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Lower Extremity Kinematic and Kinetic Differences in Runners With High and Low Arches

Dorsey S. Williams III, Irene S. McClay,
Joseph Hamill, and Thomas S. Buchanan

High- and low-arched feet have long been thought to function differently. The purpose of this study was to investigate the relationship between arch structure and lower extremity mechanics in runners with extreme pes planus and pes cavus. It was hypothesized that low-arched individuals would exhibit an increased rearfoot eversion excursion, eversion/tibial internal rotation ratio, and increased angular velocity in rearfoot eversion when compared to high-arched runners. In addition, it was hypothesized that high-arched runners would exhibit greater vertical loading rates. Twenty high-arched and 20 low-arched runners with histories of running-related injuries were included in this study. Low-arched runners were found to have increased rearfoot eversion excursion, eversion to tibial internal rotation ratio, and rearfoot eversion velocity. High-arched runners had increased vertical loading rate when compared to low-arched runners. These results suggest that arch structure is associated with specific lower extremity kinematics and kinetics. Differences in these parameters may subsequently lead to differences in injury patterns in high-arched and low-arched runners.

Key Words: foot structure, mechanics, rearfoot, coupling

Introduction

It has often been suggested that lower extremity structural deviations lead to mechanical deviations that place runners at increased risk for injury (Clement, Taunton, Smart, & McNicol, 1981; Gross, 1992; Hamill, Bates, & Holt, 1992; James, Bates, & Osternig, 1978; McClay & Manal, 1997; Smith, Clarke, Hamill, & Santopietro, 1986; Tiberio, 1988). For instance, the term “miserable malalignment syndrome” has been used to describe structural deviations including hip internal rotation, genu valgum, and foot pronation that are often seen in injured runners (James et al., 1978). Abnormal foot

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D.S. Williams, Dept. of Physical Therapy, East Carolina U., Greenville, NC 27858-4353; I.S. McClay, Joyner Sportsmedicine Institute, Harrisburg, PA 17111, and Motion Analysis Lab, U. of Delaware, Newark, DE 19716; J. Hamill, Dept. of Exercise Science, UMass, Amherst, MA 01003; T.S. Buchanan, Center for Biomedical Engineering Research, U. of Delaware.

structure is commonly implicated as a predisposing factor to injuries such as chondromalacia patella and shin splints (Franco, 1987). According to Subotnick (1985), 60% of the population have normal arches, 20% have a cavus foot, and 20% have a planus foot. These latter 40% are most interesting, as it is commonly thought that their structure will lead to some degree of compensation in lower extremity mechanics (Subotnick, 1981). Since the foot is the interface with the ground during gait, structural changes here may cause compensatory malalignment and, consequently, mechanical deviations of the entire lower extremity. Therefore, studies focused on persons with abnormal foot structure could provide insight into abnormalities in lower extremity mechanics.

There are conflicting reports in the literature regarding arch height and its relationship to kinematics. In one study, 17% of the variability present in maximum rearfoot pronation was explained from a measure of navicular drop (McPoil & Cornwall, 1996). Kernozek and Ricard (1990) found that both high-arched and low-arched people had greater rearfoot eversion excursions than those with normal arch structure. Arch height was determined using a dynamic arch index which is a footprint measurement modified from the arch index (Cavanagh, 1987). Results of a study by Hamill et al. (Hamill, Bates, Knutzen, & Kirkpatrick, 1989) suggest that static lower extremity measures including the arch index as described by Cavanagh (1987) have limited value in predicting dynamic lower extremity function. Finally, Nachbauer and Nigg (1992) found no relationship between either arch height or arch lowering and ground reaction force parameters. The results seen in these studies are likely due to the different ways that arches were categorized and the criteria used to place subjects in different arch groups.

The influence of arch structure on coupling of motion in the lower extremity has received recent attention. Nigg, Cole, and Nachbauer (1993) found that arch height (as described by Hawes, Nachbauer, Sovak, & Nigg, 1992) did not affect the individual measurements of maximum eversion excursion or maximum tibial internal rotation excursion during the stance phase of running. However, they determined that 27% of the variance present in the eversion/tibial internal rotation ratio (EV/TIR) was explained by arch height. This suggests that the individual measurements of lower extremity excursion may provide less significant information than the relative coupling between these motions. In fact, Nawoczenski et al. (Nawoczenski, Saltzman, & Cook, 1997) also found that arch height, as characterized radiographically, was significantly related to EV/TIR. Low-arched runners had a higher EV/TIR, while high-arched runners had greater relative internal rotation resulting in a lower EV/TIR. It has been suggested that a difference in this ratio places runners at risk for different injuries (McClay & Manal, 1997; Nawoczenski et al., 1997; Nigg et al., 1993). High EV/TIR, with relatively greater eversion excursions, are thought to place runners at greater risk of foot injuries. Low EV/TIR ratios result in more transverse motion transferred to the tibia, possibly increasing the risk of knee injuries.

Velocity as well as motion has also been associated with factors related to pes planus (Smith et al., 1986). Excessive angular velocity, especially when associated with eccentric muscle activity, may increase strain rates on the soft tissues and lead to injury as well. Smith et al. (1986) studied a group of runners whose orthotic intervention had resulted in a reduction of their symptoms and found that these orthotic devices had a greater effect on pronation velocity than peak pronation. These findings suggest that rate rather than motion may be a more critical factor in injury.

Ground reaction forces (GRF) have been investigated in runners with different arch structures (Nachbauer & Nigg, 1992). No differences were found in GRF timing parameters when comparing arch height and arch flattening. However, increased vertical loading rate has previously been associated with knee pain (Radin, Yang, Reigger, Kish, & O'Connor, 1991). Increased vertical loading rates have been associated with increased tibial shock (Hennig, Milani, & Lafortune, 1993). Evaluation of vertical loading rate has not been compared in individuals with differing foot types. Therefore, evaluation of loading rates may lend further insight into differences in injuries between high-arched and low-arched runners.

Based on the previous literature, few studies have utilized subjects with extreme structural deviations. Subjects with greater deviations in arch structure may be more limited in their compensatory strategies and more likely to present with mechanical deviations. If these relationships can be established in individuals with extremely high or low arch measurements, it may be possible to explain the injury mechanisms found in the individuals exhibiting similar injury patterns but with less severe arch characteristics.

The purpose of this study was to investigate the relationship between arch structure and lower extremity mechanics in runners. It was hypothesized that low-arched individuals would exhibit an increased rearfoot eversion excursion, EV/TIR, and increased angular velocity in rearfoot eversion. Additionally, it was hypothesized that high-arched runners would have greater vertical loading rates when compared to low-arched runners.

Methods

Participants for the study were recruited from the University of Delaware and its surrounding community through physicians' offices, physical therapy clinics, and fitness centers. The study included 20 high-arched runners (10 M, 10 F) and 20 low-arched runners (8 M, 12 F) between the ages of 18 and 50 (mean = 27.8 yrs ± 8.1) with no neurological abnormality, history of foot surgery, or lower extremity injury at the time of the study. Runners were excluded if they were ACL-deficient or had had lower extremity surgery in the previous 12 months. Because questions regarding injury were part of a larger study, all participants had to have a history of running-related lower extremity injury to be included in the study. Participants ran at least 6 miles a week at a minimal 8-min per mile pace. All gave informed consent prior to the study.

Participants were screened with the use of an arch ratio for inclusion in the high-arched or low-arched group. The arch ratio was defined as the height to the dorsum of the foot from the floor at 50% of the foot length divided by the individual's truncated foot length. Truncated foot length was the length of the foot from the most posterior portion of the calcaneus to the medial joint space of the first metatarsal phalangeal joint. An arch ratio of at least 0.356 was needed for inclusion in the high-arched group, and less than or equal to 0.275 for inclusion in the low-arched group. These values fell at or outside 1.5 standard deviations of the mean arch ratio measurement of 0.316 (*SD* = 0.027) based on a previously collected sample of 102 feet (Williams & McClay, 2000). This arch ratio was found to be a reliable and valid method of categorizing feet in both 10% weight bearing and 90% weight bearing. ICC values were above 0.939 for intratester reliability, above 0.811 for intertester reliability, and above 0.844 for concurrent validity (Williams & McClay, 2000).

Those who met the inclusion criteria returned to the lab for a complete gait analysis. Retroreflective markers (anatomical markers and at least three tracking markers per segment) were placed unilaterally (side of greatest previous injury involvement) on the segments of the rearfoot, lower leg, thigh, and pelvis (Figure 1). The three rearfoot markers were placed directly on the heel and extended through windows cut in the shoes. Windows allowed for unabated motion of the markers on the heel. Previous pilot work in this lab determined that these holes result in a 10% decrement in heel counter stability, as measured by an Instron materials testing device (Canton, MA).

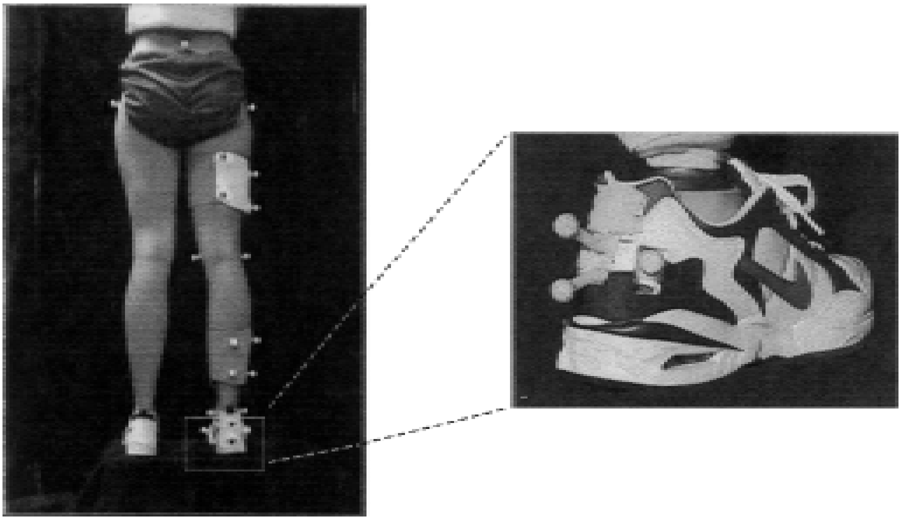

Figure 1 — Retro-reflective marker placement on the tested lower extremity. Enlargement shows placement of rearfoot markers on the calcaneus projecting through holes in the shoe.

Anatomical markers were placed over bilateral greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, medial and lateral forefoot, and at the most anterior point on the end of the shoe (Figure 1). An anatomical coordinate system was established for each foot, lower leg, thigh, and pelvis in order to determine joint kinematics. Kinematic data were collected at 120 Hz using a 6-camera VICON motion analysis system (Oxford Metrics Ltd, UK). Anatomical markers were then removed following a standing calibration. All runners wore the same brand and model of shoes in order to reduce variability related to footwear. They were then asked to run along a 25-m runway at a speed of 3.35 m/s (8 min/mile pace). Speed was monitored with photocells, and only trials within ±5% of the target speed were accepted. A force plate (BERTEC, Worthington, OH) mounted in the center of the runway recorded ground reaction forces at 960 Hz.

All data were analyzed between heel strike and toe-off and normalized to 100 data points, each representing 1% of the stance phase of gait. The 3-D coordinates of each marker were reconstructed using the VICON motion analysis software. The 3-D coordinates were filtered using a 2nd-order recursive Butterworth filter with an 8-Hz cutoff frequency. Force data were low-pass filtered at 50 Hz. MOVE 3-D software (National Institutes of Health Biomechanics Lab, Bethesda, MD) was used to determine joint kinematic data. Kinematic data were resolved about a joint coordinate system (Grood & Suntay, 1983). Finally, vertical loading rate was determined by calculating the rate of rise of the heel strike transient of the vertical ground reaction force over the interval spanning 20% to 80% of this initial peak.

Comparisons between high-arched and low-arched runners were made using a one-tailed Student's *t*-test ($p \leq 0.05$) to determine whether there were differences between high-arched and low-arched groups in EV/TIR, eversion excursion, eversion velocity, and vertical loading rate. EV/TIR was evaluated during the first 60% of stance. In order to further investigate knee mechanics in these groups, eversion to knee internal rotation ratio and peak knee flexion was also assessed. Tibial internal

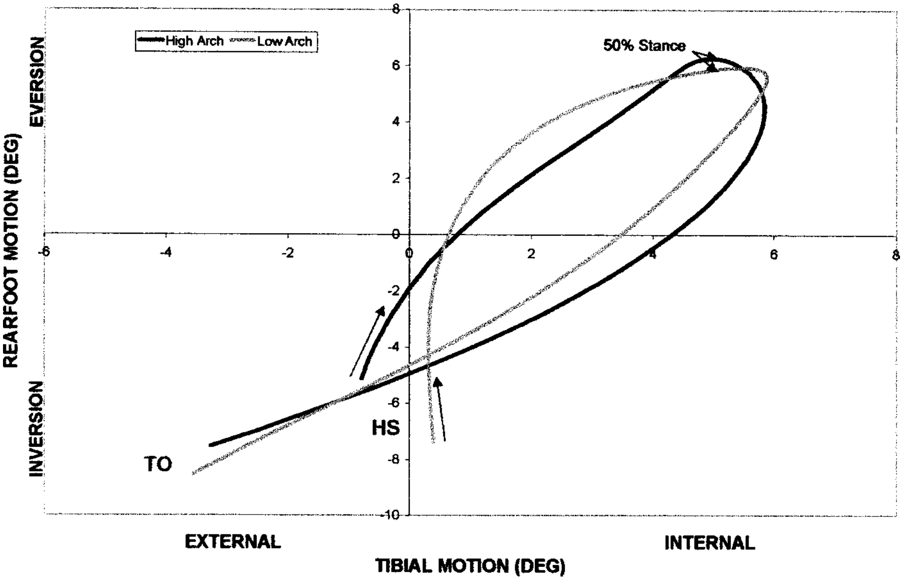

Figure 2 — Angle-angle diagram of rearfoot eversion to tibial internal rotation during stance in high-arched and low-arched runners. Note the similarity in patterns with the exception of greater tibial internal rotation in the low-arched runners in early stance.

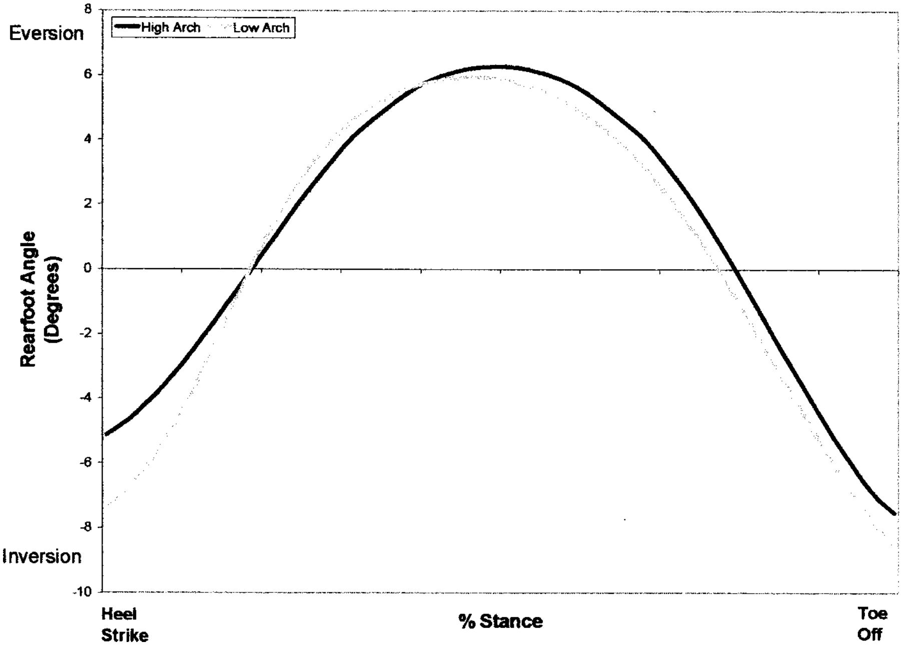

Figure 3 — Rearfoot eversion in high-arched and low-arched runners. Note higher ankle inversion at heel strike in the low-arched group.

rotation is defined as internal rotation of the tibia with respect to the foot, which is considered fixed during the stance phase of gait. Knee internal rotation is defined as internal rotation of the tibia with respect to the femur.

Results

There were no differences between groups in average height (high = 1.72 m, low = 1.74 m, $p = 0.51$) or average mass (high = 66.45 kg, low = 72.10 kg, $p = 0.18$). High-arched and low-arched runners' arch ratios fell outside 1.9 and 1.7 standard deviations, respectively, of the previously collected sample mean of 102 feet ($SD = 0.316$).

Low-arched runners exhibited a greater EV/TIR than high-arched runners (Table 1). Low-arched runners had more eversion excursion and less tibial internal rotation excursion than high-arched runners (Figure 2).

Low-arched runners had significantly greater rearfoot eversion excursion when compared to high-arched runners (Table 1). This difference was the result of the greater inversion of the rearfoot that occurred at heel strike in the low-arched group (Figure 3). Low-arched runners also showed a greater eversion velocity than high-arched runners did (Table 1). This difference represents a 32% faster eversion velocity when compared to the high-arched runners.

Vertical loading rate was determined to be significantly lower in the low-arched group when compared to the high-arched runners (Table 1). The lower loading rate is a result of a lower initial peak occurring over a longer period of time in the low-arched group (Figure 4).

The eversion to knee internal rotation coupling ratio did not differ significantly between the two groups (Table 1). The knee (tibia relative to femur) remained in greater external rotation during the first half of stance (Figure 5), while the tibia was in greater internal rotation in the low-arched runners (Figure 2). This suggests that the femur relative to the tibia was more internally rotated in the low-arched group, producing knee external rotation. Finally, low-arched runners also showed a greater peak knee flexion than high-arched runners (Table 1). This data was incorporated in order to explain differences seen in injury patterns between the two groups (Table 2).

Table 1 Kinematic Variables

	High arch	Low arch	*p* value
Arch ratio	0.367 (0.013)	0.271 (0.023)	0.000*
Eversion excursion (°)	11.90 (3.73)	13.96 (3.63)	0.047*
EV to tibial internal rotation ratio	1.29 (0.40)	1.71 (0.92)	0.037*
EV to knee internal rotation ratio	1.00 (0.37)	1.05 (0.48)	0.714
Eversion velocity (°/s)	165.96 (58.23)	219.30 (65.34)	0.006*
Peak knee flexion (°)	46.48 (4.08)	49.19 (5.45)	0.040*
Loading rate (N/s)	62.48 (13.62)	52.05 (10.79)	0.006*

Note: EV = rearfoot eversion; °/s = degrees per sec; N/s = Newtons per sec. *Statistically significant.

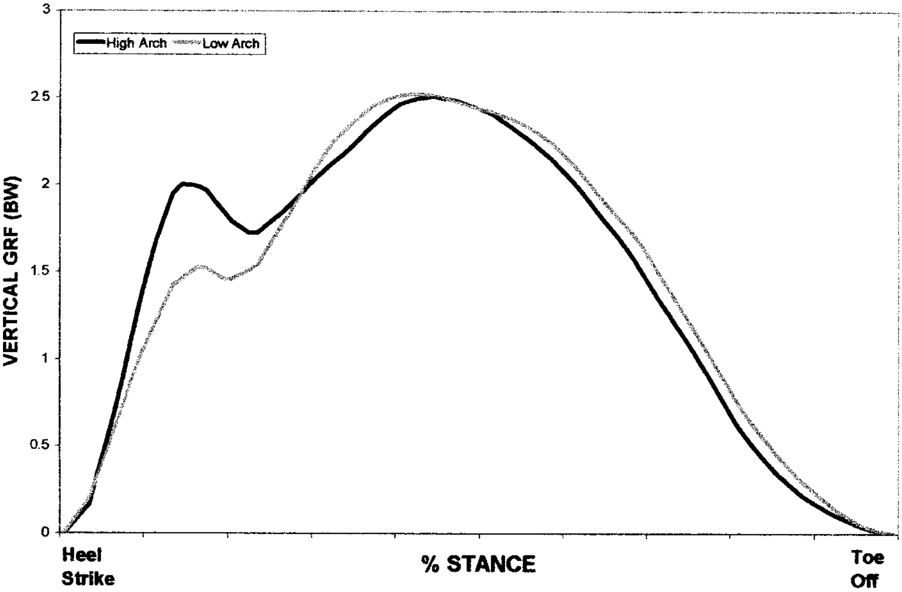

Figure 4 — Representative vertical ground reaction force curves for high-arched and low-arched groups.

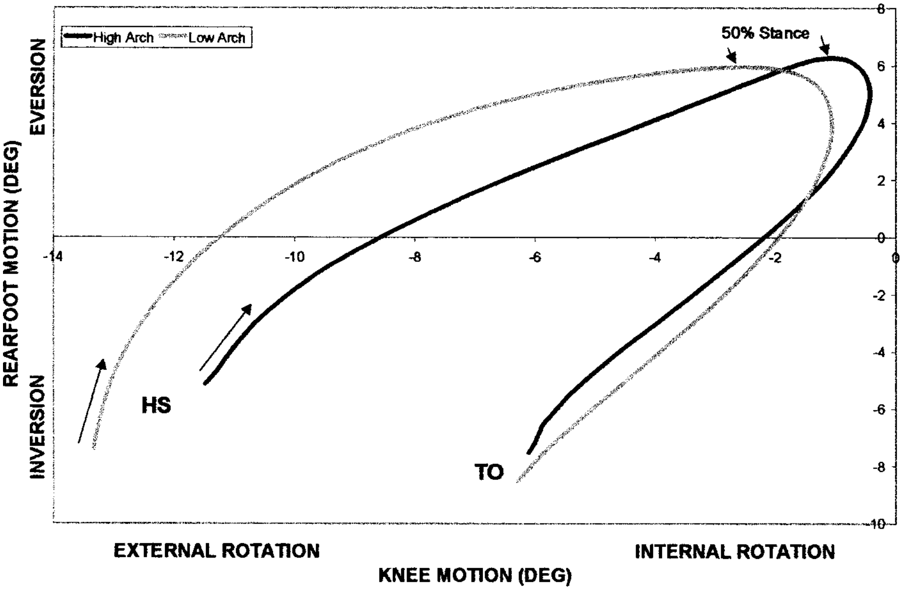

Figure 5 — Angle-angle diagram of rearfoot eversion and knee internal rotation during stance. Units are in degrees. Note the greater knee external rotation throughout the first half of stance in the low-arched runners.

Table 2 Injury Patterns

	High arch	Low arch
Knee	11	20
Foot/ankle	33	24
Bone	14	7
Soft tissue	42	56

Discussion

This study examined differences in kinematic variables between runners with different foot types. Although some differences have been found between high-arched and low-arched runners in the past (Nawoczenski et al., 1997; Nigg et al., 1993), there is still disagreement regarding relationships between arch structure, mechanics, and injury (Kernozek & Ricard, 1990; Hamill et al., 1989; Nachbauer & Nigg, 1992). This study focused on individuals with extreme differences in structure, which may be less easily accommodated mechanically. As a result, lower extremity mechanics were found to be different between groups of runners with high-arched vs. low-arched feet. These differences may account in part for the difference in injury patterns between high-arched and low-arched runners.

The values found in this study are consistent with what has previously been reported in the literature for rearfoot eversion excursions (range = 10.04 to 31.6°), rearfoot eversion velocity (range = 213.91 to 271.4°/s), and tibial internal rotation velocity (range = 113.6 to 239.8°/s) (Kernozek & Ricard, 1990; McClay & Manal, 1997; Nawoczenski et al., 1997; Nigg et al., 1993; Williams, McClay, & Manal, 2000). EV/TIR values were consistent with values of 1.53 ± 0.62 previously reported for normals in this lab (McClay & Manal, 1997). However, Nawoczenski et al. (1997) reported slightly lower values in high-arched (0.91 ± 0.65) and low-arched (1.5 ± 1.3) runners than are reported in the current study.

Although significantly lower in the high-arched group, all runners showed EV/TIR values above 1.0, which suggests there was a higher proportion of rearfoot eversion than tibial internal rotation excursion across all participants. These findings are consistent with those of Lundberg et al. (Lundberg, Svensson, Nemeth, & Selvik, 1989), who reported that the average inclination angle of the subtalar joint axis in the sagittal plane was 32° based on a measure of a fully loaded foot in vivo. Previous reports of average subtalar joint inclination of 42° (Manter, 1941) were based on cadaveric feet measured in non-weight-bearing. An axis inclined 42° in the sagittal plane would theoretically result in approximately equal transverse and frontal plane motions (EV/TIR = 1.0). However, most studies report EV/TIR values greater than 1.0 (McClay & Manal, 1997; Nawoczenski et al., 1997; Nigg et al., 1993), due to relatively more eversion than internal rotation during rearfoot pronation; this suggests that the reference EV/TIR value of 1.0 might need to be reconsidered.

The increased relative rearfoot eversion excursion in the low-arched group was associated with similar tibial internal rotation excursion (Figure 2) in both groups during the first half of stance. This accounts for the significant increase in the EV/TIR ratio in the low-arched runners. It has been suggested that this greater EV/TIR ratio will result in more foot and ankle injuries. However, injury reports from these participants (Table 2) demonstrate that low-arched runners had more knee injuries while high-arched runners had more foot and ankle injuries. Thus the EV/TIR, while statistically significant, may be clinically irrelevant and other mechanisms may be involved.

Interestingly, the eversion to knee internal rotation ratio did not differ significantly between the two groups. However, when assessing the pattern of eversion to knee internal rotation motion, it was noted that the knee was in greater external rotation in the low-arched runners during the loading phase of gait. The greater knee external rotation in the low-arched runners was associated with similar tibial internal rotation between the two groups, suggesting greater femoral internal rotation with respect to the tibia in these runners.

Since the low-arched runners had more femoral internal rotation during the first part of stance, there may have been a subsequent increase in the dynamic quadriceps angle. An increase in femoral internal rotation would place the patella in a more lateral position relative to the femur. A higher peak knee flexion angle was also seen in the low-arched runners, which may result in an increase in the patellofemoral joint contact forces. Additionally, it has been shown that there is a greater amount of lateral patellar translation with increased knee flexion (Koh, Grabiner, & DeSwart, 1992). The increase in quadriceps muscle force would be needed to prevent further knee flexion and would likely increase the patellofemoral joint contact force. Based on this example, the larger force coupled with a possibly malaligned patella may contribute to knee injuries in the low-arched population.

Low-arched runners had approximately 2° more rearfoot eversion excursion than high-arched runners during the first 60% of the stance phase. One previous study reported similar findings with low-arched runners exhibiting 2° greater rearfoot eversion excursion than high-arched individuals (Kernozek & Ricard, 1990). These results suggest that even at the extremes of arch structure, the difference in absolute eversion motion is small. However, it should be recognized that this small mechanical effect might have significant clinical implications for injury, as it represents a 17.3% difference between the two groups. Conversely, it is also possible that the lower excursion seen in the high-arched runners may have prevented them from accommodating to the surface and predisposed them to a greater number of foot injuries compared to low-arched runners (Table 2).

Increased rearfoot eversion velocity was seen in the low-arched group and was due to greater eversion excursion occurring during the same time period in the low-arched runners. This may result in an increased demand for control of frontal plane motion at the rearfoot. Increased joint velocities have been suggested as a possible mechanism of injury, especially when functioning in an eccentric manner and lengthening under load (Smith et al., 1986). For example, since the posterior tibialis acts to decelerate eversion during early stance, the increased velocity in the low-arched group may lead to a greater incidence of posterior tibialis tendinitis.

Although peak vertical ground reaction force was similar in both groups, the high-arched runners had higher vertical loading rates (Figure 4). This increased loading may help explain the increased incidence of bony injuries in the high-arched group (Table 2). This is in agreement with the previous findings that vertical loading rate is associated with tibial shock (Hennig et al., 1993) and may likely result in bony injuries (Radin et al., 1991). The high-arched runners in the current study had significantly higher rates of bony lower extremity injuries. Additionally, the foot receives the greatest shock of the lower extremity since it is the contact with the ground. This may account for the higher number of ankle and foot injuries reported in the high-arched runners (Table 2). Therefore, high-arched runners may benefit from training techniques to decrease vertical loading rate during running. Since loading rate is calculated during the passive phase of landing, this may require more preactivation of the quadriceps muscle group prior to heel contact. DeVita and Skelly (1992) found that increasing knee flexion during landing did result in smaller loading rates, suggesting that training subjects to increase knee flexion excursion during stance may decrease loading in both the active and passive phases.

In conclusion, the results of this study suggest there is a relationship between arch structure and lower extremity kinematics and kinetics during running. Low-arched runners seem to experience greater rearfoot eversion excursion, velocity, and higher eversion to tibial internal rotation ratios. High-arched runners also had greater vertical loading rates in the lower extremity when compared to low-arched runners. These differences may likely result in different injury patterns in individuals with differing foot structures. These relationships may suggest improved treatment and intervention strategies for runners.

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