SEGMENT COORDINATION RESPONSE TO ALTERATIONS IN FOOTFALL PATTERN

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Abstract
The anatomy of the subtalar joint creates a mechanical link between foot, leg, and knee rotations. A disruption in the coordination of these rotations may predispose a runner to overuse injuries. The purpose of this study was to investigate the change in foot-leg and leg-knee coordination patterns when natural rearfoot and forefoot runners alter their footfall pattern. Foot eversion/inversion, leg internal/external rotation and knee flexion/extension were measured in a group of young, healthy runners defined as either natural rearfoot runners or natural forefoot runners. Both groups ran on a treadmill with a rearfoot running (RFR) and a forefoot running (FFR) pattern for five minutes in each condition. Mean and peak foot inversion/eversion, leg internal/external rotation and knee flexion angles were calculated for each third of the stance phase. A modified vector coding approach assessed the coordination pattern between foot inversion/eversion and leg internal/external rotation (foot-leg) and between leg internal/external rotation and knee flexion (leg-knee). FFR resulted in greater mean foot angles, foot excursion peak inversion in each third of stance as well as greater mean leg angle, peak external rotation and leg range of motion during early stance. RFR resulted in greater peak eversion in each third of stance and greater mean knee angle, peak knee flexion and knee range of motion in early and mid stance. Foot-leg coordination only differed in mean phase angle during mid stance. Leg-knee coordination was different in the frequency of coordination patterns during early and late stance. Despite differences in foot, leg and knee kinematics, the shape of the foot-leg coordination pattern was similar between RFR and FFR but coordination between leg-knee rotations was altered. Neither footfall pattern displayed kinematic nor coordination pattern that suggest one footfall pattern is more optimal at preventing overuse injuries than the other.

Keywords: Vector coding, coordination, phase angles, running, footfall patterns
INTRODUCTION

Despite growing technology and research on running shoes and running associated injuries, injury rates among recreational and competitive runners have not declined (Taunton et al., 2002). Knee pathologies still remain as the most prevalent chronic running injury (van Gent et al., 2007). The timing and magnitude of segment rotations during running have been investigated as possible mechanisms for lower extremity injury particularly to the knee. The relative timing, or coordination, of foot, leg and knee rotations are anatomically and mechanically linked. In the initial phase of support during rearfoot running, sub-talar joint eversion is coupled with both internal tibial rotation and knee joint flexion (Czerniecki, 1988; Kozak et al., 1991; Nuber, 1988). As the knee joint extends during late support, the subtalar joint inverts and the tibia externally rotates. A disruption in the timing between these motions may cause excessive knee joint stress (Bates et al., 1978; Clarke et al., 1984; Hamill et al., 1992; Messier and Pittala, 1988).

There is a growing movement in the running community that suggests switching from a rearfoot running pattern (RFR) to a forefoot running pattern (FFR) may prevent many running injuries. Compared to the RFR pattern, the FFR pattern has been characterized by greater rearfoot inversion at touchdown forcing the rearfoot to rotate through greater eversion excursion with greater excursion velocities (Stackhouse et al., 2004; Williams et al., 2000). Greater eversion excursion has been found to correlate with greater tibial internal rotation excursion; a mechanism that may increase stress to the soft tissue of the knee (McCoy and Manal, 1998). Due to these factors, those who naturally run with a FFR pattern alter the coupling of sub-talar, tibial, and knee rotations. However, it is unknown if this alteration improves or disrupts lower extremity segment coupling (i.e. coordination).

Dynamical systems techniques, such as vector coding, quantify the continuous spatial coordination between segment rotations and may reveal a richer set of kinematic information than more traditional discrete analyses. Therefore, the purpose of this study was to quantify adjustments in leg and foot coordination via a modified vector coding technique in natural rearfoot and forefoot runners. A secondary purpose was to investigate the alterations to lower extremity coordination when runners change from their preferred to the alternate footfall pattern. We hypothesized that differences in foot position during stance between footfall patterns would alter the coordination patterns between the foot, leg and knee.

METHODS

Sample

Sixteen recreational runners participated in this study. Eight were classified as natural RF runners (4 males, 4 females, age = 27±5 yrs, mass = 65.95±9.64 kg, height = 1.70±0.12 m) and eight were classified as natural FF runners (4 males, 4 females, age = 26±7 yrs, mass = 69.97±14.50 kg, height = 1.75±0.08 m). Footfall patterns were defined based on the initial contact of the foot on the ground. Thus, rearfoot running (RFR) was defined as making initial ground contact with the heel while forefoot running (FFR) was defined as landing on the forward section of the foot or toes without the heel making contact with the ground. Subjects were matched for their preferred running speed. All subjects were free of cardiovascular and neurological problems and had not experienced an injury or surgery to the back or lower extremity in the past year. Each subject gave approval for participation in accordance with University IRB policy.

Protocol

Kinematic data were obtained for the right lower extremity of each subject. Three-dimensional (3D) kinematics were recorded with an eight camera Oqus motion capture system (Qualisys, Inc., Gothenberg, Sweden) operating at 200 Hz. Retro-reflective calibration markers were placed on the right and left iliac crest, right and left greater trochanter, medial and lateral femoral condyle, medial and lateral malleoli, and the heads of the first and fifth metatarsal (McCoy and Manal, 1999). Tracking markers included four non-collinear markers secured onto a rigid plate, positioned on the lateral thigh and leg, as well as a rigid plate with three non-collinear markers placed on the posterior calcaneus. Additional tracking markers, secured onto the skin or clothing, included the right and left anterior superior iliac spine and between the 5th lumbar-1st sacral vertebrae.

All subjects wore form-fitting clothing and New Balance RC 550 racing flat (New Balance, Brighton, MA, USA). Subjects ran on a treadmill at their preferred running speed (nRF = 3.02±0.32 m/s, nFF = 3.03±0.34 m/s) for five minutes under two conditions: 1) a RFR pattern; and 2) a FFR pattern. Kinematic data were recorded during the
last minute of each condition. The order of the conditions were randomized and counterbalanced. Subjects were allowed to rest for five minutes before beginning the second condition.

**Data Analysis**

Kinematic data were digitized using Qualisys Track Manager software (Qualisys, Inc., Gothenberg, Sweden) and processed in Visual 3D software (C-Motion, Inc, Rockville, MD, USA). Raw kinematic data were filtered with a 4\(^{th}\) order, zero-lag Butterworth digital low-pass filter with a cutoff frequency of 12 Hz.

Calibration markers were used to determine segment local coordinate systems, segment origins, segment length, and joint center locations. The long axes of the thigh and leg were defined as the distance between the proximal and distal joint centers. The long axis of the foot was defined as the distance between the ankle joint center and the center of the metatarsal calibration markers. Three-dimensional segment angles were calculated by a rotation matrix of the distal segment with respect to the proximal segment using a Cardan rotation sequence of \(x\) (flexion/extension) – \(y\) (abduction/adduction) – \(z\) (axial rotation) (Cole et al., 1993). Lower extremity segment angles were referenced to the lab coordinate system and knee joint angle was referenced to the thigh. Angle excursion, mean angle and peak angles for each third of stance were calculated for the foot, leg and knee. Data from initial contact with the treadmill to toe-off of the right leg were interpolated to 101 data points, with each point representing 1% of the stance phase.

A modified vector coding approach was used to determine the segment couplings of: 1) foot-leg: foot inversion/eversion (INV/EV) and leg internal/external rotation (IR/ER); and 2) leg-knee: and leg IR/ER and knee flexion/extension (FL/EX). Phase angles \(\gamma\) were derived by a vector drawn between two adjacent time points on an angle-angle plot for each segment coupling (Hamill et al., 2000; Heidersche et al., 2002; Sparrow et al., 1987).

<table>
<thead>
<tr>
<th>Coordination Pattern</th>
<th>Coupling Angle Definition</th>
</tr>
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<tbody>
<tr>
<td>Anti-phase (i)</td>
<td>(112.5^0 \leq \gamma &lt; 157.5^0; 292.5^0 \leq \gamma &lt; 337.5^0)</td>
</tr>
<tr>
<td>In-phase (ii)</td>
<td>(22.5^0 \leq \gamma &lt; 67.5^0; 202.5^0 \leq \gamma &lt; 247.5^0)</td>
</tr>
<tr>
<td>Exclusive proximal segment rotation (iii)</td>
<td>(0^0 \leq \gamma &lt; 22.5^0; 157.5^0 \leq \gamma &lt; 202.5^0; 337.5^0 \leq \gamma &lt; 360^0)</td>
</tr>
<tr>
<td>Exclusive distal segment rotation (iv)</td>
<td>(67.5^0 \leq \gamma &lt; 112.5^0; 247.5^0 \leq \gamma &lt; 292.5^0)</td>
</tr>
</tbody>
</table>

\[
\gamma_{i,j} = \tan^{-1}\left(\frac{y_{i,j} - y_{i,j+1}}{x_{i,j+1} - x_{i,j}}\right) \tag{1}
\]

where \(0 \leq \gamma \leq 360\) deg, \(i\) is a percent stance of the \(j\)th trial, and "\(i+1\)" and "\(i, j\)" are subscripts of the \(x\) and \(y\) coordinates. Coupling angles were drawn relative to the right horizontal and determined by the vertical, horizontal and 45\(^{o}\) diagonals of a unit circle. Coupling angles were also categorized into one of four coordination patterns: in-phase, anti-phase, exclusive proximal segment rotation and exclusive distal segment rotation (Table 1) (Chang et al., 2008). The frequency of each coordination pattern performed was determined for each of the Early (ES=1-33%), Mid (MS=34-66%) and Late (LS=67-100%) thirds of the support period. Coupling angles across the stance phase were averaged for each subject in each condition using circular statistics (Batschelet, 1981) and then averaged over early stance, mid stance and late stance.

A mixed factor ANOVA with subject nested within footfall pattern was performed to assess differences in coordination patterns, frequency of coordination patterns and segment and joint angles between groups and conditions (\(\alpha = 0.05\)).
RESULTS

Kinematics

Group mean ± SD values for foot, leg and knee kinematics are listed in table 2. A significant effect of footfall pattern was observed for mean foot segment angle, peak INV and peak EV for all phases of stance and for EV excursion during ES and MS (p<0.05). RFR was characterized by a more everted foot but smaller foot excursion and peak INV in each phase of stance compared to FFR (Figure 1A).

The foot angle during FFR remained in INV for all of the stance phase.

There was a significant effect of footfall pattern for mean leg segment angle, peak ER and leg excursion during ES with FFR having larger values for each parameter (Figure 1B) (p<0.05). There were no significant differences in peak IR throughout the stance phase or in leg segment angles during MS or LS.

A significant group by pattern interaction was observed for minimum FL angle during ES (p<0.05). The natural RF group had greater peak EX than the natural FF group during RFR but this relationship reversed during FFR (Figure 1C). Significant pattern and group effects were observed for knee excursion during ES (p<0.05). Both groups had greater knee excursion during the RFR condition. Significant footfall pattern effects were observed for peak knee FL angle in ES and mean knee angle, peak knee FL angle and knee excursion during MS (p<0.05). For both groups, these parameters had greater values during RFR compared to FFR.

Foot-Leg Coordination

Angle-angle plots for foot-leg coordination were similar between groups when performing the same footfall pattern (Figure 2A). However, there was a downward shift in the angle-angle pattern during RFR compared to FFR.

The vector coding results revealed no significant difference in mean phase angle during ES (p>0.05) however, the classification of the mean phase angle in ES was different between groups. The natural RF group switched from exclusive distal (foot) segment rotation during RFR to in-phase foot-leg coordination during FFR (RFR = 73.19 ± 50.64°; FFR = 65.74 ± 37.26°) (Figure 2B). The natural FF group did the opposite, switching from in-phase foot-leg coordination during RFR to exclusive foot segment rotation during FFR (RFR = 63.63 ± 42.61°; FFR = 70.97 ± 37.81°). There was a significant effect for footfall pattern during MS for the mean foot-leg phase angle (p=0.0073). The mean phase angle was greater during FFR in both groups (RFR: natural RF = 75.05 ± 56.26°, natural FF = 72.62 ± 47.98°; FFR: natural RF = 90.14 ± 41.35°, natural FF = 86.41 ± 49.87°). However, the coordination pattern was classified as exclusive foot segment rotation for both footfall.
<table>
<thead>
<tr>
<th></th>
<th>RF group</th>
<th>FF group</th>
<th>RF group</th>
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<td>Mean, c</td>
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<td>Foot (ES)</td>
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<td>Foot (MS)</td>
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<td>Foot (LS)</td>
<td>4.63 ± 2.24</td>
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<td>Leg (ES)</td>
<td>1.96 ± 3.44</td>
<td>-0.82 ± 5.74</td>
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<td>Max IR</td>
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<td>Leg (MS)</td>
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<td>Leg (LS)</td>
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<td>9.74 ± 3.63</td>
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<td>Knee (ES)</td>
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<tr>
<td></td>
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<td>-13.67 ± 5.62</td>
<td>-14.40 ± 5.70</td>
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<td></td>
<td>Max Flex, c</td>
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<td>-37.94 ± 6.71</td>
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<tr>
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<td>Excursion, b,c</td>
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<td>22.90 ± 3.36</td>
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<td>Knee (MS)</td>
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<td>-38.54 ± 6.06</td>
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<td>Excursion</td>
<td>19.11 ± 2.93</td>
<td>20.46 ± 4.91</td>
<td>20.38 ± 2.87</td>
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</table>

Table 2 – Group mean ± SD values for foot, leg and knee kinematics for the natural rearfoot (RF) group and the natural forefoot (FF) group during rearfoot and forefoot running. Means were calculated for early stance (ES), mid stance (MS) and late stance (LS).

- a, significant group by pattern interaction.
- b, significant group effect.
- c, significant pattern effect.
Figure 1 – Mean angles across the stance phase for A) foot eversion/inversion (EV/INV); B) leg internal/external rotation (IR/ER); and C) knee flexion/extension (FL/EX) during rearfoot running (RFR) and forefoot running (FFR) by both groups patterns.

During LS, both groups exhibited in-phase foot-leg coordination for each footfall pattern (RFR: natural RF = 47.97 ± 20.34°, natural FF = 46.93 ± 13.76°; FFR: natural RF = 43.71 ± 23.20°, natural FF = 44.54 ± 16.44°).
Leg-Knee Coordination

The natural RF and natural FF groups were unable to alter the leg-knee angle-angle pattern when performing RFR or FFR (Figure 2C). No significant interactions or effects were found for mean leg-knee phase angle ($p>0.05$) (Figure 2D). During RFR, both groups exhibited in-phase leg-knee coordination during ES, exclusive distal (leg) segment rotation during MS and in-phase leg-knee coordination during LS (ES: natural RF = 34.48 ± 40.98°, natural FF = 44.38 ± 54.31°; MS: natural RF = 89.87 ± 65.90°, natural FF = 75.84 ± 66.42°; LS: natural RF = 36.27 ± 52.05°, natural FF = 29.70 ± 39.37°). FFR was characterized by in-phase leg-knee coordination during ES, MS and LS (ES: natural RF = 49.03 ± 63.55°, natural FF = 40.45 ± 49.69°; MS: natural RF = 63.09 ± 66.10°, natural FF = 61.12 ± 60.73°; LS: natural RF = 33.08 ± 44.05°, natural FF = 36.99 ± 44.87°).

Coordination Pattern Frequency

No significant interactions or effects were found for the frequency of each foot-leg coordination pattern during each period of stance ($p>0.05$) (Figure 3A-C). For leg-knee coordination, a significant group by pattern interaction was observed for the frequency of exclusive distal (leg) rotation during ES ($p=0.0064$) (Figure 3D-F). When switching from RFR to FFR, the frequency of exclusive leg rotation increased in the natural RF group and decreased in the natural FF group. Additionally, the natural RF group had a higher exclusive leg rotation frequency than the natural FF group during RFR and a lower frequency during FFR. There was a significant effect of footfall pattern in the frequency of exclusive leg segment rotation MS ($p=0.0138$) which was lower for FFR. A significant pattern effect was also observed for the frequency of exclusive proximal (knee) rotation ($p=0.0185$) and in-phase leg-knee coordination ($p=0.0102$) during LS. The frequency of exclusive knee rotation was lower and the frequency of in-phase coordination was greater in FFR compared to RFR.

DISCUSSION

The mechanics of the foot, leg and knee are anatomically linked. Thus, alterations in the magnitude or relative timing of segment or joint rotations may place increased stress on the joints of the lower extremity (Bates et al., 1978; Clarke et al., 1984; Hamill et al., 1992; Messier and Pittala, 1988).
Coordination response to alterations in footfall

- RF group - RFR
- FF group - RFR
- RF group - FFR
- FF group - FFR
Figure 2 – Foot-leg and leg-knee coordination patterns of the natural rearfoot (RF) group and the natural forefoot (FF) group performing rearfoot running (RFR) and forefoot running (FFR). A&B are the angle-angle and mean phase angle plots for coordination between foot eversion/inversion (EV/INV) and leg internal/external rotation (IR/ER). The angle-angle and mean phase angle plots for leg internal/external rotation (IR/ER) and knee flexion/extension (FL/EX) coordination are presented in C and D respectively. Angles and phase angles are presented in degrees.

For example, greater rearfoot eversion has been identified in those with lower extremity injuries such as exercise induced lower leg pain (Willems et al., 2006), knee pathologies (Bates et al., 1978) and plantar fasciitis (Messier and Pittala, 1988). McClay and Manal (1998) reported greater peak eversion and greater incidence of injury in a group of runners defined as excessive pronators. In the present study, the RFR pattern involved greater peak foot eversion throughout stance compared to FFR which may suggest the kinematics of RFR may lead to injury. However, peak eversion values during RFR in this study would not be defined as excessive or detrimental by Clarke et al. (1984) and may not be detrimental. The FFR pattern forced the foot to remain in foot inversion for the duration of the stance phase, resulting in greater mean frontal plane foot angle and peak inversion angle in each third of stance. The effect of a greater excursion accompanied by the foot remaining in inversion is unknown, but preventing adequate foot eversion may limit sufficient impact shock attenuation (Denoth, 1983). Both RFR and FFR utilized kinematic patterns that have previously been related to possible injury mechanisms in running; greater peak eversion and greater frontal plan excursion respectively.

A previous study by McClay and Manal (1997) observed a positive correlation between greater eversion excursion and tibial internal rotation and suggested this may lead to increased knee stress. Although greater magnitudes of foot motion where observed throughout stance during FFR, differences in leg rotation between conditions only existed during early stance and were greater during FFR compared to RFR.
Coordination response to alterations in footfall

A

B

C

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Figure 3 – Mean frequency of each coordination pattern for (A-C) foot-leg and (D-F) leg-knee coordination during (A&D) early stance, (B&E) mid stance and (C&F) late stance.
Since greater leg internal rotation may increase knee joint stress (McCay and Manal, 1997), those who naturally run with a FFR pattern may be at risk for injury, especially if greater leg internal rotation is combined with greater rearfoot motion (Bates et al., 1978; Hamill et al., 1992; Messier and Pittala, 1988).

Knee flexion was investigated in this study because it is coupled with foot eversion and leg internal rotation (Hamill et al., 1992; McClay and Manal, 1997). Since FFR resulted in greater frontal plane foot excursion, it may be expected the FFR pattern would result in greater knee flexion excursion. However, the RFR pattern resulted in greater knee flexion excursion and peak knee flexion angles during early and mid stance. Although increased knee flexion angle at touchdown may contribute to increased patellofemoral joint compressive forces (Smidt, 1973), increasing knee flexion excursion has been identified as a mechanism to reduce impact loading (Derrick et al., 1998; DeVita and Skelly, 1992; Hamill et al., 1992). Therefore, greater knee flexion excursion during RFR may be a mechanism to attenuate the passive vertical ground reaction force peak present in RFR but not in FFR (Cavanagh and Lafortune, 1980). Greater knee flexion excursion during RFR may be a result of greater stride lengths compared to FFR (Hamill et al., 2010), which may also assist to increase impact shock attenuation (Derrick et al., 1998; Mercer et al., 2003). This suggests that reduced stride length combined with lower knee flexion values may result in greater impact shock and less impact shock attenuation in FFR.

Previous reports have found good coupling relationships between foot eversion/inversion and leg internal/external rotation during both RFR and FFR (Pohl and Buckley, 2008). In the present study, the foot-leg angle-angle patterns were similar between RFR and FFR despite differences in foot and leg kinematics. Greater eversion throughout stance during RFR resulted in a downward shift in angle-angle pattern and may have driven the differences in mean phase angle during mid stance between conditions (see Figure 2A). The mean foot-leg phase angle during mid stance was greater in FFR; however, it was categorized into the same coordination pattern for both footfall patterns, exclusive distal (foot) rotation.

Although no significant group effects were observed in kinematics or coordination, the natural FF group performed both footfall conditions with greater leg internal rotation, resulting in a slight shift to the left in the foot-leg angle-angle pattern for this group (see Figure 2A). Despite these shifts in angle-angle pattern, the lack of significant group effects demonstrates both groups were able to perform the alternate footfall pattern with similar foot kinematics and coordination as the natural runners for each pattern, which is consistent with previous reports (Williams et al., 2000). Similar coordination between patterns suggests that one footfall pattern may not prevent more running injuries than the other. Therefore, in terms of foot-leg coordination, there may not be a justification for habitually changing from one footfall pattern to another.

Shifts in the leg-knee angle-angle patterns were also observed (See Figure 2C); however these shifts were between groups rather than footfall patterns. Unlike the foot-leg angle-angle patterns, each group maintained the same leg-knee coordination for both footfall conditions that did not match the coordination pattern executed by the natural runners of that footfall pattern. This was not evident by examining the knee kinematics (see Figure 1C), as it appeared each group was able to successfully adapt the knee kinematics of the alternate footfall pattern. However, examining the leg-knee coordination patterns (Figure 2C, D) reveals both groups were not able to adapt leg-knee coordination when switching from RFR to FFR. The differences in coordination may be driven by greater leg internal rotation exhibited by the natural FF group and greater knee flexion exhibited by the natural RF group. Although these differences were not statistically significant between groups, they may be a result of habitually performing a specific footfall pattern and affect the ability to adapt leg-knee coordination when altering footfall patterns. Therefore, it may be that runners of each footfall pattern are susceptible to different types of injuries rather than one footfall pattern imposes a kinematic pattern that prevents injuries.

Although there were differences in the leg-knee angle-angle patterns between groups, there was no significant difference in mean leg-knee phase angle between footfall patterns. However, when performing each footfall pattern, the mean leg-knee phase angle during mid stance was classified as exclusive distal (leg) rotation in the natural RF group but classified as in-phase coordination in the natural FF group. Additionally, a significant group by pattern interaction was observed for the frequency of exclusive distal (leg)
rotations in early stance and significant pattern effects were found for exclusive proximal (knee) rotation and in-phase rotation in late stance. These differences suggest each group used different coordination strategies to accomplish the same knee angle within a footfall pattern. Despite these differences in leg-knee coordination characteristics and the inability of each group to adopt the leg-knee coordination pattern of the alternative footfall pattern, there does not appear to be a disruption in the coupling of leg internal rotation and knee flexion rotations within each group or footfall pattern. Although adaptations in leg internal rotation and knee flexion mechanics may change with training to use an alternative footfall pattern, neither pattern exhibited a leg-knee coordination pattern that may be more optimal at preventing overuse injuries in running than the other. However, training to adopt an alternate running pattern may disrupt leg-knee coordination and result in injury due to the inherent differences in leg and knee kinematics between groups.

CONCLUSION

Foot-leg coordination patterns were similar between RFR and FFR despite differences in foot, leg and knee kinematics. However, differences between groups in leg-knee angle-angle patterns indicate that coordination between leg-knee rotations did not adjust to altering footfall pattern. It appears that differences in the knee angle between subject groups may be driving the differences in leg-knee coordination. Interactions between groups and footfall patterns found for knee kinematics and leg-knee coordination characteristics may suggest altering footfall pattern may not reduce potential for injury. However, training to adopt an alternate running pattern may disrupt leg-knee coordination and result in injury due to the inherent differences in leg and knee kinematics between groups. The subjects in this study were free of injury and did not display excessive kinematic patterns shown to contribute to injury by previous studies. It is unknown whether switching running footfall patterns would improve running kinematics in a group or runners who are predisposed to injury or have a history of injury.

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