr>
<td>CGS</td>
<td>23.04 ± 4.92</td>
<td>25.77 ± 6.89</td>
<td>22.93 ± 4.54</td>
</tr>
<tr>
<td>TibTP/CalFP (LS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGS</td>
<td>17.70 ± 6.81</td>
<td>16.49 ± 6.21</td>
<td>15.48 ± 4.83</td>
</tr>
<tr>
<td>CGS</td>
<td>12.69 ± 5.33</td>
<td>16.11 ± 5.34</td>
<td>15.89 ± 6.67</td>
</tr>
</tbody>
</table>

Note. TGS, Treatment Group shoe-only condition; CGS, Control Group shoe-only condition; min, minutes; AS, entire stance phase; ES, early stance phase; MS, midstance phase; LS, late stance phase.

Figure 3 — Group means for the TibTP/CalFP coupling coordination variability (CV) during the Early Stance phase when subjects wore the Shod condition. The thin line represents the Control group while the thick line represents the Treatment Group.
the CFO condition. Conversely, while running in the Shod condition, coordination variability significantly decreased. There were no significant findings for any of the other couplings.

It has been suggested that increased coordination variability may be essential during locomotion to (1) provide flexibility to perturbations and uncertain environments (Holt et al., 1995) and (2) facilitate changes in coordination patterns (Van Emmerik & Van Wegen, 2000). Regarding flexibility or adaptability of a system, flexibility is defined as the ability to use all degrees of freedom to perform a task.

With this in mind, it is plausible that a custom foot orthotic intervention plays a role in maintaining coordination variability for the Tib\textsubscript{TP}/Cal\textsubscript{FP} coupling during the early stance phase. While running in the Shod condition, coordination variability significantly decreased in the injured runners, which may indicate that the flexibility of the system becomes compromised during the early stance phase. In this phase, several important dynamic events occur including the following: maximum impact peak, maximum loading rate, and maximum rearfoot eversion velocity. Thus, it is possible that foot orthoses help to maintain a level of flexibility during early stance over the course of a 30-min run. When the Injured group performed the 30-min run in the Shod condition, there was a significant decrease in coordination variability as the run progressed.

**Figure 4** — Ensemble average of the Tib\textsubscript{TP}/Cal\textsubscript{FP} coupling coordination variability (CV) at 0 (A), 15 (B) and 30 (C) minutes of the run. The Control Group Shod Condition (thin line) and Treatment Group Shod Condition (thick line) conditions are represented across the stance phase.
The second hypothesis was aimed to determine if the Injured and Control groups exhibited any differences in coordination variability through the course of the 30-min run in the Shod condition. It was hypothesized that the Injured group would exhibit significantly decreased coordination variability when compared with the Control group.

For the TibTP/CalFP coupling, there were significant differences in coordination variability exhibited by the groups throughout the course of the 30-min run in the Shod condition (Figures 3 and 4). The significant Group × Time interaction during the early stance phase indicates that the groups responded differently and exhibited different degrees of TibTP/CalFP coupling variability. Throughout the course of the 30-min run, the coordination variability exhibited by the Control group did not significantly change. However, the coordination variability for the Injured group significantly decreased as the run progressed. A post hoc analysis of the coordination variability during the Early Stance phase revealed that the coordination variability exhibited by the Injured group was significantly greater than the Control group (p = .02; ES = 0.23) at the beginning of the run. As the run progressed to completion, the coordination variability during the early stance phase significantly decreased in the Injured group.

Several researchers have compared intralimb coordination variability in a group of healthy subjects and a group of subjects with patellofemoral pain syndrome (Hamill et al., 1999; Heiderscheit et al., 2002) and iliotibial band syndrome (Miller et al., 2008). These authors reported that subjects with patellofemoral pain syndrome and Iliotibial band syndrome exhibited significant decreases in coordination variability for some of the couplings of interest when compared with a group of healthy controls. In light of this, Hamill et al. (1999) suggested that a reduction in coordination variability may be an indication of a greater repeatability of action between joint and segment couplings that eventually could lead to constant stress to biological tissues and eventual overuse injury. In the current study, the Control and Injured groups responded differently when running for 30 min in the Shod condition. It is impossible to conclude whether these differences are an indication of true group differences that may help to explain a causal factor or a clinical manifestation of the injury itself without conducting a prospective study. However, there were significant differences between the two groups in the coordination variability of the TibTP/CalFP coupling over the course of the 30-min run.

The third hypothesis was that there would be no significant differences between the Injured group (CFO condition) and Control group (Shod condition) over the course of the 30-min run. The hypothesis was supported for all of the coordination variability variables. Specifically, differences in coordination variability exhibited during the early stance phase between the Injured and Control groups (TibTP/CalFP and KnTP/RFP couplings; Shod Condition) were no longer present (Figure 5). This finding suggests that when the Treatment group wore the CFO intervention, the coordination variability exhibited during the Early Stance phase better resembled that of the healthy Control group.

The final hypothesis involved analyzing whether any phase angle differences were exhibited between groups, between conditions in the Treatment Group and across the 30-min run. Interestingly, significant Time main effects were found for the KnTP/RFP coupling during the Late Stance phase. As the run progressed, the phase angles for the KnTP/RFP coupling approached 45° indicating that the rotations of the rearfoot and knee became increasingly symmetrical. In other words, phase angles of 45° represent a 1:1 coupling between joints or segments. This finding indicates that the coupling of rearfoot inversion and knee external rotation became more synchronous during the Late Stance phase as the run progressed.

The current study revealed interesting findings with regards to the TibTP/CalFP and KnTP/RFP coordination...
variability during the Early Stance phase. This is of particular interest because maxima for rearfoot eversion velocity, impact peak and vertical loading rate occur during the Early Stance phase. These dynamic variables have been associated with overuse running injury mechanism and have been shown to be decreased with custom foot orthotic intervention (MacLean et al., 2006; MacLean et al., 2008). The custom foot orthoses used in the current study consisted of a thermoplastic shell component that extended from the posterior heel to the metatarsal heads (1 cm, proximal). It is plausible that we observe changes with a CFO intervention during the loading phase because this is when the foot is in contact with the orthosis.

When the Injured group (clinical sample) in the current study performed the 30-min run in the Shod condition, TibTP/CalTP coordination variability during the Early Stance phase significantly decreased throughout the course of the run. This was not the case when the subjects wore the CFO intervention. The TibTP/CalTP coordination variability exhibited by the Treatment group (CFO condition) was the same as that exhibited by the Control group (healthy sample) during the Early Stance phase. This finding suggests that custom foot orthoses helped to maintain coordination variability during the early stance phase throughout the course of the run in the injured runners. In addition, when wearing the orthoses, the injured runners exhibited degrees of coordination variability that resembled that of the healthy, control group of runners.

In 2005, Ferber et al. analyzed coordination patterns and variability in a group of runners who had been treated with custom foot orthotic therapy. The authors reported that there were (1) no significant differences between the healthy control and treated runners for the Shod condition and (2) no significant differences when comparing orthotic conditions in the Treatment group. Ferber et al. (2005) collected five acceptable, overground trials whereas the current study used a 30-min run protocol. We were interested in investigating a running protocol that was more ecological. That is, a protocol that better resembles what occurs when an individual typically goes for a run. It may be that certain changes in coordination pattern and variability occur continuously over time. This might partly explain the difference in results between the current study and previous work.

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