A Perturbation Study of Lower Extremity Motion During Running

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The present study explored kinematic adaptation in the lower extremity to running in shoes with 10° valgus and varus midsole perturbations. Rearfoot motion and knee flexion/extension data on nine subjects were collected using a Selspot II system during treadmill running in the two test shoes and in a neutral shoe condition. Maximum pronation was significantly altered by an amount approximately the same as the shoe perturbation, but there was no substantial adaptation in the amount of knee flexion. From the rearfoot patterns it was inferred that time to maximum pronation may be an unreliable variable to describe the pattern of rearfoot motion; the two-phase profile using rearfoot velocity may be more useful. It was concluded that certain subtle sagittal plane kinematic adaptations in timing and velocity patterns did occur at the knee in response to the shoe perturbations.

Abnormal motion of the subtalar joint during running has been linked to knee injury (Bahlsen, 1988; Clement, Taunton, Smart, & McNicol, 1981; Frederick, 1986; James, Bates, & Osternig, 1978; Luethi, Frederick, Hawes, & Nigg, 1986; Nigg & Bahlsen, 1988). Opinions vary, however, as to the exact characteristics of the motion that may be involved in the pathogenesis of knee injury. Several authors have implicated the amount of motion (Bates, James, & Osternig, 1978; Bates, Osternig, Mason, & James, 1979; Cavanagh, 1980; Clarke, Frederick, & Cooper, 1983; Clarke, Frederick, & Hamill, 1983, 1984; Nigg, 1986), and “excessive” subtalar joint pronation is perhaps the most frequently discussed kinematic abnormality that is mentioned in the literature on running injury.

Some authors believe that rate of pronation is another important parameter to be taken into consideration (Cavanagh, Clarke, Williams, & Kalenak, 1978; Clarke, Frederick, & Hamill, 1983; Edington, Frederick, & Cavanagh, 1990; Rodgers & LeVeau, 1982; Smith, Clarke, Hamill, & Santopietro, 1986; Williams & Ziff, 1991). Bates and his associates have also suggested that the timing of the pronatory motion in relation to flexion and extension of the knee motion may be important (Bates et al., 1979). Despite this, rearfoot motion has
generally been studied in isolation rather than in conjunction with other move-
ments of the lower extremity.

The present study was designed to systematically alter lower extremity
motion in a group of runners by providing shoes with midsoles that were built
with 10° varus and valgus orientations. In order to examine the possible adaptation
and interaction of motion at the two joints in response to the shoe treatments,
both rearfoot motion and flexion/extension of the knee were studied while
subjects ran in these shoes.

**Review of Literature**

In his classic study of the joints of the ankle, Inman (1976) reported that the
mean axis of the subtalar joint was directed medially 23° and 42° upward with
respect to the sagittal and coronal planes, respectively, but he also showed that
there was large interindividual variation. The result of this oblique orientation of
the axis is that subtalar joint motion, when viewed with respect to the cardinal
planes of the body, involves abduction/adduction and dorsiflexion/plantarflexion
of the foot together with eversion/inversion of the calcaneus. Inman (1976)
therefore suggested that internal tibial rotation would always accompany subtalar
joint pronation and that external rotation would always accompany supination.

Although this concept has been widely assimilated into the orthopaedic
literature, radiographic studies of cadaveric limbs (Van Langelaan, 1983) and in
vivo studies (Lundberg, Svensson, Bylund, Goldie, & Selvik, 1989) have pointed
out some limitations in the theory. In particular, Lundberg et al. (1989) have
shown that subtalar joint supination and external tibial rotation are much more
closely linked than subtalar pronation and internal tibial rotation.

Despite the obliquity of the joint axes with respect to the cardinal planes
of the body and the migration of instantaneous joint axes, most research into
rearfoot motion has been done by calculating rearfoot angles projected onto a
frontal plane (Bates et al., 1978, 1979; Cavanagh, 1980; Clarke, Frederick, &
Cooper, 1983; Nigg, 1986). More recently, Soutas-Little, Beavis, Verstraete, and
Markus (1987) have shown that the inversion/eversion component of rearfoot
motion pattern calculated from a two-dimensional analysis has only minor
deviations from the three-dimensional pattern between footstrike and a time
approximately 200 ms after footstrike.

Areblad, Nigg, Ekstrand, Olsson, and Ekstrom (1990) have compared a
three-dimensional approach to rearfoot motion measurement with a series of
single camera measurements taken through a 40° range of camera positions.
Their graphical results indicate that the two-dimensional estimate of the maximum
angle of pronation (their $\beta_{max}$ angle) varied by approximately 3° over a 10° range
of camera placement centered on the foot axis. Marker placement error has also
been shown to produce errors of similar magnitude (Edington et al., 1990).

Various functions have been attributed to pronation. A number of authors
have suggested that pronation has a damping effect on the impact loading of the
foot (Bates et al., 1978; Clarke et al., 1984; Fetto, 1986). Brody (1986) states
that "pronation unlocks the foot for surface adaptation." Pronation has also been
described as a compensatory mechanism for anatomical abnormalities (Clarke et
al., 1984). In their review, Clarke et al. (1984) reported data from nine studies
with a wide variety of experimental protocols. The weighted mean value for
maximum pronation of those studies in which the subjects wore neutral shoes without orthoses was $-9.5^\circ$ (range of mean values $-7.2$ to $-11.7^\circ$) and the time to maximum pronation was 76 ms (range of mean values 45–99 ms). These variations found by the different investigators are probably due not only to individual differences between subjects but also to the different shoes and different running speeds used.

A typical pattern of rearfoot motion as a function of time is shown by Williams (1985). The curve is characterized by a rapid initial phase of pronation immediately after footstrike, followed by a period in which there is a small amount of continued pronation during foot flat before supination begins. Variations of this pattern include a reversal of the initial pronation before a clear second peak (Clarke et al., 1984) and an immediate onset of supination after the first early peak of pronation (Cavanagh, 1987).

Rearfoot velocity during running at 3.8 m·s$^{-1}$ in a neutral shoe condition has been reported at between $-532$ and $-789$ deg·s$^{-1}$ (Cavanagh et al., 1978; Clarke, Frederick, & Hamill, 1983; Edington et al., 1990; Rodgers & LeVeau, 1982; Smith et al., 1986). Clarke, Frederick, and Hamill (1983) found the time to maximum rearfoot velocity to be 27 ms while Cavanagh et al. (1978) reported a time to peak of 15 ms. These differences are likely to reflect the accuracy of footstrike and peak value determination, as well as different numerical methods and intersubject variations.

Clarke et al. (1984) found no statistically significant differences in any parameter of pronation between running on a treadmill and overground running while the subjects were running at 3.8 m·s$^{-1}$. However, a number of factors that do affect the magnitude and timing of pronation have been reported. These include foot structure (Francis, 1981), the speed of running (Andrew, 1986; Nigg, 1986; Smith et al., 1986), and a variety of shoe design parameters. In a recent perturbation study, Williams and Ziff (1991) demonstrated systematic changes in rearfoot angle and velocity consequent to variation in foot placement relative to the midline.

The features of footwear that have been most studied include flare (Clarke, Frederick, & Hamill, 1983; Nigg & Bahlsen, 1988; Stacoff, Denoth, Kaelin, & Stuessi, 1988), and hardness of the midsole (Francis, 1981; Nigg, 1986; Nigg & Morlock, 1987; Stacoff & Kaelin, 1983; Stacoff et al., 1988). The effect of in-shoe orthoses has been studied by several groups. Cavanagh et al. (1978) used up to three layers of 6-mm felt inside the medial border of the shoe and reported that maximum pronation was reduced by approximately 2 or 3$^\circ$ for each 6-mm insert. A nearly threefold reduction in maximum rearfoot velocity was also found in the three-layer condition.

Other studies using a more realistic therapeutic intervention in injured runners have found the response of subjects to be more variable (Rodgers & LeVeau, 1982; Smith et al., 1986). Rodgers and LeVeau (1982) found a mean reduction in maximum pronation of only 0.6$^\circ$ when subjects used orthoses, and Smith et al. (1986) found a mean reduction of 0.8 and 1.2$^\circ$ for soft and semirigid orthoses, respectively. Both groups also reported reductions in pronation velocity when the orthotic devices were used (a nonsignificant 50 deg·s$^{-1}$ [Rodgers & LeVeau, 1982], 110 and 76 deg·s$^{-1}$ for soft and semirigid orthoses, respectively [Smith et al., 1986]).

Despite the possible implication of excessive pronation in the pathogenesis
of knee injuries, we could only locate one publication (Bates et al., 1979) in which the simultaneous motion of the subtalar and knee joints has been reported. Bates et al. (1979) studied the timing of maximum knee flexion and maximum pronation during running at speeds of 3.83–4.47 m·s⁻¹ and found that the peaks for the two joints were almost simultaneous, with maximum pronation preceding maximum knee flexion by approximately 5 ms, which was the duration between two frames of film. They suggested that, since tibial rotation occurs as a result of motion at both the knee and subtalar joints, it is critical that knee flexion and subtalar joint pronation "be synchronous and complementary."

Methods

Specially built shoes (Figure 1), all with a midsole hardness of 38 on the Shore A scale, were used in this study to examine the effects of shoe design on rearfoot motion, knee motion, and the relation between these two. The shoes are referred to as a valgus shoe, a varus shoe, and a neutral shoe, depending on the effect of the shoe on foot position. The varus shoe is designed to force the subject to supinate, and the valgus shoe forces the subject to pronate. The unloaded varus and valgus angles were 10° over the whole length of the shoe with respect to the horizontal.

The nine subjects in this study were selected from a population of runners who wore size 10 shoes and had neither excessive rearfoot motion (defined as maximum pronation >16°) when running in a neutral shoe nor arch indices greater than 0.29, indicating that no subjects with severely planus feet were included in the study (Cavanagh & Rodgers, 1987). The physical characteristics of the subjects and other information concerning their running styles are shown in Table 1.

Prior to data collection the subjects were familiarized with treadmill running.
Table 1

Physical Characteristics and Other Relevant Information on the Subjects

<table>
<thead>
<tr>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (N)</th>
<th>Rearfoot-striker?</th>
<th>AI</th>
<th>STJ ROM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26</td>
<td>185</td>
<td>784.8</td>
<td>yes</td>
<td>0.212</td>
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<tr>
<td>2</td>
<td>19</td>
<td>170</td>
<td>686.7</td>
<td>yes</td>
<td>0.207</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>175</td>
<td>667.1</td>
<td>yes</td>
<td>0.155</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
<td>180</td>
<td>775.0</td>
<td>yes</td>
<td>0.264</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>178</td>
<td>824.0</td>
<td>yes</td>
<td>0.245</td>
</tr>
<tr>
<td>6</td>
<td>28</td>
<td>184</td>
<td>696.5</td>
<td>yes</td>
<td>0.287</td>
</tr>
<tr>
<td>7</td>
<td>33</td>
<td>185</td>
<td>686.7</td>
<td>no</td>
<td>0.208</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>180</td>
<td>686.7</td>
<td>yes</td>
<td>0.195</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>182</td>
<td>706.3</td>
<td>no</td>
<td>0.285</td>
</tr>
<tr>
<td>Mean</td>
<td>25</td>
<td>179</td>
<td>723.8</td>
<td>–</td>
<td>0.228</td>
</tr>
</tbody>
</table>

AI = arch index; STJ ROM = subtalar joint range of motion (degrees).

by a 15-min acclimation session at the test speed of 3.8 m·s\(^{-1}\). The passive range of motion of the subtalar joint was also measured. Kinematic data were collected with a Selspot II optoelectronic system at a sampling frequency of 200 Hz per target. Two cameras were used, as shown in Figure 2, and a total of seven LED targets were placed on the subjects’ right lower extremity. Four targets on the posterior aspect of the leg and shoe were used to calculate rearfoot angles according to Clarke, Frederick, and Hamill (1983). Since two targets were placed on an assumed midline of the heel counter, a calibration was taken without the shoe on the subject to adjust the derived shoe angles to the measured values of varus and valgus deviation.

This procedure controlled for error in marker placement and ensured, for example, that a shoe valgus angle of 10° would be measured correctly regardless of marker placement. Targets were also placed on the greater trochanter, the lateral femoral epicondyle, and the lateral malleolus of the right leg. An inertia switch attached to the rear lateral border of the shoe was used to indicate footstrike (see Figure 3). It should be noted that this method may result in a different determination of the time of footstrike than what is observed from film or video.

The rearfoot angle was calculated, as shown in Figure 3, as the difference between the leg and rearfoot segment angles to the vertical, after the shoe correction to account for error in marker placement was performed. Pronation (defined here as calcaneal valgus) was, by convention, assigned a negative angle (Cavanagh et al., 1978; Clarke et al., 1984). The knee angle, calculated as shown in Figure 3, was defined at 0° during upright standing to correct for between-subject errors in marker placement since all subjects were asked to stand in the same posture (full knee extension). These data, collected during an initial test while the subject stood erect with the knees fully extended at a specified location on the treadmill, also were used to examine the subjects’ response to the shoes during standing. Data were then collected for a 10-second period during steady running. A counterbalanced design was used to determine the order in which the subjects ran in the three different shoes.
Analysis of Data

Three-dimensional coordinates for the seven markers were calculated using the standard transformation procedures provided by the Selspot MultiLab system. The knee angle was calculated using these three-dimensional coordinates while the rearfoot angle was calculated as a projection of the angle on a frontal plane. The collection window was extended from 70 ms before footstrike until 275 ms after footstrike in order to have safe margins for filtering and differentiation procedures. A fourth-order Butterworth filter (low pass, zero time lag, cutoff 12 Hz arbitrarily chosen) was used to smooth the three-dimensional coordinates, and a 5-point numerical differentiation procedure was used to calculate angular velocities (Ingen Schenau, 1972). Ten footstrikes per subject for each condition were averaged and standard deviations at each sampling observation were also calculated. A two-factor (Shoe Type × Joint) repeated-measures ANOVA was used to analyze the results. If there was a significant joint/shoe interaction, the simple effects for joints and shoes were explored. A Duncan's multiple comparison procedure was used to perform post hoc comparisons.
Figure 3 — Location of the LED targets and the inertia switch. Conventions for the calculation of leg, shoe, rearfoot, and knee angles are also shown.

Table 2

Mean Values and Standard Deviations for Standing Calibration Angles (in degrees)

<table>
<thead>
<tr>
<th>Shoe type</th>
<th>Leg  M</th>
<th>Leg  SD</th>
<th>Shoe  M</th>
<th>Shoe  SD</th>
<th>Rearfoot  M</th>
<th>Rearfoot  SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varus</td>
<td>4.3</td>
<td>2.0</td>
<td>10.3</td>
<td>0.7</td>
<td>6.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Neutral</td>
<td>5.4</td>
<td>2.2</td>
<td>-0.9</td>
<td>1.1</td>
<td>-6.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Valgus</td>
<td>4.9</td>
<td>2.6</td>
<td>-11.0</td>
<td>3.7</td>
<td>-15.9</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Results

The response of the subjects to the different shoes during standing are shown in Table 2. The mean rearfoot angles and shoe angles in the three conditions were all significantly different from each other, but there was no significant difference in the mean leg angles. The approximate $5^\circ$ varus of the lower leg resulted in rearfoot angles of 6.1, $-6.4$, and $-15.9^\circ$ for the varus, normal, and valgus conditions, respectively. These are close to the $5$, $-5$, and $-15^\circ$ values that would
Figure 4 — Rearfoot angles (and standard deviations) (upper curves) and knee angles (lower curves) as functions of time for a typical subject in all three shoe conditions. The times of maxima in the rearfoot angle curves are indicated by the symbols.

be expected if the shoes assumed their unloaded orientations during standing with 5° of varus of the leg.

The dynamic rearfoot and knee angles as functions of time during running for the subject closest to the mean response in all three shoe conditions are shown in Figure 4. The standard deviations have been excluded for the knee data since the three curves were so close together. Many of the group trends reported below are evident in Figure 4. For example, it is apparent from the figure that, while
there was a marked response to the different shoes in the rearfoot angle, the knee angle patterns were remarkably similar in all shoe conditions.

A comparison of the maximum pronation values for the three shoe conditions in all subjects (Table 3) indicated that all conditions were significantly different from each other ($p<.01$). The peak values for the varus, neutral, and valgus shoes were $-2.3^\circ$ ($SD 2.5$), $-11.8^\circ$ ($SD 2.7$), and $-21.7^\circ$ ($SD 3.5$). The value for each perturbated shoe was within half a degree of the $10^\circ$ difference that was built into the shoe when compared to neutral. There were no significant differences in the magnitude of maximum knee flexion between shoe conditions.

As can be seen in Figure 4, times to maximum pronation varied widely between shoe conditions but the times to maximum knee flexion were closely grouped. During the first 150 ms there were clearly two phases in each rearfoot curve, an initial rapid phase of pronation during the first 50 ms and a prolonged phase in which the endpoint of the motion was maintained with little further motion. In contrast, the knee flexion phase was followed immediately by knee extension. It also appears that the gradients of the initial pronation phase increased progressively from the varus, through neutral, to the valgus shoe condition.

The group data for important events in the joint angle curves are shown in Table 3. The time to maximum pronation was 118.3 ms ($SD 19.2$ ms), 98.3 ms ($SD 20.2$ ms), and 108.9 ms ($SD 18.2$ ms) for the varus, neutral, and valgus shoe conditions, respectively. When running in the neutral shoe, subjects reached peak pronation significantly earlier than in the varus shoe ($p<.01$) or the valgus shoe ($p<.05$). The time to maximum knee flexion was 87.8 ms ($SD 6.2$ ms), 90.0 ms ($SD 7.1$), and 93.3 ms ($SD 9.0$) for the varus, neutral, and valgus shoe, respectively. The time of peak knee flexion in the varus shoe was significantly earlier ($p<.05$) than that in the valgus shoe.

### Table 3

Means and Standard Deviations for Relevant Rearfoot and Knee Parameters  
(angles in degrees, velocities in deg $\cdot$ s$^{-1}$, time in milliseconds)

<table>
<thead>
<tr>
<th>Shoe</th>
<th>MP deg</th>
<th>MKF deg</th>
<th>TMP ms</th>
<th>TMKF ms</th>
<th>MRV deg $\cdot$ s$^{-1}$</th>
<th>MKV deg $\cdot$ s$^{-1}$</th>
<th>TMRV ms</th>
<th>TMKV ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varus</td>
<td>$-2.3^*$</td>
<td>36.0</td>
<td>118.3*</td>
<td>87.8*</td>
<td>$-296.8^*$</td>
<td>470.2*</td>
<td>20.6*</td>
<td>32.2</td>
</tr>
<tr>
<td>SD</td>
<td>2.5</td>
<td>4.0</td>
<td>19.2</td>
<td>6.2</td>
<td>135.1</td>
<td>66.3</td>
<td>12.4</td>
<td>8.0</td>
</tr>
<tr>
<td>Neutral</td>
<td>$-11.8^*$</td>
<td>35.4</td>
<td>98.3*</td>
<td>90.0</td>
<td>$-408.0^*$</td>
<td>448.0*</td>
<td>11.1*</td>
<td>30.6</td>
</tr>
<tr>
<td>SD</td>
<td>2.7</td>
<td>4.1</td>
<td>20.2</td>
<td>7.1</td>
<td>122.7</td>
<td>83.7</td>
<td>4.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Valgus</td>
<td>$-21.7^*$</td>
<td>31.2</td>
<td>108.9*</td>
<td>93.3*</td>
<td>$-492.4^*$</td>
<td>415.1*</td>
<td>10.0*</td>
<td>31.1</td>
</tr>
<tr>
<td>SD</td>
<td>3.5</td>
<td>5.5</td>
<td>18.2</td>
<td>9.0</td>
<td>121.0</td>
<td>100.2</td>
<td>3.5</td>
<td>10.5</td>
</tr>
</tbody>
</table>

MP: max. pronation (deg); TMP: time to max. pronation (ms); MRV: max. rearfoot ang. vel. (deg $\cdot$ s$^{-1}$); TMRV: time to max. rearfoot ang. vel. (ms); MKF: max. knee flex. (deg); TMKF: time to max. knee flex. (ms); MKV: max. knee ang. vel. (deg $\cdot$ s$^{-1}$); TMKV: time to max. knee ang. vel. (ms).

*Value significantly different from others in the column similarly indicated ($p < 0.01$).

**Values significantly different from others in the column similarly indicated ($p < 0.05$).
The interplay between rearfoot motion and knee motion for all shoe conditions is illustrated in the knee angle versus rearfoot angle diagrams for a typical subject in Figure 5. For the group as a whole, peak knee flexion was 30.5 ms (SD 15.3) earlier than maximum pronation in the varus shoe ($p<.01$) and 15.6 ms (SD 15.9) earlier in the valgus shoe ($p<.05$). There was no significant difference between the peaks in the neutral shoe, where the peak knee flexion occurred 8.3 ms (SD 15.2) earlier than peak pronation. The descending "loop" regions of the angle-angle diagrams (highlighted in the diagrams) indicate that knee extension occurred concurrently with a small amount of pronation in both perturbated shoe conditions whereas knee extension occurred almost exclusively with supination in the neutral shoe.

The two phases of the pronation curves and the effect of the shoe on the initial rates of pronation mentioned above were confirmed by an analysis of the

![Figure 5](image_url)

Figure 5 — Rearfoot angle as a function of knee angle for the three shoe conditions in a typical subject. Footstrike is indicated with a vertical bar, and the direction is indicated with an arrow. The highlighted areas indicate simultaneous pronation and knee extension.
rearfoot velocity data. Typical curves, shown in Figure 6, illustrate the progression of peak velocities from valgus to varus shoe conditions and the delayed peak of velocity in the varus shoe condition. Analysis of variance for group data on maximum rates of pronation (Table 3) indicated that all shoe conditions were significantly different from each other (p<.01), with valgus greater than neutral, which was greater than the varus condition. The actual values were −296.8 (SD 135.1), −408.0 (SD 122.7), and −492.4 (SD 121.0) degrees per second for the varus, neutral, and valgus shoe, respectively. The maximum knee angular velocity for the varus shoe (470.2, SD 66.3 deg·s⁻¹) was significantly greater (p<.01) than for the valgus shoe (415.1, SD 100.2 deg·s⁻¹), and the maximum knee velocity for the neutral shoe (448.0, SD 83.7 deg·s⁻¹) was greater than that for the valgus shoe (p<.05).

The peak values for rearfoot angular velocity occurred at 10.0 ms (SD 3.5), 11.1 ms (SD 4.2 ms), and 20.6 ms (SD 12.4 ms) for the valgus, neutral, and varus conditions, respectively. The time for the varus condition was significantly different from both valgus and neutral (p<.01). At the knee there was no significant difference between conditions in the timing of the peaks in the angular velocity. The values were 31.1 (SD 10.5), 30.6 (SD 6.4), and 32.2 (SD 8.0) ms for the valgus, neutral, and varus conditions, respectively. However, the peak of rearfoot velocity was always significantly earlier than the peak knee flexion velocity in all conditions (p<0.01).

Figure 6 — Rearfoot angular velocities as functions of time for a typical subject at the three shoe conditions.
Discussion

The typical pattern of rearfoot motion found in the present study (shown in Figure 4) is similar to those presented by Bates et al. (1978), Clarke et al. (1984), Williams (1985), and Cavanagh (1987). A model curve, similar to that found in this study, was formulated by Clarke et al. (1984) based on characteristic rearfoot motion parameters from the various studies. Only two subjects in this study showed the alternative pattern with a clear second peak of pronation presented by Clarke et al. (1984) and Smith et al. (1986). Future studies might explore differences in knee and rearfoot motion between rearfoot and midfoot strikers, and it should be noted that all but two of the subjects in this study were rearfoot strikers.

The findings that maximum pronation and maximum rates of pronation were significantly different between all shoe conditions were expected. However, the lack of significant differences in maximum knee flexion between shoe conditions was somewhat surprising. Based on Inman’s model of the subtalar joint as a mitered hinge (Inman, 1976), it might be expected that changes in knee motion would result from the rather large perturbation (19.4°) applied to the foot. However, Lundberg et al. (1989) have shown through static in vivo studies that leg and foot motions are not well coupled in the region of internal rotation and pronation, respectively, and thus our view of the relationship between subtalar and knee joint motions may be in need of modification.

It is widely believed that knee extension, in the final 30° of the range of motion, is accompanied by external rotation of the tibia with respect to the femur, the so called “screw home” mechanism (Williams & Warwick, 1980). Although this effect has not been well explored quantitatively, if it occurs within the range of knee flexion encountered during early support (between approximately 7 and 35°), then one might anticipate that internal rotation of the tibia with respect to the femur occurs by virtue of the measured knee flexion. Thus the classical literature (Inman, 1976; Williams & Warwick, 1980) would suggest that the motion at both subtalar and knee joints during the early support phase of running tends to cause internal tibial rotation, and some compensation in the flexion-extension pattern at the knee might be expected if internal rotation was increased by a shoe perturbation.

A major unknown in this respect is the compensation that may be occurring at the hip as far as internal femoral rotation is concerned. Clearly, internal tibial rotation can be completely resolved by internal rotation of the femur without any additional stresses on the knee. It is quite likely that there were differences in internal femoral rotation between the three shoe conditions that were not measured in this experiment. Such adaptation was found by Lafontaine (1984) during walking using the same shoes with the technique of intracortical pins. However, if the screw-home theory is correct, then internal tibial rotation can also be resolved to some extent by flexion of the knee, and we may therefore have expected to see more knee flexion in the valgus shoe condition than either the neutral or varus shoe.

That such adaptation was not found suggests that either the screw-home theory does not hold in this range of motion for the loaded conditions of knee motion used in this study, or that increased internal femoral rotation was present to compensate for the changes. A third possibility is that there was indeed
increased axial rotation of the tibiofemoral joint in the valgus shoe condition and that this resulted in increased strain on the ligamentous structures of the knee joint. A major limitation of the present study is that internal-external rotations at the knee joint were not measured.

The general features of the rearfoot velocity profiles were similar to those presented by Clarke et al. (1984). Although compensation for footwear changes did not occur in the absolute amount of knee flexion, a number of significant kinematic adaptations were found in the velocity data. The pattern of peak velocity changes at the two joints was, as shown in Figure 7, in opposite directions. As the footwear progressively caused less pronation, the velocity of pronation decreased, yet the velocity of knee flexion increased. The anatomical basis for these systematic changes is not clear. They were accompanied by a significantly later peak velocity of pronation in the varus shoe than either of the other shoe conditions.

Peak knee flexion occurred significantly earlier than peak rearfoot angle in both perturbed shoe conditions, but there was no significant difference between these two peaks in the neutral shoe condition. Bates et al. (1979) also found near synchrony of these two peaks in normal subjects using neutral shoe conditions. If "mistiming" of pronation and knee flexion has resulted from the shoe perturbations used in the present experiments, it may be represented by the 30.5-ms and 15.6-ms lead of peak knee flexion over peak rearfoot angle in

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**Figure 7** — Mean maximum knee angular velocity (top) and mean maximum rearfoot angular velocity for the three different shoes.
the varus and valgus shoes, respectively. The time of peak rearfoot velocity was always earlier than the time of peak knee flexion velocity in all trials.

Any consideration of variations of the timing in the peak values for angular motion of the two joints must embrace the notion that the velocity profiles of the two motions are fundamentally different. The peak value of the rearfoot angle curve usually occurs at a time of very little change in the angle, and thus its timing may vary considerably, even between trials in the same subject under the same conditions. The knee angle curve, on the other hand, has a clearly defined peak with relatively high rates of change on either side of the peak. The implication of the variability in the timing of peak rearfoot angle is that it may not be a very useful parameter to define the most important endpoint of the movement.

Although the most rapid events of the pronatory movement are different in magnitude between the shoe conditions, they reach a similar level of change at about the same time. After the first 50 ms, the rearfoot only pronates for an additional 1 to 2°. Thus a variable that defines the distinct change in the gradient of the rearfoot angle versus time curve may be more characteristic and informative than a simple consideration of the timing of the peak value. Such a variable might be the time when rearfoot velocity has fallen below a given criterion value such as −200 deg·s⁻¹. This notion is illustrated by the data in Figure 8, where the sum of the average absolute differences in rearfoot velocity of valgus and varus shoes compared to the neutral shoe is plotted at 25-ms intervals. The difference in rearfoot velocity between conditions declines sharply as time from footstrike increases, until approximately 50 ms, after which there is little difference between the curves.

The limitations of a two-dimensional analysis were explored by examining the standard deviation of the rearfoot angle versus time plots at intervals throughout the contact phase. An example of this approach is shown in Figure

![Graph](image)

**Figure 8** — Sum of absolute differences between rearfoot velocities in valgus and varus shoes compared to neutral shoe at six times after footstrike. The ordinate is \[\text{ABS} (V_{\text{valg}} - V_{\text{neu}}) + \text{ABS} (V_{\text{var}} - V_{\text{neu}})\] where \(V_{\text{valg}}, V_{\text{var}},\) and \(V_{\text{neu}}\) are the mean peak rearfoot velocities in the valgus, varus, and neutral shoes, respectively, for all subjects.
where the mean and standard deviation for 10 contacts in a single subject are shown. There is a progressive increase in the standard deviation of the curve after 175 ms. Although this could represent inherent variability of the subject, it is more likely to be a reflection of the errors involved in angle calculations based on the projection of out-of-plane targets onto a single frontal plane. The standard deviation at each 5 ms of the rearfoot angle curves for each available trial was expressed as a fraction of the overall mean standard deviation for that trial. The mean times at which this fraction exceeded 1.5 and 2.0 was 206 (SD 10.0) and 216 (SD 8.0) ms, respectively.

This approach may offer a quantitative method to clarify some of the limitations of two-dimensional analysis that have been described (Areblad et al., 1990; Soutas-Little et al., 1987). It is likely that the apparent deviations in the rearfoot angle versus time curves from each other after 200 ms (see Figure 4) was a result of this inaccuracy rather than a representation of real differences in the response to the different shoe conditions. It would also appear that the estimate of rearfoot angle deteriorates well after the time of interest in the present study.

Three other studies have employed an experimental condition similar to the neutral shoe condition used in the present experiment (Clarke, Frederick, & Hamill, 1983; Clarke, Frederick, & Hlavac, 1983; Smith et al., 1986). Their subjects also ran in neutral shoes on a treadmill at an approximate 7 min-mile\(^{-1}\) (3.8 m-s\(^{-1}\)) pace. The values for maximum pronation reported in these studies

![Figure 9](https://via.placeholder.com/150)

**Figure 9** — A typical mean rearfoot angle curve as a function of time showing the instantaneous standard deviations for 10 contacts. Note the increase in the standard deviation after approximately 175 ms.
were $-11.7, -11.4,$ and $-11.3^\circ$, respectively, extremely similar to the value of $-11.8^\circ$ found in the present study. In the chosen stride length condition of Williams and Ziff (1991), subjects ran at $3.6 \text{ m/s}$ and exhibited maximum pronation values of $15.7^\circ$.

The mean times of maximum pronation reported by Clarke, Frederick, and Hamill (1983) and Clarke, Frederick, and Hlavac (1983) were both 94 ms compared to the present value of 98.3 ms. The mean values for maximum rearfoot velocity reported by Clarke, Frederick, and Hamill (1983) and Smith et al. (1986) were $-532$ and $-540 \text{ deg/s}$ compared to the value of $-408.0 \text{ deg/s}$ found in the present study, whereas Williams and Ziff (1991) reported values in their chosen condition of $-474.8 \text{ deg/s}$. There was a major difference between the values reported here for time to maximum rearfoot velocity (11.1 ms) and the value of 27 ms found by Clarke, Frederick, and Hamill (1983).

**Concluding Remarks**

All perturbation studies of this nature suffer from the limitation that subjects have not had equal practice under the novel conditions (in this case the varus and valgus shoes) compared to the normal condition (in this case the neutral shoes). In addition, studies of rearfoot motion in shoes generally infer information on movements of the rearfoot from measurements made on the surface of the shoe. Both of these limitations must be borne in mind when interpreting the results of the present study.

Despite the rather extreme perturbations made to the shoe/foot interface in the present study, no change was found in the maximum knee flexion during the support phase. However, there were changes in certain timing and velocity parameters at the knee, suggesting that some kinematic adaptation did occur. Other likely adaptations that need to be studied in the future in order to gain more insight in knee injuries in running include changes in internal femoral and tibial rotation as a response to perturbation at the foot. The analysis of the rearfoot angle and velocity curves has suggested that time to maximum pronation may not be a particularly relevant parameter in understanding the relationship of knee motion to rearfoot motion, or indeed rearfoot motion in its own right. This is because the phase of the curve in which the maximum usually occurs is characterized by a very small angular velocity of rearfoot motion. The use of a threshold value in the velocity curve may serve as a useful device to delineate the two phases that are present in most rearfoot angle versus time data.

The alterations in shoe design used in the present study achieved rather predictable responses in rearfoot angle, in contrast to other experiments where in-shoe orthotic devices were used (Rodgers & LeVeau, 1982; Smith et al., 1986). The alterations in timing and velocity elicited were somewhat less predictable, however, and further work is clearly needed to understand the complexities of the response to shoe or orthotic intervention besides changes in the maximum rearfoot angle.

**References**


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