A comparison of three-dimensional lower extremity kinematics during running between excessive pronators and normals

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Abstract

Objective. The purpose of this research was to compare the three-dimensional kinematics of runners exhibiting excessive rearfoot pronation with those having normal rearfoot pronation.

Design. The study design was a comparative investigation of two types of running patterns.

Background. Excessive rearfoot pronation is often linked with overuse injuries of the lower extremity. However, the literature is void of papers describing the rearfoot motion of runners presenting with excessive rearfoot pronation. Many knee-related injuries in runners are associated with increased rearfoot pronation; however, knee mechanics in this population of runners have yet to be studied. Finally, three-dimensional studies are needed to describe joint motion fully during running and these are also lacking.

Methods. Eighteen subjects (nine excessive pronators — PRs; nine normals — NLS) were studied during treadmill running at 3.35 m/s. Retroreflective markers were placed on the foot, shank and thigh segments and recorded with four 200 Hz video cameras. Three-dimensional kinematics were computed.

Results. A downward shift of the eversion curve was seen in the PR group resulting in an everted position of the rearfoot at both footstrike and toe-off compared with an inverted posture seen in the NL group. The amount of toe-out was not significantly different between the two groups. At the knee, the PR group demonstrated significantly less adduction and significantly greater flexion than the NL. Mean peak velocities of the PR group were greater in all angular measures except knee adduction. However, only foot dorsiflexion and eversion and knee flexion velocities were significantly different.

Conclusions. Kinematic differences were noted at both the rearfoot and the knee of the runners who exhibit excessive rearfoot pronation.

Relevance

The kinematic differences (i.e. higher peak positions and velocities) noted at both the rearfoot and knee may be related to the greater propensity for injury associated with excessive rearfoot pronation in runners. With greater insight into the etiology of overuse injuries, intervention strategies to minimize these differences can be developed. © Elsevier Science Ltd. All rights reserved


Introduction and ankle, along with transferring abnormal stresses further up the kinetic chain. This has led to a heightened interest in the function of the subtalar joint (STJ) where pronation occurs.

The STJ, comprised of the articulation between the talus and calcaneus, has an axis orientation which crosses all three cardinal planes of the body. Therefore, motion at this joint can be resolved into three components. Dorsiflexion (DF) and plantarflexion (PF) occur in the sagittal plane of the foot, inversion
(INV) and eversion (EV) occur in the frontal plane, and abduction (ABD) and adduction (ADD) take place in the transverse plane.

The STJ is difficult to study with standard motion analysis techniques owing to the inability to place external markers on the talus. Therefore, researchers have routinely placed markers on the tibia and the calcaneus and have studied the motion of the combined subtalar/talocrural joints\textsuperscript{4,10}, referred to in this paper as rearfoot motion. Owing to the orientation of the axes of the talocrural and STJs, the majority of sagittal plane (DF/PR) motion measured between the tibia and calcaneus occurs at the talocrural joint. Similarly, most of the frontal (INV/EV) and transverse (ABD/ADD) plane motion occurs at the STJ. This has been supported by the work of Lundberg\textsuperscript{11} who, using in vivo techniques, found little relative frontal and transverse plane motion between the tibia and talus during STJ pronation.

Although many two-dimensional (2D) studies have been reported, there is a dearth of three-dimensional (3D) data on either the rearfoot or knee joint during running. The only papers that are available\textsuperscript{4,10} focus on methodology using one or two subjects. There are no published papers which have compared the rearfoot and knee kinematics of identifed excessive rearfoot pronators with those with normal rearfoot mechanics. Yet, excessive pronation is the biomechanical problem most often cited as being associated with lower extremity injuries\textsuperscript{1-3}.

Knee joint dysfunction is reported to represent 26–40% of all running injuries seen by sports medicine professionals\textsuperscript{1,12-14}. Yet, very little attention has been focused on abnormal knee joint mechanics. The largest component of knee motion occurs in the sagittal plane. Although this component of the motion has been most thoroughly studied, the resultant information has lent relatively little insight into etiology of running-related injuries.

Data regarding transverse plane (axial) rotations may lend more insight into knee joint problems. In closed chain pronation, the talus, and consequently the tibia, rotates inwardly. Therefore, it has been postulated that excessive pronation leads to excessive internal rotation (IR) of the tibia and hence places abnormal rotational stress on the musculoskeletal structures of the knee joint\textsuperscript{6,15}. Increased rotation under loaded conditions may result in excessive torsional stresses experienced by the tibia itself. These ideas have yet to be substantiated.

Finally, we were interested in the relationship between excessive pronation and increased toe-out. Theoretically, one might expect greater toe-out with excessive pronation as ABD is one of the components of pronation. It is much easier to pronate the foot when it is toed outwardly compared with when it is toed inwardly. If this relationship is found to exist, then reducing toe-out might result in reducing excessive pronation.

Therefore, this was a preliminary study to examine the 3D patterns of motion at the foot and knee during running and to explore whether differences in these patterns exist between runners with normal rearfoot motion and those who pronate. It was hypothesized that the runners with excessive rearfoot pronation would exhibit greater peak values at both the rearfoot and knee than runners with normal rearfoot pronation. This is a first step in identifying kinematic variables that might be related to an increased risk of injury. Once these abnormalities have been recognized, interventions to minimize them can be explored in order to reduce these risks.

**Methods**

Eighteen recreational runners (18–40 years) volunteered for this study. These were chosen from a group of runners recruited from the community, local podiatrists and local running clubs. Subjects were screened during treadmill running at 3.35 m/s. Markers were placed on the tibia and heel counter of the shoe, as described by Clarke et al.\textsuperscript{5}. The peak 2D EV measure was used as a criterion during the screening process as it could be obtained quickly. In addition, normal rearfoot EV values during running reported in the literature\textsuperscript{5,7-5} are based upon 2D measures. The right foot was used in all cases, except when the left foot demonstrated the greater amount of EV. Values between 8 and 15° placed one in the normal (NL) group, based upon the work of Clarke et al.\textsuperscript{5}, whereas values greater than 18° placed one in the excessive pronator (PR) group. The criterion of 18° was based upon a recent screen of 2D peak rearfoot EV on 100 subjects in our laboratory. The mean EV value of these 100 subjects was 12.7° with a standard deviation of 4.2°. A value of 18° was chosen to ensure a greater than one standard deviation between the NL and PR groups. Injury at the time of the experiment excluded one from the study.

As a result of the screening, nine subjects were assigned to each of the PR or the NL groups based upon their peak 2D EV values measured during the screening phase. These subjects then returned to the laboratory for the full evaluation. Three markers were placed on the femur, lower tibia and rearfoot segments (Figure 1) in a manner similar to that described by Soutas-Little et al.\textsuperscript{10}. This particular orientation enabled the markers to define the anatomical coordinate system and to be used to track the motion of the segments. Following a standing calibration trial, subjects ran on a treadmill operating at 3.35 m/s. Data were collected with a four-camera (200 Hz) Motion Analysis System (Motion Analysis Corp., Santa Rosa, CA, USA). Five footstrikes were collected from each subject. The contact phases of
the three trials with the least number of marker drop-outs (maximum of three consecutive drop-outs) were used for analysis. All coordinate data were filtered with a second-order recursive Butterworth filter with an 8 Hz cut-off frequency. This cut-off frequency was based upon a fast Fourier transformation analysis of the data.

Custom software was developed in order to calculate 3D joint coordinate system angles\textsuperscript{16}. The coordinate system of the foot and tibia constructed is as described by Soutsas-Little \textit{et al.}\textsuperscript{10}, with a modification of this procedure applied to the femur. All angles were referenced to standing, with the exception of INV/EV of the foot. A zero reference for INV/EV was defined when the vertical axes of the calcaneus and tibia were parallel. This study focused on the loading phase of gait and, although we assessed the entire contact period, peak motions (and velocities) occurring in the first 60\% of stance were analyzed. These variables include peak rearfoot DF, EV and ABD along with knee flexion (FL), ADD and IR. Peak values are not always representative of the amount of motion a joint experiences. Therefore, excursions were also calculated as shown in Figure 2. As ABD is a component of rearfoot pronation, we were interested in exploring whether PRs exhibited a greater out-toeing of the foot during contact. To investigate this, ADD of the foot with respect to the laboratory coordinate system (LABABD) was also calculated. In addition to the kinematic parameters, an injury history was recorded for each subject.

Independent \textit{t}-tests were utilized to compare peak angular position and velocity data and excursions for both the rearfoot and the knee. A significance level of \( p < 0.015 \) was used to minimize the chance of making a type I error, since multiple comparisons were made for each of the three components of motion at each joint. Linear regression analysis was used to assess the relationships between rearfoot EV excursion and knee IR excursion, rearfoot EV and LABABD and rearfoot ABD and LABABD. The variable rearfoot ABD was chosen over knee IR as a closer measure of pure tibial motion. Knee IR is a relative measure and depends upon the movement of both the tibia and femur. However, once the foot is plantigrade it no longer rotates outward\textsuperscript{23}, and rearfoot ABD is achieved through IR of the tibia. A level of \( p < 0.05 \) was used to determine whether a significant relationship existed.

\textbf{Results}

The initial screening of subjects resulted in two distinct groups with mean peak 2D EV angles of \(-11.5^\circ\) and \(-21.1^\circ\) for the NL and PR groups respectively. The following represents the mean data for three footstrokes for these two groups. Owing to problems encountered with femoral marker tracking and identification, knee data were available for only ten subjects (five PR and five NL).

Mean 3D rearfoot and knee data were averaged across trials and subjects. The patterns of movements for each of the NL and PR groups are presented for the rearfoot in Figure 3 and the knee in Figure 4. At the rearfoot the general pattern of motion was DF, EV and ABD during the first half of stance, followed by PF, INV and ADD during the latter half. The knee exhibited a pattern of FL, ADD and IR, followed by a reversal of these motions with EXT, ABD and ER occurring in the second half of stance.
Table 1 contains the comparisons of the peak rearfoot angular kinematics between the PR and the NL subjects. The PR group demonstrated nearly twice the magnitude of rearfoot EV as the NL group. However, rearfoot EV excursions were found to be similar. Rearfoot EV position at heelstrike was significantly different, with the PR subjects landing everted (−8.5°) and the NL subjects landing in a slightly inverted (1.7°) position. In addition, the PR subjects remained in −4.8° of rearfoot EV at toe-off.

Figure 3. Mean 3D rear-foot kinematic patterns for the PR (dotted line) and NL (solid line) groups.
whereas the NL group was in slight INV (1.7°). Rearfoot ABD excursions were not significantly different; however, a trend toward greater DF excursion was seen in the PR subjects (p = 0.018). LABABD was similar for both the groups (NL: −9.7°; PR: −8.0°) and was not found to be significantly correlated to peak rearfoot EV (Table 2). However, the subject with the highest peak rearfoot EV (−28.2°) did exhibit the greatest LABABD (−32.6°). A significant negative correlation was found (R = 0.47, p = 0.0005) between LABABD and peak rearfoot ABD, and between LABABD and

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**Figure 4.** Mean 3D knee kinematic patterns for the PR (dotted line) and NL (solid line) groups.
Table 1. Comparison of angular kinematics for the 3D parameters of the rearfoot across the NL (n = 9) and PR (n = 9)

<table>
<thead>
<tr>
<th>Variable</th>
<th>PR (sd)</th>
<th>NL (sd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak DF</td>
<td>19.6 (4.5)</td>
<td>17.4 (4.3)</td>
</tr>
<tr>
<td>time to DF</td>
<td>0.140 (0.017)</td>
<td>0.138 (0.013)</td>
</tr>
<tr>
<td>Peak EV</td>
<td>-21.2 (4.0)</td>
<td>-11.2 (2.7)**</td>
</tr>
<tr>
<td>time to EV</td>
<td>0.091 (0.028)</td>
<td>0.092 (0.026)</td>
</tr>
<tr>
<td>EV at HS</td>
<td>-8.5 (5.4)</td>
<td>1.7 (4.5)**</td>
</tr>
<tr>
<td>EV at TO</td>
<td>-4.8 (7.2)</td>
<td>1.7 (5.1)**</td>
</tr>
<tr>
<td>Peak ABD</td>
<td>-4.0 (7.2)</td>
<td>-3.2 (5.9)</td>
</tr>
<tr>
<td>time to ABD</td>
<td>0.102 (0.020)</td>
<td>0.103 (0.022)</td>
</tr>
<tr>
<td>LABABD</td>
<td>-8.0 (13.2)</td>
<td>-9.7 (5.0)</td>
</tr>
<tr>
<td>DF excursion</td>
<td>18.7 (3.8)</td>
<td>16.5 (2.7)</td>
</tr>
<tr>
<td>EV excursion</td>
<td>12.8 (3.5)</td>
<td>12.7 (4.1)</td>
</tr>
<tr>
<td>ABD excursion</td>
<td>9.6 (3.6)</td>
<td>8.9 (3.1)</td>
</tr>
</tbody>
</table>

Significant differences are marked by ** (p < 0.015).

Discussion

The general 3D patterns of motion of the rearfoot noted in the present study were consistent with the few studies in the literature addressing running\textsuperscript{4,10}. STJ pronation, which is the combined motion of DF, EV and ABD\textsuperscript{17,18}, occurs during the first half of stance. As stated earlier, difficulty in placing an external marker on the talus limits our ability to measure true subtalar (talo-calcaneal) motion. However, motion of the rearfoot (tibio-calcaneal joint) appeared to follow the same pattern as the STJ with the motions of pronation (DF, EV and ABD) occurring in the first half of stance followed by the components of supination (PF, INV and ADD) in the latter half.

Rearfoot differences between the two groups were most notable in the frontal plane motion, as evidenced by the twofold increase in peak EV noted in the PR group. A downward shift of the EV curve (Figure 3) was seen for the PR group remaining in EV the entire contact. These subjects, therefore, landed and pushed off in an everted position. It has been suggested that, when the rearfoot is everted, the arch is lowered and the foot becomes a mobile adaptor that allows for shock attenuation and accommodation to uneven surfaces\textsuperscript{17,18}. During rearfoot INV, the arch is raised and the bones of the midfoot become 'locked up', hence allowing the foot to become more stable. This relationship between rearfoot and midtarsal joint motion was demonstrated,\textit{in vivo}, by Lundberg\textsuperscript{11}. Stability of the foot is important both at contact, when the foot begins to bear the weight of the runner, and during the end of contact, when the foot needs to become a rigid lever for push-off. Therefore, excessive pronation may lead to less stable initial contacts with the ground and less efficient push-off phases due to the everted position of the rearfoot at these times.

The incidence of running-related injuries was higher in the PR subjects compared with their NL counterparts. A total of 67% (6/9) of the PR subjects reported injuries which included patellar tendinitis, achilles tendinitis, 'shin splints', knee ligament damage and ankle sprains. Only 22% (2/9) of the normal subjects sustained injuries which included IT band syndrome and an inguinal hernia. However, no distinct distribution of injuries could be identified in the present study owing to the small sample size.

Table 2. Results of linear regression analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation (y)</th>
<th>r</th>
<th>p</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>LABABD peak ABD</td>
<td>0.387x + 7.13</td>
<td>0.47</td>
<td>0.0006**</td>
<td>18</td>
</tr>
<tr>
<td>LABABD-ABD exc</td>
<td>-0.138x + 10.62</td>
<td>0.40</td>
<td>0.003**</td>
<td>18</td>
</tr>
<tr>
<td>LABABD-peak EV</td>
<td>-0.006x - 16.34</td>
<td>0.10</td>
<td>0.970</td>
<td>18</td>
</tr>
<tr>
<td>EV exc-KIR exc</td>
<td>-0.368-9.72x</td>
<td>0.49</td>
<td>0.04**</td>
<td>10</td>
</tr>
</tbody>
</table>

Significant differences are marked by ** (p < 0.05).
deviations above the population mean determined in our laboratory, also exhibited the greatest LABABD (−32.6°). Therefore, it is possible that this relationship exists when mechanics are extreme.

A significant negative correlation was noted between LABABD and rearfoot ABD. As the amount of toe-out increases there is probably less available range at the rearfoot for the tibia to rotate internally; this might explain this inverse relationship. However, running with excessive toe-out might impose more strain on the midfoot, as the arch has a greater tendency to collapse in this position as the body weight progresses forward.

Studies of 3D kinematics of the knee during running are lacking; however, the patterns identified in this study are similar to those reported for walking.19–21. Frontal plane motion constitutes the smallest component of the total knee movement and is typically the most variable. All studies agree that, as the knee flexes during the first half of stance, the tibia rotates internally.19–21. The IR of the tibia rotates the talus internally leading to subtalar pronation.

Knee FL and foot pronation are thought to occur together to assist in attenuating the impact of contact.15. This relationship may account for the significantly greater peak knee FL seen in the PR group. However, FL excursion, like EV excursion, was similar between groups. As can be seen in Figure 4, there was an upward shift of the FL curve in the PR group. Although these subjects moved through similar excursions, they landed in greater knee FL and, consequently, achieved higher peak values. With increasing knee FL, it has been reported that patello-

![Figure 5](image-url). Top panel: results of the correlations between LABABD and peak rearfoot ABD (top graph) suggesting that, as toe-out increases, IR of the tibia decreases. Bottom panel: results of correlation between knee IR excursion and rearfoot EV excursion.
femoral joint compressive forces increase. This, along with a possible altered patellofemoral contact profile, could place a runner at risk for patellofemoral joint syndromes which are often associated with excessive pronation and reported to be the most common injury seen in runners.

Significant differences were also noted in the frontal plane, with both ADD and ADD excursion being less in the PR subjects. These subjects landed in slight ABD (or genu valgus) and moved through less ADD excursion than their NL counterparts. This may be a reflection of a more valgus posture of the knee often associated with a pronated foot posture.

Increased pronation is thought to lead to excessive IR of the knee. Mean peak IR and IR excursions were higher in the PR subjects, but the differences were not significant. However, significance might have been obtained with a larger sample size. Although mean rearfoot EV and knee IR excursions were not significantly different between the groups, results of the correlation between the two variables across all subjects suggest that greater EV excursion translates into higher knee IR excursion. This could result in greater stress to the knee joint and the structures that support it.

It has been proposed that greater angular velocities translate into higher strain rates on the musculoskeletal system. The results of the present study suggest significantly higher knee FL and rearfoot DF and EV velocities in the PR group. During the loading phase of gait, the quadriceps muscle is eccentrically controlling knee FL, the posterior tibialis is acting to decelerate pronation and the gastrosoleus muscle is restraining the forward movement of the tibia over the foot. With increased angular velocities, these muscles may become overworked in attempting to control the foot and knee resulting in an overuse injury such as tendinitis. Interestingly, patellar tendinitis, posterior tibialis tendinitis and achilles tendinitis are among the ten most common running injuries cited by Clement et al. in their study of 1650 patients. In the present study, the subject who reported having patellar tendinitis displayed one of the highest peak knee FL velocities of the PR group. Similarly, one of the highest peak DF velocities of the PR group was noted in a subject who had a history of achilles tendinitis. However, much larger-scale studies are needed to examine some of the injury mechanisms proposed here.

**Summary**

This study provides data not previously available comparing lower extremity kinematics between runners with normal rearfoot mechanics with those who demonstrate excessive rearfoot pronation. The results of this preliminary work are promising, suggesting significant kinematic differences at the foot and knee in excessive rearfoot pronators. In addition, trends were identified which may be significant with larger sample sizes. Some of the angular findings noted in this study were subtle. However, the clinical significance of these small differences becomes magnified by the repetitive nature of running. Minor deviations repeated over many footstrikes can result in cumulative stresses to the musculoskeletal system. In order to understand further the consequence of excessive pronation on lower extremity kinematics, a larger-scale study is currently under way. With greater insight into the etiology of running-related injuries, improved intervention strategies can be developed.

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**References**


