

# Orthotic intervention in forefoot and rearfoot strike running patterns

Carrie Laughton Stackhouse<sup>a,\*</sup>, Irene McClay Davis<sup>b,c</sup>, Joseph Hamill<sup>d</sup>

<sup>a</sup> Motion Analysis Laboratory, Shriners Hospitals for Children, 3551 North Broad Street, Philadelphia, PA 19140, USA

<sup>b</sup> Joyner Sportsmedicine Institute, Mechanicsburg, PA 17055, USA

<sup>c</sup> Department of Physical Therapy, University of Delaware, Newark 19716, DE, USA

<sup>d</sup> Department of Exercise Science, University of Massachusetts, Amherst, MA 01003, USA

Received 8 March 2001; accepted 4 September 2003

## Abstract

**Objective.** To compare the differential effect of custom orthoses on the lower extremity mechanics of a forefoot and rearfoot strike pattern.

**Design.** Fifteen subjects ran with both a forefoot and a rearfoot strike pattern with and without orthoses. Lower extremity kinematic and kinetic variables were compared between strike pattern and orthotic conditions.

**Background.** Foot orthoses have been shown to be effective in controlling excessive rearfoot motion in rearfoot strikers. The effect of orthotic intervention on rearfoot motion in forefoot strikers has not been previously reported.

**Methods.** Five trials were collected for each condition. Peak rearfoot eversion, eversion excursion, eversion velocity, peak inversion moment, and inversion work were compared between conditions. Kinematic variables in the sagittal plane of the rearfoot and in the frontal and sagittal plane of the knee were also determined.

**Results.** Increased rearfoot excursions and velocities and decreased peak eversion were noted in the forefoot strike pattern compared to the rearfoot strike pattern. Orthotic intervention, however, did not significantly change rearfoot motion in either strike pattern. Reductions in internal rotation and abduction of the knee were noted with orthotic intervention.

**Conclusions.** Foot orthoses do not differentially effect rearfoot motion of a rearfoot strike and a forefoot strike running pattern. Orthotic intervention has a larger and more systematic effect on rearfoot kinetics compared to rearfoot kinematics.

## Relevance

Due to the similarity in response to orthotic intervention, foot strike pattern should not be a factor when prescribing a foot orthoses for controlling rearfoot motion.

© 2003 Elsevier Ltd. All rights reserved.

**Keywords:** Forefoot strike pattern; Lower extremity mechanics; Orthotic intervention

## 1. Introduction

The effects of orthotic intervention on rearfoot motion have been studied extensively. While some studies have shown no effect (McCulloch et al., 1993; Stacoff et al., 2000; Nawoczinski et al., 1995) others have reported a reduction in some component of rearfoot motion including peak rearfoot eversion (Bates et al., 1979; Rodgers and Leveau, 1982) total rearfoot range of motion (eversion excursion) (Baitch et al., 1991; Novick and Kelley, 1990), and rearfoot eversion velocity (Smith

et al., 1986). Some of the discrepancy in the literature is related to the small (but perhaps clinically relevant) effect size combined with high variability in response to orthotics and relatively low subject numbers in many of the studies.

All orthotic studies to date have been performed on runners who strike the ground with their heel first (rearfoot strikers). However, there are individuals who do not utilize this type of strike pattern when running. Kerr et al. (1983) filmed a total of 753 runners during a 10-km road race and a marathon and reported that nearly 20% made initial ground contact with their midfoot or forefoot. Additionally, a survey study reported that 27% of males and 39% of females strike the ground with their forefoot (the authors did not specify

\* Corresponding author.

E-mail address: [claughton@shrinenet.org](mailto:claughton@shrinenet.org) (C.L. Stackhouse).

whether their group included sprinters who are mostly forefoot strike (FFS) runners) (Brunet et al., 1990).

FFS runners have been shown to exhibit different rearfoot mechanics compared to rearfoot strike (RFS) runners (McClay and Manal, 1995). RFS runners land in approximately 5° of rearfoot inversion and evert to approximately 10° of eversion at midstance. FFS runners exhibit similar peak eversion values at mid-stance compared to rearfoot strikers but contact the ground in a greater degree of inversion, resulting in greater eversion excursions and eversion velocities. Foot orthotic devices (FODs) are designed to provide rearfoot control in early stance, when the heel is on the ground. While the heel may contact the ground during mid-stance in a FFS pattern, the rearfoot is not in contact with the ground in early stance when orthotics are purported to provide rearfoot control. Therefore, a FFS pattern may be a contraindication for the prescription of a biomechanical foot orthosis.

While the focus of orthotics studies have been on the rearfoot, orthotic devices are also prescribed to runners with overuse injuries of the knee. Pronation of the subtalar joint is coupled with internal rotation of the tibia, which, in turn accompanies flexion of the knee (Hamill et al., 1992; McClay and Manal, 1997). Therefore, restricting movement of the rearfoot complex may indirectly control knee motion and result in alleviating knee pain (Eng and Pierrynowski, 1993; Way, 1999). However, few studies have examined the effect of foot orthotics on knee mechanics. Furthermore, no studies have assessed the effect of a foot orthosis on the knee kinematics of a FFS pattern.

The purpose of this study was to compare the effect of orthotic intervention on the rearfoot motion of both a FFS and RFS pattern. It was hypothesized that FODs would decrease peak rearfoot eversion, eversion excursion, and eversion velocity with a RFS pattern but not with a FFS pattern. It was also expected that orthotics would decrease knee abduction and internal rotation in the RFS pattern but not in the FFS pattern as these motions are associated with pronation.

## 2. Methods

Fifteen runners between the ages of 18 and 45 years and with no history of orthotic use participated in this study. Subjects were recruited by sending flyers to local running clubs, to the cross-country team at the university, and to physical education running classes at the university. All subjects were free of injury at the time of the study. Previous research has shown that RFS runners, when asked to run with a FFS pattern, do not differ in rearfoot kinematics or kinetics from natural FFS runners (Williams et al., 2000). In order to simplify subject recruitment and increase statistical power by

utilizing a repeated measures design, the participants in this study were all RFS runners. Any subjects exhibiting abnormal standing lower extremity alignment (i.e. genu varum, pes planus, pes cavus) were excluded. In addition, subjects who lacked normal rearfoot range of rearfoot motion (approximately 10° eversion to 20° inversion), or exhibited forefoot malalignments (varus or valgus), were also excluded. All subjects exhibited a standing relaxed calcaneal position between 0° and 5° of eversion. The University Human Subjects Review Board approved all methodological procedures and subjects gave an informed written consent prior to participation.

Semi-rigid FODs, fabricated from suborthelene with neoprene covers, were constructed from non-weight bearing, neutral positioned plaster casts (Losito, 1996). As all subjects exhibited lower extremity alignment and structure that was within normal limits, all orthoses were posted similarly with 6° of varus posting to assist in controlling eversion. No forefoot posting was added as subjects with forefoot deformities were excluded. The subjects underwent a gradual two-week adjustment period with the FODs. After this adjustment period, the subjects returned to the lab for collection of three-dimensional kinematic and ground reaction force data on their dominant leg.

Retro-reflective markers were placed over the greater trochanters bilaterally, the lumbo-sacral joint, medial and lateral femoral condyles, medial and lateral malleoli, on the medial and lateral borders of the first and fifth metatarsal head respectively, and on the forefoot in order to establish anatomical coordinate systems for the pelvis, thigh, shank, and foot segments.

Additionally, non-collinear tracking markers were placed on each segment. Efforts were made to reduce the effects of marker artifact due to skin movement by choosing marker placement sites with minimal underlying soft tissue. In addition, a previous study comparing bone pin data to skin marker data was done to determine the optimal marker configuration for the shank (Manal et al., 2000). All subjects ran in Nike Air Pegasus shoes (Nike, Beaverton, OR). Holes were cut out of the heel counter to allow the markers to be attached to the calcaneus and project through the shoe. This was accomplished by attaching the marker bases directly to the heel. Once the shoe was on, angled extensions were placed on the bases to which the markers were attached. The angulation of the extensions was determined through pilot work with the goal of providing minimal angular error (a maximum error of 1.28° was determined). The optimal size of the holes was determined such that the markers could project through the shoe without interference during running. Subsequent tests with an Instron materials testing device (Instron Corp., Canton, MA, USA) revealed an acceptable 10% decrement in heel counter stability as a result of the holes.

Five trials for each of four conditions were collected: RFS without the FOD, RFS with the FOD, FFS without the FOD, FFS with the FOD. Several practice trials were performed with the FFS pattern so the subjects could adjust their gait pattern before any data were collected. A  $3.7 \text{ m s}^{-1}$  ( $\pm 5\%$ ) running speed was monitored by two photoelectric beams and a timer.

Video data were collected at 120 Hz with a 6 camera motion analysis system (VICON, Lake Forest, CA, USA). Marker coordinates were low-pass filtered at 8 Hz. Ground reaction force data were collected at 960 Hz with a Bertec force plate (Bertec Corp., Columbus, OH, USA) and were low-pass filtered at 50 Hz. Filtering these data decreased the noise in the center of pressure data in early stance, which allowed a more accurate assessment of the strike index used to verify the strike pattern for each trial (Cavanagh and Lafortune, 1980).

Rearfoot and knee joint kinematics and kinetics were calculated using *MOVE3D* (National Institutes of Health Biomechanics Laboratory, Bethesda, MD, USA) as well as additional custom software. All angular displacement data were resolved about a joint coordinate system (Grood and Suntay, 1983). Angular velocity and angular kinetic data were calculated using a helical axis method. In order to resolve the axis about a more meaningful anatomical orientation, the direction cosines were calculated to correspond to flexion–extension, abduction–adduction, and internal–external rotation.

The primary variables of interest included peak rearfoot eversion, eversion excursion, eversion velocity, inversion moment, and inversion work. Rearfoot inversion moment and inversion work values were normalized to height and weight of each subject. While the focus of the study was on the frontal plane rearfoot mechanics, secondary variables of interest included peak dorsiflexion velocity, and dorsiflexion excursion. In addition, peak knee flexion, knee flexion velocity, and knee flexion excursion were also included in the analysis in order to provide further information on the effect of the orthotic devices on knee mechanics. Once the discrete values were extracted, each of the rearfoot and knee angular curves from the subjects' five trials were normalized to 100% of stance then averaged to produce composite mean curves for each subject. Ensemble average curves were then made for each experimental condition.

### 2.1. Statistical analysis

Two-way repeated measures analysis of variance (ANOVA) tests were performed to determine differences in rearfoot kinematic and kinetic parameters with two main effects: orthotic condition and strike pattern ( $P < 0.05$ ). Summary statistics (mean and standard deviation) were calculated for secondary variables of interest for the main effects.

## 3. Results

The rearfoot and knee angular graphs for a FFS and RFS pattern are presented in Figs. 1 and 2. During the first half of stance of the FFS pattern, the foot landed in plantarflexion and immediately moved into dorsiflexion. In contrast, the RFS pattern began in a dorsiflexed position followed by some plantarflexion to get the foot plantigrade, and then moved into dorsiflexion. In the frontal plane, both strike patterns began with rearfoot inversion followed by immediate eversion, however the FFS pattern exhibited greater inversion at foot strike and consequently greater eversion excursion (Fig. 3). The FFS pattern demonstrated a significantly lower inversion moment and significantly greater eversion velocity compared to the RFS pattern. No differences were found in inversion work between strike patterns (Fig. 3). The patterns of knee movement are similar between strike patterns (Fig. 2). Descriptive statistics (means and standard deviations in Table 1) reveal decreased knee flexion velocity, and knee flexion excursion and increased dorsiflexion velocity, and dorsiflexion excursion for the FFS pattern compared to the RFS pattern (Table 1).

No significant interactions were found between orthotic intervention and strike pattern for any of the variables suggesting there were no differential effects of the orthoses on FFS and RFS patterns. The rearfoot kinematic patterns were not significantly effected by the orthotic intervention. Approximately two thirds of the subjects demonstrated at least a 20% reduction in rearfoot motion kinematic and kinetic variables. On average, a 24% and 33% reduction in inversion moment and inversion work (respectively) were noted with orthotic use (Fig. 3). A post-hoc power assessment indicated that 8–10 additional subjects would have been needed to attain significance in the rearfoot kinetics. A shift in the knee angular patterns in the orthotic condition was noted in the frontal and transverse planes for both strike patterns (Fig. 2). In the secondary variables of interest, orthotic intervention increased dorsiflexion excursions and reduced knee flexion velocities (Table 1).

## 4. Discussion

The purpose of this study was to determine the effects of an orthotic device on the rearfoot motion of both a FFS and RFS pattern. Contrary to the initial hypothesis, the FODs had a similar effect on rearfoot mechanics for both running patterns. Although there were no significant findings for peak eversion, eversion velocity, or eversion excursion, there were some subjects who did demonstrate a reduction in rearfoot eversion with orthotic use. These data suggest that the response to orthotic intervention is highly variable. Greater numbers of

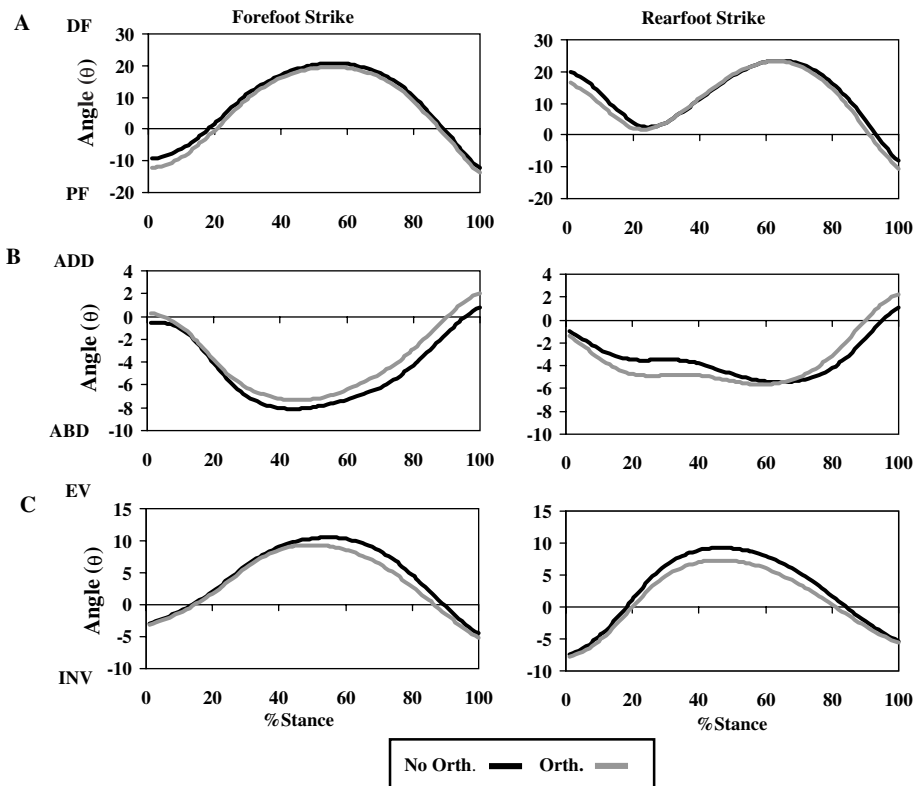


Fig. 1. Rearfoot angles in degrees. (A) Sagittal plane motion: dorsiflexion (DF) and plantarflexion (PF). (B) Transverse plane motion: adduction (ADD) and abduction (ABD). (C) Frontal plane motion: eversion (EV) and inversion (INV). Slight reductions in plantarflexion and eversion occurred when the foot orthosis was worn in both the FFS and RFS pattern. In the transverse plane, a slight reduction in abduction occurred throughout stance when the foot orthosis was worn for the FFS pattern while a slight increase in foot abduction occurred in the first half of stance when the foot orthosis was worn for the RFS pattern.

subjects may assist with determining whether there may be common factors among individuals who do get rearfoot motion control with orthoses. This may help with targeting those patients who are the best candidates for orthotic intervention.

The lack of a significant orthotic effect on rearfoot mechanics may indicate that the type of material used or the amount of rearfoot posting was not substantial enough to elicit a change in rearfoot motion. However, the lack of significant findings has been supported by other studies and may be a reflection of variability in response to FODs (Stacoff et al., 2000; Nawoczenski et al., 1995). Stacoff et al. (2000) reported that the effects of FODs on rearfoot motion were small, insignificant, and inconsistent between subjects. While this study included healthy individuals, variability has been reported in studies with asymptomatic, normally aligned subjects (Stacoff et al., 2000) and studies in which a patient population was used (Rodgers and Leveau, 1982). This variability in response to orthotic intervention may explain, in part, the lack of agreement in the orthotic literature. More work is needed, however, in order to verify this.

While the reduction in inversion moment and inversion work with the use of the FOD was non-significant,

there was possibly a clinically relevant reduction in the means of these variables. Inversion moment and inversion work during the first half of the stance phase during running and walking are indicative eccentric control of eversion. The tibialis posterior provides the major control of this movement. The reductions in inversion moment and inversion work may provide a clearer mechanism for alleviating injuries with orthotic use such as posterior tibial tendonitis.

The investigation into sagittal rearfoot motion revealed an increase in dorsiflexion excursion with the use of the FOD. While Bates et al. (1979) and McCulloch et al. (1993) did not report excursions, they did note an increase in peak dorsiflexion with orthotic use. The FOD may elevate the medial arch of the foot, resulting in a more mediolateral position of the subtalar joint axis leading to an increase in dorsiflexion about this axis. Little is known regarding the effects of FODs on midfoot motion due to the difficulty in measuring these mechanics with surface markers. However, it is likely that along with the small reduction in rearfoot motion, midfoot motion was limited as well. These reductions may have led to a compensatory increase in dorsiflexion excursion to allow the forward progression of the tibia over the foot.

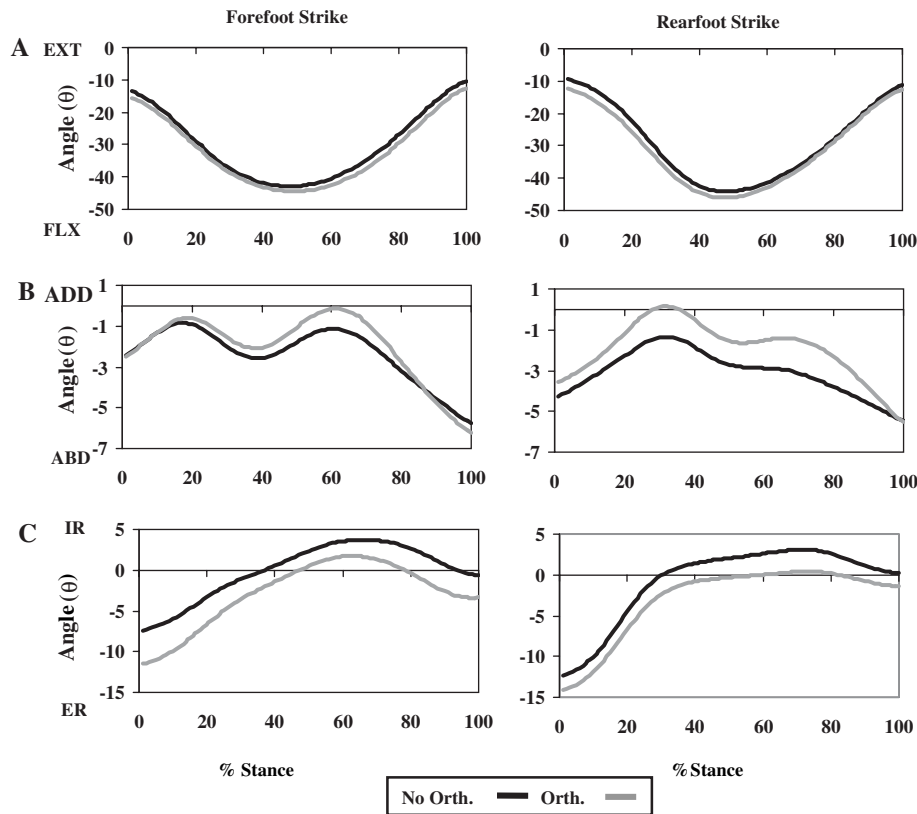


Fig. 2. Knee angles in degrees. (A) Sagittal plane motion: extension (EXT) and flexion (FLX). (B) Frontal plane motion: adduction (ADD) and abduction (ABD). (C) Transverse plane motion: internal rotation (IR) and external rotation (ER). Note the decrease in knee abduction (genu valgum) and the decrease in internal rotation with the use of the orthosis in both the FFS and RFS pattern.

While the focus of orthotic research has been on rearfoot mechanics, knee pain is reported to decrease with the use of a FOD (Eng and Pierrynowski, 1993; Way, 1999). However, the mechanism by which this occurs has not been well understood. In the current study, mean knee flexion velocity decreased with orthotic intervention for both RFS and FFS patterns. This may result in reduced strain rates placed upon soft tissues at the knee joint, thereby alleviating knee pain, such as that associated with patellar tendonitis. It was also interesting to note that the FOD decreased internal rotation and abduction (genu valgum) by approximately  $2^\circ$  throughout most of stance for both FFS and RFS patterns (Fig. 3). Eng and Pierrynowski (1993) also found a decrease in frontal plane knee motion with orthotic intervention while Nawoczenski et al. (1995) reported a decrease in transverse plane motion. A decrease in internal rotation of the knee would be expected in the presence of a decrease in rearfoot eversion as various studies have shown these motions to be coupled. As the knee response was similar between strike patterns, orthotics may potentially relieve certain knee injuries in both RFS and FFS running patterns.

This was the first study to investigate the differential effect of FODs on RFS and FFS running patterns. As healthy subjects were used, caution must be exercised

when extrapolating these data to an injured or at risk population. These findings may be magnified in a patient population, however, studies including populations with specific abnormal mechanics or specific injuries are needed to further validate this.

While there was a substantial adjustment period to the orthotic and to the FFS running pattern for these subjects, it must be recognized that different findings may occur when natural forefoot strikers are prescribed rearfoot motion control orthotics. Differences in the response to orthotics between natural FFS runners and RFS runners who have been trained to run on their forefoot may be possible if there are differences in sensory signaling or muscle action between these groups. The role of sensory signaling in response to rearfoot control orthotics has not been shown, however, the FFS patterns of these natural RFS runners were very similar in their kinematics and kinetics to those of natural FFS runners reported in the literature (Williams et al., 2000). This indicates that both movement patterns and possibly muscle actions are similar between these two types of runners when they are using a FFS pattern. Further studies are needed to determine whether natural FFS runners and RFS running with a FFS pattern respond to orthotic intervention in a similar manner.

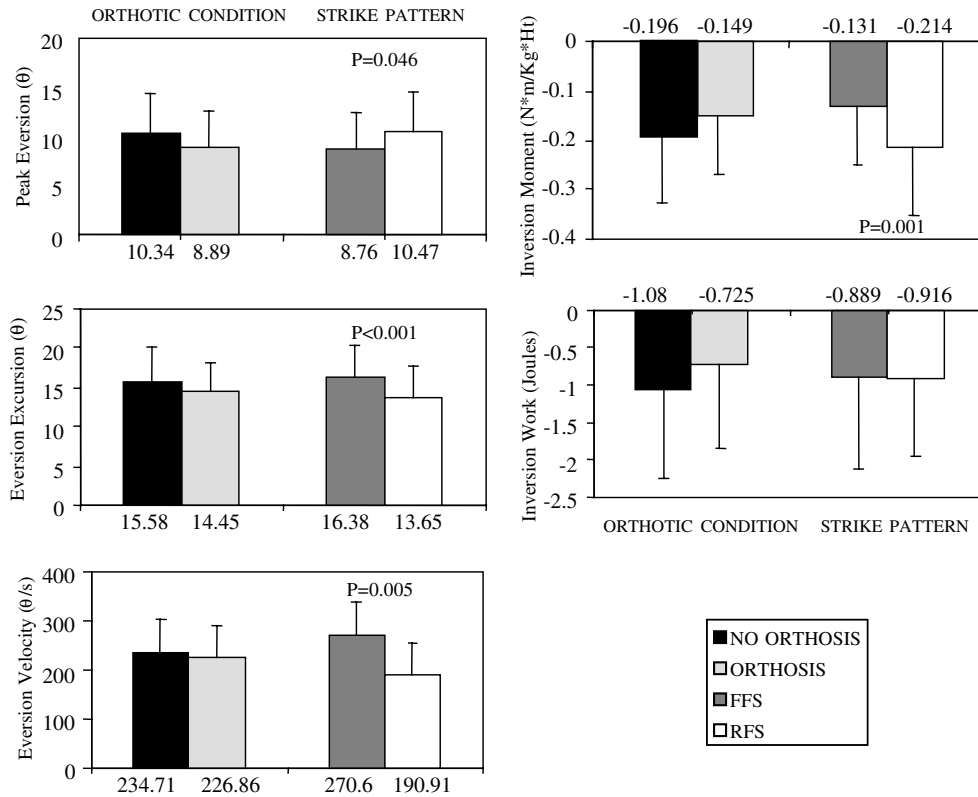


Fig. 3. Means and standard deviations of primary variables of interest: Values include peak eversion, eversion excursion, eversion velocity, peak inversion moment, and inversion work. Inversion moment was normalized to subject height (Ht) and weight. Wearing the foot orthosis had a larger effect on rearfoot kinetics compared to rearfoot kinematics. Reductions in inversion moment and inversion work by 24% and 33% respectively occurred in the orthotic condition for the FFS pattern and RFS pattern combined. Significant differences in the rearfoot kinematic variables and inversion moment were present between the FFS and RFS pattern.

Table 1  
Secondary variables of interest

	Non-orthotic	Orthotic	FFS	RFS
<i>Rearfoot</i>				
Dorsiflexion velocity ( $\theta/s$ )	362.24 (66.89)	381.85 (59.76)	426.73 (78.15)	317.36 (48.51)
Dorsiflexion excursion ( $\theta$ )	24.30 (4.87)	26.51 (4.21)	31.57 (4.31)	19.24 (4.77)
<i>Knee</i>				
Peak knee flexion ( $\theta$ )	-43.89 (5.12)	-45.54 (5.65)	-44.04 (5.65)	-45.39 (5.12)
Knee flexion velocity ( $\theta/s$ )	464.73 (50.25)	444.32 (45.52)	435.96 (56.16)	473.09 (39.61)
Knee flexion excursion ( $\theta$ )	33.51 (4.77)	31.74 (3.69)	30.54 (4.20)	34.71 (4.25)

Means and (standard deviations) for main effects of orthotic and strike pattern.

In summary, the results of these data suggested that the use of custom molded semi-rigid FODs produce similar effects on rearfoot motion, regardless of strike pattern. While these differences were non-significant, all rearfoot motion variables were reduced with orthotic intervention. While the group average reduction in rearfoot motion may not be a large enough reduction to be clinically significant, there were many subjects who demonstrated reductions in rearfoot kinematics and kinetics on the order of 20% or greater with orthotic intervention. More studies with larger numbers of subjects are needed as individual responses to orthotics seem to be highly variable. It was noted that FODs had

a greater effect on frontal plane kinetics compared to kinematics. This suggested that kinetic variables may be a strong indicator of the effect of orthotic intervention and should be included when assessing the efficacy of FODs.

**Acknowledgements**

This work was supported by Foot Management Inc. (Salisbury, MD, USA). The authors would like to thank Dr. James Richards, Dr. David Barlow, and Dr. Dorsey S. Williams for their critical review of this work.

## References

- Baitch, S.P., Blake, R.L., Finegan, P.L., Senatore, J., 1991. Biomechanical analysis of running with 25° inverted orthotic devices. *J. Am. Podiatric Med. Assoc.* 81, 647–652.
- Bates, B.T., Osternig, L.R., Mason, B., James, L.S., 1979. Foot orthotic devices to modify selected aspects of lower extremity mechanics. *Am. J. Sports Med.* 7, 338–342.
- Brunet, M.E., Cook, S.D., Brinker, M.R., Dickinson, J.A., 1990. A survey of running injuries in 1505 competitive and recreational runners. *J. Sports Med. Phys. Fitness* 30, 307–315.
- Cavanagh, P.R., Lafortune, M.L., 1980. Ground reaction forces in distance running. *J. Biomech.* 13, 397–406.
- Eng, J., Pierrynowski, M.R., 1993. Evaluation of soft foot orthotics in the treatment of patellofemoral pain syndrome. *Phys. Therapy* 73, 62–70.
- Grood, E.S., Suntay, W.J., 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J. Biomech. Eng.* 105, 136–144.
- Hamill, J., Bates, B.T., Holt, K.G., 1992. Timing of lower extremity joint actions during treadmill running. *Med. Sci. Sports Exercise* 24, 807–813.
- Kerr, B.A., Beauchamp, L., Fisher, V., Neil, R., 1983. Footstrike patterns in distance running. In: Kerr, B.A. (Ed.), *Biomechanical Aspects of Sport Shoes and Playing Surfaces: Proceedings of the International Symposium on Biomechanical Aspects of Sport Shoes and Playing Surfaces*. University Press, Calgary, pp. 135–142.
- Losito, J.M., 1996. Impression casting techniques. In: Valmassy, R.L. (Ed.), *Clinical Biomechanics of the Lower Extremities*. Mosby, St. Louis, pp. 279–294.
- Manal, K., McClay, I., Stanhope, S., Richards, J., Galinat, B., 2000. Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study. *Gait and Posture* 11, 38–45.
- McClay, I., Manal, K., 1995. Lower extremity kinematic comparisons between forefoot and rearfoot strikers. In: *Conference Proceedings: 19th Annual Meeting of the ASB*, Stanford, CA, pp. 211–212.
- McClay, I., Manal, K., 1997. Coupling parameters in runners with normal and excessive pronation. *J. Appl. Biomech.* 13, 1629–1637.
- McCulloch, M.U., Brunt, D., Vander Linden, D., 1993. The effect of foot orthotics and gait velocity on lower limb kinematics and temporal events of stance. *JOSPT* 17, 2–10.
- Nawoczanski, D.A., Cook, T.M., Saltzman, C.L., 1995. The effect of foot orthotics on three-dimensional kinematics of the leg and rearfoot during running. *JOSPT* 21, 317–327.
- Novick, A., Kelley, D.L., 1990. Position and movement changes of the foot with orthotic intervention during the loading response of gait. *JOSPT* 11, 301–311.
- Rodgers, M.M., Leveau, B.F., 1982. Effectiveness of foot orthotic devices used to modify pronation in runners. *JOSPT* 4, 86–90.
- Smith, L.S., Clarke, T.E., Hamill, C.L., Santopietro, F., 1986. The effects of soft and semi-rigid orthoses upon rearfoot movement in running. *Podiat. Sports Med.* 4, 227–233.
- Stacoff, A., Reinschmidt, C., Nigg, B.M., van den Bogert, A.J., Lundburg, A., Denoth, J., Stussi, E., 2000. Effects of foot orthosis on skeletal motion during running. *Clin. Biomech.* 15, 54–64.
- Way, M.C., 1999. Effects of a thermoplastic foot orthoses on patellofemoral pain in a collegiate athlete: a single subject design. *JOSPT* 29, 331–338.
- Williams, D.S., McClay, I.S., Manal, K., 2000. Lower extremity mechanics in runners with a converted forefoot strike pattern. *J. Appl. Biomech.* 16, 210–218.