The practice of classifying individuals into distinct subgroups is common in research and in clinical practice. Such classifications have several important benefits. First, they provide a better description of what might be considered typical or normal. Second, they provide the relative prevalence of a particular subgroup compared with another. Finally, classification can assist a clinician during evaluation of individuals with pain or dysfunction to select the most appropriate treatment.

To date, most classification schemes for the foot have not used patterns of motion but rather classify the static shape or alignment of the foot and then attempt to document that this alignment or shape dictates motion. These classification schemes have also used static, typically nonweightbearing, measurements such as navicular height,1-3 arch type,4-7 rearfoot angle during stance,8, 9 medial longitudinal arch angle,10, 11 and the presence of rearfoot or forefoot alignment while the subtalar joint is held in its “neutral” position.12,15 Finally, Redmond et al16 proposed a foot classification system called the Foot Posture Index that is based on six postural characteristics of the foot in quiet standing. Although each of these measurements has some value relative to evaluating and designing a treatment intervention program for a patient, they provide little or no information about what the motion pattern of these individuals actually is or whether that motion pattern might be atypical.

We were unable to find a classification system based on the actual motion pattern exhibited by individuals rather than on a static measurement or a discrete point on the motion curve. A classification of rearfoot motion based on the pattern of movement would provide a better idea of exactly what is typical or normal foot motion during walking and, thus, would improve evaluation and treatment schemes for foot-related disorders.

With respect to classification schemes based on motion, the most common method used in the literature has been to classify motion as being either excessive or limited in magnitude.2, 17, 20 Although this is the most common classification method, there are no
accepted criteria for what should be considered excessive or limited. Such attempts at dynamic classification have been further hindered by the many different ways to record foot motion during locomotion and the variety of reference points used to define a neutral or zero position.

The purpose of this study was to identify common frontal plane rearfoot inversion and eversion motion patterns in an asymptomatic population during walking. As such, this study attempts to describe the variety and relative frequency of the different motion patterns exhibited by healthy, asymptomatic individuals during walking.

**Methods**

**Participants**

Two hundred seventy-nine individuals (119 men and 160 women) aged 18 to 45 years (mean ± SD, 27 ± 4.2 years) served as subjects for this study. The participants had a mean ± SD height of 170.5 ± 8.6 cm and a mean ± SD body mass of 70.2 ± 12.8 kg. At the time of the study, none of the participants had a history of congenital deformity, pain, or traumatic injury to either of their lower extremities at least 6 months before participation in the study. The institutional review board at Northern Arizona University approved the study, and all of the participants provided informed written consent before the start of data collection.

**Instrumentation**

Movement of the lower leg and rearfoot of each individual’s right extremity was measured using the 6D-RESEARCH electromagnetic motion analysis system (Skill Technologies Inc, Phoenix, Arizona). This system is based on the Fastrak tracking device (Polhemus, Colchester, Vermont) and uses an electromagnetic transmitter with up to four electromagnetic sensors. The sensors measure 2.8 × 2.3 cm and have a mass of 17 g. The signals from each sensor are input into a digital signal processor that computes the sensor’s position and orientation relative to a transmitter. It has an effective accurate radius of 76 cm from the transmitter. Within this range, it has an accuracy of 0.8 mm and 0.15° root mean square. Although a 76-cm radius is typically too small for recording a full walking stride, it is sufficient for analyzing the stance phase of a single limb. For the present study, the electromagnetic transmitter was positioned at a height of 96 cm, at the midway point of a 6-m raised walkway. The walkway was raised to a height of 76 cm to avoid any possible distortion of the electromagnetic fields caused by metal reinforcement in the laboratory’s concrete floor. Two electromagnetic sensors were used to collect the angular position data of the lower leg and rearfoot during walking. Joint coordinate system angles for the ankle as defined by Allard et al were calculated using the rearfoot and lower-leg sensors. As such, movement about an anteroposterior axis (Y) was defined as inversion/eversion. The rotation order used in calculating these angles was Y, X, Z. The sampling rate for each sensor was 60 Hz, and the resulting angles were smoothed by using a 6-Hz low-pass digital Butterworth filter.

The temporal occurrences of heel strike and toe-off were recorded using two force-sensing switches (Interlink Electronics, Camarillo, California). The switches were secured to the plantar surface of each participant’s right heel and hallux with adhesive tape. The signal produced by each switch was recorded and synchronized with the kinematic data.

**Procedure**

After the recording of the individual’s height and body mass, the two electromagnetic sensors were attached to the right lower extremity of each individual using double-sided adhesive tape. One sensor was placed on the tibial crest, just below the tibial tubercle, and one on the posterior aspect of the calcaneus, just proximal to the calcaneal fat pad (Fig. 1). The sensor on the tibia represented lower-leg movement,
and the calcaneal sensor represented rearfoot movement. These locations were selected because of minimal soft-tissue presence, which reduced the possibility of sensor-skin movement during walking. The sensors were connected to a microcomputer for data collection by means of a 30-foot serial cable. The individual’s right lower extremity was then positioned so that the calcaneus and the lower leg were perpendicular to the supporting surface, the long axis of the foot was parallel to the line of progression, and the heel was centered with the second metatarsal. While in this position, each sensor’s orientation was initialized relative to the laboratory reference frame. This position was used as the “zero” reference point for all angular measurements.

After initializing the sensors, each participant walked along the walkway at a self-selected speed. The participant’s stance phase duration for each trial was monitored by one of us (M.W.C.) to ensure the consistency of their walking speed. Any trial in which the stance phase duration deviated more than 10% from the mean of all other trials was deleted and another trial was performed. This process was repeated until a total of five walking trials were recorded for each individual. Angular movement of the rearfoot relative to the lower leg was then calculated with a Visual Basic computer program and was stored for later analysis. Frontal plane inversion and eversion movement of the rearfoot relative to the lower leg was considered to represent rearfoot motion. The five walking trials of each participant were first normalized to that participant’s stance phase duration and then were ensemble averaged to allow for comparison across trials and between groups of participants.

Data Analysis

Type 2,1 intraclass correlation coefficients (ICCs) were used to assess the between-trial reliability of each participant’s stance phase duration.24 The consistency of the motion trials obtained with the electromagnetic system for each participant was estimated by using the coefficient of multiple correlation, described by Kadaba et al.25

The mean motion pattern of all 279 participants was then calculated to provide an average pattern for all of the participants. Classification of frontal plane rearfoot motion patterns was performed by first grouping individuals based on the magnitude of the coefficient of multiple correlation between them and at least one other individual’s pattern. The coefficient of multiple correlation, as described by Kadaba et al.25 is a way to measure the consistency of motion patterns rather than distinct points on the motion pattern. The coefficient of multiple correlation calculates a value between 0 and 1.0 that represents the consistency between two motion patterns. The closer the value is to 1.0, the more consistent are the two patterns. Because of its ability to determine pattern consistency, it was believed that it could be used to group similar patterns of motion. A variety of coefficient of multiple correlation values ranging from 0.70 to 0.95 were initially applied to the data. With this method, it was found that lower coefficient of multiple correlation values did not seem to identify truly similar patterns, yet the larger values overly grouped the patterns. A coefficient of multiple correlation value of 0.88 was finally selected because it identified a sufficient number of patterns without seeming to overly combine groups that should not be. As a result, individuals with a composite coefficient of multiple correlation of 0.88 or greater were considered to have the same pattern of rearfoot motion and, therefore, were grouped together. Because the coefficient of multiple correlation is sensitive to the absolute angle and to the shape of the motion patterns, each resulting pattern was visually inspected by one of us (M.W.C.) to determine whether, in fact, two groups had the same shape but just different starting or ending points. If on visual inspection the patterns were considered to be the same, they were then combined. Figure 2 illustrates two motion patterns that were identified as being different by means of coefficient of multiple correlation analysis but that on visual inspection were determined to have the same pattern or shape and, therefore, should be grouped together.

To illustrate how each of the resulting motion patterns differed, descriptive statistics on 12 variables...
calculated from each individual’s motion pattern were obtained. The 12 frontal plane kinematic variables were rearfoot angle at the instant of heel strike, maximum rearfoot eversion angle, time to maximum rearfoot eversion angle, total rearfoot eversion range of motion, average rearfoot angle, total rearfoot eversion and inversion range of motion, time spent in eversion, eversion-time integral, maximum rearfoot inversion angle, average rearfoot eversion velocity, peak rearfoot eversion velocity, and time to peak rearfoot eversion velocity. These variables were selected because of their overall representation of rearfoot kinematics during walking. Figure 3 illustrates how eight of the 12 variables were calculated for this study.

**Results**

When using the force-sensitive foot switches attached to the plantar surface of the participant’s right foot, mean ± SD stance phase duration was calculated to be 672 ± 51 msec. Regarding the between-trial reliability of the stance phase duration, the calculated ICC was 0.912, with a 95% confidence interval of 0.899 to 0.925. The mean ± SD within-participant coefficient of multiple correlation value for rearfoot eversion/inversion was found to be 0.908 ± 0.061. The mean ± SD between-participant coefficient of multiple correlation value for rearfoot eversion/inversion was found to be 0.683 ± 0.081. The mean frontal plane motion pattern for the rearfoot from all 279 participants was very similar to that previously reported in the literature. Pattern classification using a coefficient of multiple correlation value of 0.88 or greater resulted in 30 different patterns. The number of individuals in each pattern group ranged from 1 to 83, with an average of 18 per group. Each pattern was then visually analyzed to determine whether it was actually different in shape or whether there was simply a difference in magnitude or starting and ending points. Visual inspection of the groups revealed that some of the 30 groups could be further combined because they had the same shape. Using this iterative process, the 30 patterns were eventually combined into just four. Plots of the four resulting groups are found in Figure 4. Pattern 1 consisted of 176 individuals (63.1%) with a similar frontal plane rearfoot motion pattern (Fig. 4A). Because most of the participants exhibited this pattern, we labeled this pattern of frontal plane rearfoot motion as “typical eversion.” Pattern 2 consisted of 87 individuals (31.2%) with a similar frontal plane rearfoot motion pattern (Fig. 4B). This pattern was labeled “prolonged eversion” because of the gradual eversion from heel strike to maximum eversion. Pattern 3 consisted of nine individuals (3.2%) with a similar frontal plane rearfoot motion pattern and was labeled “delayed eversion” because of the characteristic inversion followed by eversion during the first 50% of the stance phase duration (Fig. 4C). Finally, pattern 4 consisted of just seven individuals (2.5%) with a similar frontal plane rearfoot motion pattern and was labeled “early eversion” because the pattern is characterized by rapid eversion in the first 10% of the stance phase duration (Fig. 4D). The mean values for each of the 12 kinematic variables for these four patterns are displayed in Table 1. Figure 5 illustrates the four rearfoot patterns.

**Discussion**

On the basis of the criteria suggested by Landis and Koch, the reliability of the stance phase duration values was “almost perfect” because of an ICC of 0.912. Within-participant motion pattern repeatability was also very high as measured by a coefficient of multiple correlation value of 0.908. These measurements of reliability and consistency are slightly larger than those previously reported by Liu et al and Moseley et al. The higher values reported in the present study may be related to the larger sample size compared with these other studies.

Differences in the magnitude of rearfoot eversion were seen among the four different motion patterns. The typical pattern showed the least amount of absolute rearfoot eversion during walking. In comparison, the early pattern showed the greatest amount of
absolute rearfoot eversion during walking. These differences, however, were small (1.5°) (Table 1). Other notable features of the four groups include the early pattern showing the greatest eversion velocity and the delayed pattern showing the least (Table 1). Despite these dissimilarities, the delayed and early patterns constituted only 6% of all individuals measured in this study. As such, it would seem from the results of this study that high-velocity rearfoot eversion is relatively uncommon and that lower-velocity motion is much more common. If it is present, it will be very early during the stance phase of walking.

It was not possible to compare the results of this study with those of the previously published literature because we could not find research that attempted to classify normal rearfoot motion during walking based on the shape or pattern of that motion. Previous research has typically looked at discrete values of the rearfoot motion pattern, such as the magnitude of eversion rather than the actual shape or pattern. The results of the present study, therefore, contribute to the literature regarding normal rearfoot motion. It is interesting that the present study identified only four different patterns and that 94.3% of all of the participants were represented by one of two different patterns (typical or prolonged). This finding supports the theory that most foot injuries that are not related to a systemic disease process are caused by errors in training and repetitive overuse. As such, this information would be valuable to clinicians when they evaluate individuals and attempt to determine the cause of their symptoms.

Although it is unlikely that any classification system is completely accurate, this is one of the first
steps needed to study whether particular interventions are more effective in some subpopulations than in others. The results of the present study indicate that the coefficient of multiple correlation can be used to classify normal, asymptomatic rearfoot motion patterns of healthy adults during walking. This information should provide researchers and clinicians with a better idea of exactly what is a “typical” or “normal” foot motion pattern during walking. This information should help to improve evaluation and treatment paradigms related to foot disorders.

The present study has a variety of limitations that the reader should consider when attempting to interpret these results. First, the classification performed considered only frontal plane rearfoot motion. Foot motion is a composite of many motions occurring in more than one plane, and, as such, it is likely that a different classification would result if another aspect of foot motion were to be used. Another limitation of the present study is that the resulting classification was based on three-dimensional rearfoot motion analysis and, therefore, is not practical in a clinical setting. For the current proposed classification to be useful, clinically relevant measurements need to be identified that characterize and identify each of these groups of individuals. Future research should, therefore, focus on determining whether the same classification could be made when using static or nonweight-bearing measurements.

Although future research needs to be conducted to determine whether certain types of lower-limb and foot conditions are more prevalent in the four identified groups of motion patterns, the data from the present study provide researchers and clinicians with information related to what might be referred to as normal motion.

Conclusions

The methods used in this study yielded four distinct groups of individuals based on their frontal plane rearfoot motion pattern. Most of the participants (94.3%) exhibited one of two patterns (typical or prolonged). The two remaining patterns were represented by only 6% of the individuals measured. Based on the results of this study, there seems to be two dominant rearfoot motion patterns. Further research is warranted.

Financial Disclosure: None reported.
Conflict of Interest: None reported.

References

27. Cornwall MW, McPoiL TG: Motion of the calcaneus, navicular and first metatarsal during the stance phase of walking. JAPMA 92: 67, 2002.