

Dorsal First Ray Mobility in Women Athletes With a History of Stress Fracture of the Second or Third Metatarsal

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Study Design: Retrospective case-control study.

Objective: To examine the amount of dorsal first ray mobility in subjects having a history of stress fracture of the second or third metatarsal as compared to control subjects, and to test the influence of navicular drop, length of the first ray, and generalized joint laxity on the measure of dorsal mobility.

Background: Instability of the first ray may cause the lesser metatarsals to carry greater weight and contribute to the incidence of metatarsal stress fracture. Stability of the first ray is believed to be compromised when subtalar joint pronation continues into late stance, the first metatarsal is short, or an individual has generalized joint laxity. To date, no research has assessed the relationship of these etiological factors to the measure of first ray mobility.

Methods and Measures: Fifteen women athletes having a history of a second or third metatarsal stress fracture were matched by age, body mass, and sport activity to women athletes without fracture. Dorsal first ray mobility was quantified by a device using a standard load of 55 N. Change in vertical height of the navicular during stance was the measure of foot pronation. Relative length of the first ray navicular segment compared to the length of the second ray navicular segment was measured by caliper. Generalized joint laxity was evaluated using the Beighton 9-point scale. Within-day repeated measures assessed reliability. Differences between groups were determined by independent *t* test. Multiple polynomial regression analysis assessed the relationship between dorsal mobility and navicular drop, length of the first ray, and joint laxity.

Results: Interrater reliability coefficients ranged from 0.36 for metatarsal length to 0.71 for navicular drop. The intrarater reliability coefficient for dorsal first ray mobility was 0.93. Dorsal first ray mobility was not significantly different between the 2 groups. With regression analysis, the Beighton score was the only variable retained as a significant predictor of dorsal mobility ($R^2 = 0.24$).

Conclusion: Results do not support the theory that describes the unstable first ray as a common cause of metatarsal stress fracture. In addition, this investigation found generalized joint laxity to be a significant predictor of dorsal first ray mobility. *J Orthop Phys Ther* 2002;32:560-567.

Key Words: dorsal mobility, first metatarsal, generalized joint laxity

Fracture of healthy bone caused from repetitive overload is termed a fatigue stress fracture.^{2,12}

Stress fracture of the metatarsals affects up to 14% of women athletes.^{6,8} Fractures of the second or third metatarsals are the most common and account for 75% of all metatarsal stress fractures occurring in sports.^{29,35} Risk factors for development of fracture in women athletes include a history of menstrual disturbance caused by intensive physical activity,^{6,10} low bone density,¹⁰ less muscle mass⁵ and mechanical dysfunction of the foot.^{13,39,44}

An unstable first ray and its resultant decreased capacity to carry weight has been theorized as a mechanical cause of a second or third metatarsal stress fracture.^{32,33,44} Instability is described clinically as excessive dorsal excursion of the first metatarsal with a soft end point of motion.^{33,34} Although the existence of the unstable first ray is well accepted,^{15,18,25,32,34} the condition remains objectively undefined. Dudley Morton³³ first proposed the unstable first ray as a source of second metatarsal injury. Morton believed that ground reac-

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tive forces elevated the unstable first ray and pronated the forefoot, transferring greater weight onto the central metatarsals.³³ Supporting this premise, individuals classified with instability of the first ray have prominent wear calluses under the second and third metatarsal heads,³² and hypertrophic changes of the second metatarsal have been observed on radiograph.^{22,34}

A short first metatarsal has been postulated to cause increased first ray mobility.³³ When the first metatarsal is shorter than the second, excessive motion is thought necessary for the first ray to maintain ground contact. Over time, laxity may develop. Although the association between mobility and length has not been investigated, Drez et al¹⁴ reported length of the first ray relative to the second ray to be statistically the same for subjects with metatarsal stress fracture as compared to control subjects.

Other factors believed to coexist with the unstable first ray have not been substantiated with experimental data. Pronation of the subtalar and midtarsal joints that continues into late stance is suggested to lower the mechanical advantage of the fibularis (peroneus) longus muscle in stabilizing the first ray.^{23,33} As a consequence, connective tissues limiting dorsal excursion of the first ray are unduly stressed and laxity into dorsiflexion develops.²³ The amount of pronation is often evaluated clinically by measuring navicular drop.^{7,43} Measurement of navicular drop records the vertical change in displacement height of the navicular bone when the foot moves from subtalar neutral to a position of relaxed calcaneal stance.⁷

A separate but perhaps related factor of first ray instability may be the generalized condition of multijoint laxity. Patients with hallux valgus, a pathology directly related to the unstable first ray,^{18,25} have a greater incidence of generalized joint laxity.¹¹ This gives evidence that individual differences in connective tissue stiffness and joint flexibility may be an underlying cause of the unstable first ray.

This study compared dorsal first ray mobility in women subjects with a history of metatarsal stress fracture to noninjured matched controls. A second purpose was to examine the association between the measure of navicular drop, length of the first ray, and generalized joint laxity as factors related to dorsal mobility. The null hypotheses tested were that dorsal first ray mobility (1) does not differ between groups, and (2) is unrelated to navicular drop, length of the first ray, or generalized joint laxity.

METHODS

Subjects

Measures of first ray dorsal mobility, navicular drop, metatarsal length, and generalized joint laxity

were made in 30 women athletes 14 to 24 years of age who participated in high school or college sports. Fifteen subjects who had recovered from stress fracture of the second metatarsal ($n = 11$) or of the third metatarsal ($n = 4$) were matched by limb, age, body mass, and sport activity to noninjured control subjects. The diagnosis of fracture was confirmed by bone scan²⁸ or radiograph¹² at the time of presentation for health care. Subjects developed fracture while active in track or cross-country ($n = 10$), basketball ($n = 2$), volleyball ($n = 1$), gymnastics ($n = 1$), or golf ($n = 1$). All subjects signed an informed consent statement approved by the institutional review board of Physiotherapy Associates, Memphis, TN.

Procedure

Subjects with a history of fracture were identified from a review of cases. A single investigator performed the review and recruited subjects. Control subjects matched by sport activity were recruited from area colleges and high schools. Data for each subject were collected during a single test session. The sequence of testing was ordered. Navicular drop was measured first, followed by metatarsal length, joint laxity, and first ray dorsal mobility. Examiners were blinded to each other's results and had no knowledge of subject group assignment.

Two examiners measured navicular drop using a 0.02-mm-resolution dial caliper (Brown & Sharp, North Kingstown, RI).⁴³ Measurement was rounded to the nearest 0.01 mm. With the subject standing, the height of the navicular tuberosity was recorded while the examiner palpated congruency of the talar head in the mortise joint, and remeasured in relaxed stance. Intrarater reliability for this measure ($ICC > 0.97$) has been shown in a previous study.⁴³

The 2 examiners measured length of the first ray relative to the second.¹⁴ Length of the first ray navicular segment was measured with the same 0.01-mm precision by placing the jaws of the caliper onto the navicular tubercle and the dorsal crease of the first metatarsophalangeal joint line. The caliper was then used to measure the distance between the navicular tubercle and the second metatarsophalangeal dorsal joint line. Relative shortness in length of the first ray navicular segment as compared to the second ray navicular segment was computed for analysis.

The 2 examiners concluded their portion of the evaluation by assessing generalized joint laxity using the 5 measures described by Beighton³: (1) passive extension more than 90° of the fifth metacarpophalangeal joints, (2) opposition of the thumbs to the volar surface of the forearm, (3) hyperextension over 10° at the elbows, (4) hyperextension over 10° at the knees, and (5) forward flexion of the trunk measured in standing.

Good interrater reliability ($\kappa > 0.7$) has been found using the Beighton score to evaluate hypermobility syndrome.⁹ Assessed values of navicular drop, length of the first ray, and the Beighton score obtained by the most experienced examiner (6 years) were used for regression data analysis. Repeat measurements taken by the second examiner were used to assess reliability.

A third examiner measured first ray dorsal mobility with a load cell device using methods previously detailed.¹⁷⁻¹⁹ A manually operated screw mechanism on the device imposed a dorsiflexion force of 55 N to the head of the first metatarsal while simultaneous measures (in mm) of dorsal mobility were recorded.²⁰ A load imposed in this manner is tolerable for most subjects¹⁷⁻¹⁹ and sufficient to cause displacement to the entire first ray navicular segment.¹⁵ The measurement was repeated to assess reliability. Intrarater reliability for this measure has been demonstrated ($ICC \geq 0.85$, $SEM \leq 0.37$ mm).¹⁷⁻¹⁹

Twenty-seven of the subjects were examined at monthly test sessions. Three subjects having a fracture history could not attend the designated sessions. These individuals were examined at times that precluded all examiners from being present. As a result, repeat measures of navicular drop, length of the first ray, and joint laxity were not collected on 2 subjects; 1 subject had only the measurement of dorsal mobility repeated.

Data Analysis

Intraclass correlation coefficients ($ICC_{3,1}$) and the SEM^{40} for measures of navicular drop, metatarsal length, and first ray dorsal mobility assessed reliability between examiners and repeat trials. Agreement between examiner scoring of joint laxity was assessed using a weighted κ statistic.

Data collected from the fatigue-fractured foot and the matched limb of controls were analyzed for between-group comparison, and for the association between variables. An independent t test assessed the difference in measured variables between groups (fracture versus control). Multiple polynomial regression assessed association between dorsal first ray mobility and navicular drop, metatarsal length and tissue laxity. Because nonlinear regression relationships with dorsal mobility were possible, polynomial regression was utilized rather than the assumption of linear regression. An α level of statistical significance was set at 0.05.

RESULTS

Mean values of first ray dorsal mobility, navicular drop, the shortened length of the first metatarsal as compared to the second, and scores of generalized joint laxity for both groups are listed in the Table. Intrarater reliability for the measurement of first ray

dorsal mobility was 0.93, and interrater reliability for the measurements of navicular drop and Beighton score were 0.71 and 0.70, respectively. Measurement of metatarsal length demonstrated poor interrater reliability ($ICC = 0.36$). The SEMs ranged from 0.4 mm for first ray dorsal mobility to 3.5 mm for metatarsal length.

Between-group comparison of first ray dorsal mobility did not demonstrate a significant difference ($P = 0.23$). The mean first ray dorsal mobility of the group with a history of a stress fracture was 4.9 mm as compared to 4.3 mm for the control group (Table). Using a clinically significant difference value of 1 mm, this analysis had 70% power to detect such a difference. No difference was found between groups with regard to navicular drop, metatarsal length, or Beighton³ scoring (Table).

In the multiple polynomial regression analysis for prediction of dorsal first ray mobility, only generalized joint laxity was retained as significant predictor ($P = 0.03$, $R^2 = 0.24$, second order regression). Metatarsal length approached significance ($P = 0.09$), but along with navicular drop ($P = 0.5$), was not retained.

TABLE. Means, standard deviation and reliability coefficients for the measurements made on women with a history of metatarsal stress fractures and a matched control group.

	Stress Fracture	Controls	Reliability
Dorsal mobility (mm)	4.9 ± 1.5	4.3 ± 1.0	0.93 (0.4)*
Navicular drop (mm)	7.0 ± 2.7	6.2 ± 2.9	0.71 (1.5)*
Metatarsal length difference (mm)	11.9 ± 3.8	11.2 ± 4.5	0.36 (3.5)*
Beighton score	4 ± 2	4 ± 2	0.70†

* Intraclass correlation coefficients (standard errors of measurement).

† Kappa statistic.

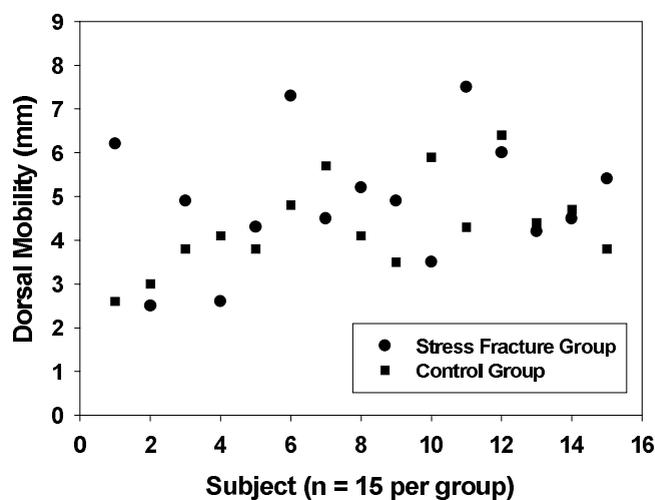


FIGURE 1. Scatter plot comparing first ray dorsal mobility between women with a history of metatarsal stress fracture and a matched control group.

DISCUSSION

Contrary to published theory,^{32,33,44} we found no difference ($P = 0.23$) in the amount of dorsal first ray mobility in subjects with a history of second or third metatarsal stress fracture as compared to matched controls. Variability appears higher in the stress fracture group (Figure 1) but analysis could not reject equal variances ($P > 0.2$). Only 2 subjects had dorsal mobility over 7.0 mm, a value nearing 2 standard deviations larger than the mean. Both subjects had a history of a second metatarsal fracture and were injured while running cross-country. Runners have greater incidence of metatarsal stress fractures^{4,21,28} and for these 2 athletes, excessive mobility at the first ray may well have contributed to their development of fracture.

The size of the sample tested was relatively small. A larger sample would have increased the power to detect small differences between groups, but it is uncertain whether a difference in mobility smaller than 1 mm would have clinical significance. Mean dorsal first ray mobility in subjects with a history of fracture was 4.9 mm. Dorsal first ray mobility in subjects without a history of fracture averaged 4.3 mm. These values are comparable to the mean (4.2–4.5 mm) dorsal mobility in populations that were asymptomatic.^{17,18} Unlike our findings, previous research^{18,25} has linked the condition of first ray instability to pathology. Dorsal first ray mobility in patients having hallux valgus was found to average 6 mm by Glasoe et al¹⁸ and 9 mm by Klaue et al.²⁵ These averages were 2 standard deviations greater than the respective means of control subjects sampled in the latter studies. The device used by Klaue and colleagues²⁵ did not stabilize the lesser metatarsals, which may explain why the amount of dorsal mobility they report is greater. Measures obtained by device and without stabilization of the second metatarsal may overestimate the amount of dorsal mobility specific to the first ray.²⁰

The second metatarsal is the most frequently fractured forefoot bone.^{29,35} Eleven of the subjects we sampled fractured the second metatarsal. Compared to the other metatarsals, the second carries the greatest loads during gait,^{13,37} is the longest, and based on a diameter-to-length relationship, the least robust.^{21,39} Ten subjects developed fracture while running track or cross-country. Gross and Bunch²¹ collected data on runners using transducers placed beneath the forefoot and modeled the data to predict that the peak force and bending strain at the second metatarsal was 7 times that of the first. To prevent stress fractures, distance runners are advised to cross-train to protect the metatarsals from the repetitive loads incurred during running.²⁶

Stress fractures are a complex multivariate problem. Variables not tested that could influence the development of metatarsal stress fracture in women

athletes include the health of bone related to diet and menstrual irregularities,^{6,10} training intensity,²⁶ and shoe wear.³⁰ Another factor associated with fracture may be the height of the longitudinal arch. A higher incidence of metatarsal fracture has been demonstrated in both the planus^{16,24,28} and cavus foot.^{24,41,42} Kaufman and colleagues²⁴ found that subjects with either a planus or cavus foot condition had a 2 times greater risk of developing fracture when compared to individuals with a normal arch. Our study was not designed to investigate the height of the longitudinal arch as a related cause of fracture. We did, however, measure navicular drop. Navicular drop has been shown to average between 6 and 9 mm in asymptomatic populations^{1,31,36} and the means we report (Table) are within this range. This suggests that the arch of subjects sampled did not tend towards being too flexible or stiff.

The etiology of an unstable first ray has been discussed in theory for nearly 70 years.^{27,33,38} We used regression analysis to find that generalized joint laxity was a significant predictor ($P = 0.03$) of dorsal mobility (Figure 2). The interrater reliability (Table) assessed for joint laxity Beighton³ scoring and the intrarater reliability of dorsal mobility measurements are comparable to good-to-excellent reliability coefficients reported elsewhere.^{9,17,18} Beighton³ scoring of the subject explained 24% ($R^2 = 0.24$) of the variance in first ray dorsal mobility. The coefficient of determination (R^2) computed was substantially influenced by the extreme values of a single subject (Figure 2). This subject had multiple-joint hypermobility³ and received the maximum score possible on the Beighton scale (first ray mobility measured 7.5 mm, the largest of any subject examined). A previous study¹⁷ identified gender and forefoot alignment to account for 40% of the variance in dorsal mobility. Dorsal mobility was greater in women, and increased

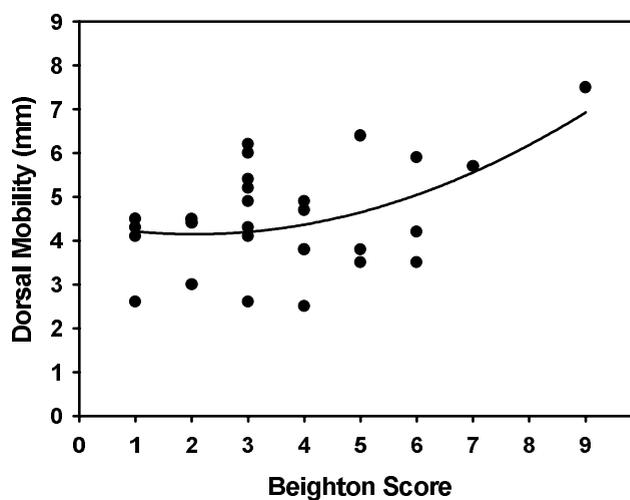


FIGURE 2. Scatter plot and second order regression of Beighton joint laxity score as a predictor of first ray dorsal mobility ($R^2 = 0.24$).

as alignment of the forefoot progressed towards a greater varus deformity.¹⁷ Further study is needed to explore the combinations of factors that may fully explain the variability in first ray dorsal mobility.

Length of the first metatarsal approached significance ($P = 0.09$), but along with navicular drop, was not retained as a predictor of dorsal first ray mobility. Lengths of the first and second ray navicular segments were measured using a palpatory technique. This method of measurement was not reliable between examiners (ICC = 0.36, SEM = 3.5 mm). Because the metatarsal heads are round, the examiners felt unsure of their ability to palpate the metatarsophalangeal joint line, making the measurement difficult to obtain.

Two other methods have been described to quantify length of the first ray relative to the second. Rodgers and Cavanagh³⁷ palpated to place markings beneath the heads of the first and second metatarsals, then measured the respective difference in lengths from the markings left in footprints. Drez and coworkers¹⁴ quantified length of the metatarsals from radiographs. Neither study^{14,37} assessed reliability. In our study, radiographic testing was not warranted because the subjects were asymptomatic. If a more reliable and precise measure were taken, the length of the first ray might have been a significant predictor of dorsal mobility. Navicular drop was used in this investigation as an indirect measure of subtalar and midtarsal joint pronation. Measures of the magnitude of pronation occurring during dynamic activities may be better predictors of first ray mobility.

Dorsal first ray mobility was measured under controlled test conditions with a mechanical device using a standard load of 55 N.¹⁷⁻²⁰ Loads greater than 55 N imposed by mechanical means are painful²⁰ and may exceed the amount of force needed to attain a full measure of dorsal mobility.^{15,19} This noninjurious load force is small when compared to the magnitude of force acting on the first metatarsal during gait. Results may have been different had a larger load been imposed. Additional research is needed to investigate movement of the first ray as it relates to the kinetics of gait.

It is also important to note that this study used a retrospective rather than prospective design. A lack of differences between groups after recovering from fracture does not rule out the possibility that excessive dorsal mobility of the first ray may have been a contributing factor in the development of fracture. If so, excessive dorsal mobility was no longer consistently present postfracture. A prospective longitudinal study with a large sample size would be necessary to determine the potential predictive value of first ray dorsal mobility as a screening test for stress fracture risk.

CONCLUSION

Instability and the resulting insufficiency of the first ray to carry weight has been postulated as a causal factor of central metatarsal stress fracture. This study measured dorsal first ray mobility in women athletes having a history of second or third metatarsal stress fracture. We found no difference in the amount of first ray dorsal mobility in subjects having a history of fracture as compared to controls. Generalized joint laxity was identified as a significant predictor of first ray mobility, with an increased amount of dorsal mobility in individuals having multiple joint laxity. This study fails to support the simple cause-and-effect theory that associates an unstable first ray to the development of metatarsal stress fracture in this population.

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Invited Commentary

I would like to take the opportunity to congratulate Mr. Glasoe and his associates for a very interesting and valuable study. Theories concerning how the foot functions during locomotion and the influence of such things as first ray mobility on that motion, as well as the cause of lower extremity injuries, are numerous. Unfortunately, most of these theories have existed for decades without proper substantiation and very little challenge. Because of this, clinicians have little or no evidence on which to base either their evaluation or treatment schemes and frequently

assume that because these theories have existed for so long, they must be correct. The influence of first ray mobility is a very good example of this clinician dilemma and the authors of the present paper should be commended for adding to our understanding and clarifying the important elements that clinicians should focus on during their evaluation and treatment of individuals with foot-related conditions.

The authors are certainly correct in their statement concerning the multi-dimensional nature of

metatarsal stress fractures. To that end, the paper does a very good job of identifying the various additional factors that may contribute to metatarsal stress fractures in women athletes and to identify the limitations of their study in completely answering the question. Although their study helps to clarify the role that first ray dorsal mobility may or may not have in overall foot motion, and more specifically, in the incidence of metatarsal stress fractures, the contribution could certainly have been greater if the authors had made their design more inclusive. Many of the omissions in data collection identified in the study such as diet, menstrual irregularity, training intensity, and footwear could easily have been, and certainly should have been, collected. Because they were not, the study is weaker than it might have been otherwise. The authors also mention that planus and cavus foot structures have been identified in the literature as contributing factors in metatarsal stress fractures. Despite this acknowledgement, they fail to report or use data that they already had regarding this factor. In the process of measuring navicular drop, they collected information concerning the height of the medial longitudinal arch, which could have been included in the analysis.

The authors focus on their finding that generalized joint laxity was a significant predictor of dorsal first ray mobility, while pointing out that this result was substantially influenced by the extreme value of

a single subject. They seem, however, to discount this effect in their conclusions. The scatter diagram, shown in Figure 2, clearly illustrates the effect of the single outlier subject. Because of the effect of that one subject, the authors' interpretation is difficult to accept. Another misinterpretation of the data is made relative to the importance of the contribution of first ray hypermobility to metatarsal stress fractures in runners. Although it is true that 2 cross-country runners developed metatarsal stress fractures and had more than 7 mm of dorsal mobility, it is also true that there were an additional 8 runners who developed stress fractures, yet did not have excessive first ray mobility. Such data do not suggest a strong association between running, first ray hypermobility, and metatarsal stress fractures.

As mentioned previously, the information concerning the evaluation and treatment of foot conditions is relatively sparse and frequently based on observation and conjecture rather than objective measurement. Despite the limitations of the present study, the authors have addressed this issue and made an important contribution to the literature.

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Authors' Response

We thank Dr. Cornwall for his thoughtful commentary. Most of his comments pertain to the limitations of this study. We are pleased to have the opportunity to clarify these issues for the reader.

Our analysis was designed to investigate clinical theory regarding the proposed relationship between metatarsal stress fracture and dorsal mobility of the first ray. We did not intend to investigate all possible factors contributing to stress fracture. Although collecting subject self-report data on factors such as diet and training may seem relatively easy to do, because of the retrospective nature of the study, we believe the accuracy of such data would be questionable. To investigate other recognized factors of stress fracture that perhaps coexisted at the time of injury would have required subjects to self-report from memory, resulting in high susceptibility to estimation error and recall bias.⁵ A prospective longitudinal study design would be optimal to accurately investigate such additional factors.

Dr. Cornwall also suggested that as a component of our navicular drop measure, we present data regarding the height of the medial longitudinal arch investigated across the stress fracture and control groups. Based on that suggestion, we have since ex-

tracted the caliper measures of navicular height in resting stance and compared them across groups. There was no significant difference in navicular height across groups ($P = 0.27$) with values averaging 29 mm (standard deviation = 5.2 mm) in the stress fracture group and 30 mm (standard deviation = 4.9 mm) in the control group. However, radiographic classification of arch height is considered superior to palpation and caliper measurement methods.⁶

As discussed in the paper, we agree with Dr. Cornwall that the regression analysis results, which found joint laxity to be a significant predictor of dorsal mobility, were substantially influenced by the extreme values of a single subject. However, the definition and management of "outlying" data involves judgment as to whether the data represent the true spectrum of values expected and representative of a population. The data point in question included over 7 mm of dorsal mobility and a Beighton score of 9. Although dorsal mobility more than 7 mm is not common, other studies^{3,4} measuring dorsal mobility with this same device have recorded values equally as high as these. And certainly a score of 9, as described by Beighton,¹ would not be considered an anomaly. If a larger sample size were tested, more

values in this range would be expected. We have no reason to conclude that this data point is based on measurement error rather than true data, and therefore have no objective rationale for exclusion of the data point.⁵ We believe that the exclusion of data without justification would be a mistake. We have therefore provided the graphical scatter plot as well as the R^2 value, and have indicated the influence of this data point to the reader in the discussion.

Our study found that instability of the first ray was not consistently greater in subjects with a history of central metatarsal stress fracture. Despite this primary conclusion, which is based on average results, we felt it important to discuss the fact that only 2 subjects of the 30 tested had dorsal first ray mobility greater than 7 mm. We descriptively identified these subjects as runners and stated that for these 2 cases, instability of the first ray may have contributed to stress fracture. We were not suggesting that this individual subject data presented an overall argument for an association between running, first ray hypermobility, and metatarsal stress fracture, as that would have contradicted our primary findings. Rather, we felt it was important to recognize that group means are not always representative of an entire population and subgroups of subjects may exist when considering raw data.

We are glad Dr. Cornwall provided the commentary on this study. His contributions to the physical therapy profession as a researcher and clinician have been significant. Dr. Cornwall has built a measurement device and is now testing dorsal first ray mobil-

ity in the gait research laboratory at Northern Arizona University.² We look forward to learning from his work.

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