Measurement of Dorsal First Ray Mobility: A Topical Historical Review and Commentary

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Abstract
Despite evidence that instability of the first ray (first metatarsal and medial cuneiform) alters the loading mechanics of the foot, surprisingly few studies have linked the condition with disorders of the foot. A factor limiting this research is the difficulty associated with measuring first ray mobility (FRM). To quantify dorsal FRM, clinicians and researchers have devised a variety of methods that impose a dorsally directed load, and record displacement. The methods include manual examination, radiographs, mechanical devices, and handheld rulers. Since different methods yield different results; each of these methods is worthy of scrutiny. This article reviews the methods used to quantify dorsal FRM and offers commentary on how the testing procedures could be standardized. The measurement of dorsal FRM informs surgical decisions, orthotic prescriptions, and research design strategies mostly as it pertains to the identification and treatment of first ray hypermobility. This review found sufficient support to recommend continued use of radiographs and mechanical devices for quantifying dorsal displacement, whereas measurements acquired with handheld rulers are prone to the same subjective error attributed to manual examination procedures. Since measures made with radiographs and existing mechanical devices have their own drawbacks, the commentary recommends ideas for standardizing the testing procedure and calls for the development of a next-generation device to measure dorsal FRM. This future device could be modeled after arthrometers that exist and are used to quantify stability at the knee and ankle.

Level of Evidence: Level V, expert opinion.

Keywords: foot, first metatarsal, hypermobility, clinical measurement, arthrometer

Background
In an article published in 1928, Dudley Morton claimed that instability of the first ray (first metatarsal and medial cuneiform) alters the loading mechanics of the foot resulting in weight being transferred from the first metatarsal head toward the central forefoot. Since Morton published this theory, many authors (including Ward Glasoe and Thomas Michaud) have suggested in their writings that instability (hypermobility) of the first ray predisposes to a wide range of disorders. The disorders include hallux valgus, central metatarsal stress fractures and joint disruption, hammer toes, acquired flatfoot deformity, and tibialis posterior tendon dysfunction. Despite evidence of a lateral shift in plantar pressures, cortical hypertrophy of the second metatarsal, and callus formation beneath the central metatarsals, at the present time, surprisingly few studies have linked first ray hypermobility with altered foot mechanics. A chief factor limiting this area of research has been the difficulty associated with measuring first ray mobility (FRM). According to Wanivenhaus, the joint surfaces of the first metatarsal and medial cuneiform interlock, and motion into dorsiflexion is restricted by a plantar ligament. Additionally, because the cuneiforms are wedge shaped and rest in contact with each other, the metatarsocuneiform joints function to stabilize the midfoot and to distribute load across the medial longitudinal arch in supporting weight.

Dorsal FRM has been quantified in a large number of studies. The methods include serial radiographs, mechanical devices, or by means of a...
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Manual stress test examination, which over the past 30 years has morphed into quantifying FRM with a handheld ruler. Though no standards currently govern the testing procedure, clinicians usually impose a dorsally directed force to the first metatarsal head and record linear movement as displacement. The measurement does not track the trajectory of joint motion, but instead indicates a direction and quantifies the length of the shortest path traveled by the first ray. Due to the intersegmental nature of foot motion, the measurement of dorsal FRM cannot be ascribed to any specific joint, and because the load imposed is not easily controlled, different methods yield different results.

Research has reported normative values. Dorsal FRM in healthy adults ranges from 3 to 8 mm. Toward the extreme, in women with hallux valgus it averages between 7 and 10 mm. In one article, Glasoe and Coughlin made the consensus statement that dorsal FRM averages 5 mm in adults, with values exceeding 8 mm suggesting evidence of hypermobility. A study by Klaue et al defined hypermobility at 9 mm, whereas a study undertaken by Singh et al defined hypermobility at 10 mm. Any attempt to objectify a threshold for identifying the hypermobile condition matters only if the measurement is valid, because the error associated with measuring FRM may well exceed 3 mm.

This article presents a historical overview of the methods originally proposed to measure dorsal FRM. The purpose of this topical review is to improve the measurement of dorsal FRM, as this paper synthesizes the psychometric properties (reliability and validity) of the data collected with one or more of these methods. The commentary that follows recommends ideas for standardizing the testing procedures and calls for the future development of a portable arthrometer that could be used in clinical practice and research to measure dorsal FRM.

**Figure 1.** Dorsal (straight arrow) first ray mobility examined manually in isolation to the lesser metatarsals. Dorsiflexion is coupled with inversion (curved arrow) as the load is imposed.

**Historical Overview**

**Manual Examination**

Morton introduced the manual examination approach nearly a century ago. The examination is performed (Figure 1) by delivering a dorsally directed force to the first ray with one hand, while the other hand holds the lesser metatarsals stationary. Though Morton’s writings provide little guideline to interpret the physical findings, comparison with the opposite side or across a large number of patients is presumed sufficient to allow the experienced examiner to identify evidence of hypermobility.

Building upon Morton’s concept of examining the structural integrity of the first ray by hand, several paradigms have been introduced over time to objectify the test result. The earliest came in 1949 when Hiss declared that the first through fifth metatarsals should possess a movement ratio of 2:1:2:4:5, meaning that the first metatarsal should move twice as much as the second, the same as the third, half as much as the fourth, and so on. In the 1970s, Root and colleagues introduced an alternate technique whereby dorsiflexion of the first ray was compared with plantarflexion of the first ray, with hypermobility identified when dorsiflexion exceeded plantarflexion. Still another paradigm suggests that the first ray may be judged to be hypermobile during the delivery of a dorsal stress-force should the head of the first metatarsal lift above the plane of the lesser metatarsals. Manual examination of FRM is quick to perform, requires no special equipment, and therefore continues to be used to screen for hypermobility.

Though simplicity is the requisite element for any clinical test, examining FRM by hand (Figure 1) lacks diagnostic accuracy, irrespective of the examiner’s training or experience. Though research has repeatedly demonstrated that manual estimates of FRM are unreliable, the examination continues to be performed in the clinic and in clinic-based studies to assess for hypermobility. Therefore, it seems reasonable to conclude that this will change only after an alternative method becomes the accepted standard, and provided the technique can be easily adopted into practice.

**Radiograph Measurements**

In the modern era, radiographs serve as the criterion standard for quantifying FRM. Surgeons rely on weightbearing stress test radiographs to confirm inclusion of tarsometatarsal arthrodesis when correcting foot deformity, and researchers use radiographs to validate other methods used to quantify the measure of dorsal FRM.

The modified Coleman block test is preferred. As described by Alexander in 1990, the protocol involves standing a patient on a block to maximally dorsiflex the first
ray (Figure 2). Change in the sagittal plane position of the first ray is then tracked on sequential lateral view radiographs. Tracking displacement on radiographs has limitations, however, because foot motion is multiplanar, and out-of-plane movement cannot be accurately captured on standard radiographs. The three-dimensional loading behavior of the first ray has been most studied in women with hallux valgus. In this group, weight acceptance moves the first ray in equal proportions of dorsiflexion and inversion, and to lesser extent, adduction. The modified Coleman block test remains one option for quantifying dorsal FRM, provided the examiner can accept the expected projection error associated with radiographic analysis.

In a study published in 2018, Tavara-Vidalon et al used the modified Coleman loading method (Figure 2) and quantified both sagittal and frontal plane displacement measures of FRM on anteroposterior radiographs. Load was delivered by standing the patient on a system of wedges placed beneath the first metatarsal head. Maximal displacement occurred when the second metatarsal began to unload. Points then digitized on the series of radiographs marked the fixed position on the medial malleolus, and the head of the first metatarsal as its position changed in both the sagittal and frontal planes under the imposed load. Testing young participants without “morphological or functional alterations,” the measurements of FRM were demonstrated to be highly reliable (intraclass correlation coefficient [ICC] = 0.95) with dorsal linear displacement averaging 6.47 mm and inversion angular displacement averaging 2.69 degrees (Figure 2). Though not quantified in this particular study, displacement of the first ray could also be measured in the transverse plane. Measuring displacements in 3 planes could potentially help guide surgeons in the selection of corrective procedures in the treatment of first ray deformity. To avoid measurement error, however, the repeated digitization of points marking the location of the first ray must be highly precise. Thus, one can only speculate if this method would work on aged patients with joint surface erosions.

Since radiographs are not always feasible or necessary, FRM is most often quantified in clinical studies with a mechanical device or handheld rulers. Both of these methods use a motion detector that rests in contact with the first ray. Unlike radiographs, a motion detector has freedom to follow the trajectory of the first ray when a displacement load is imposed.

### Mechanical Devices

Rodgers and Cavanagh built the first device in 1986. It was free-standing and instrumented with a force transducer and electronic sensor that output a force-displacement measurement. The external load was mechanically delivered, and displacement was measured from beneath the first metatarsal head. Without validating the measurement, Birke et al. used this device to quantify dorsal FRM in a clinical study. Owing to a flaw in the design of the device, the measurement could not distinguish movement of the first ray from compression of the plantar fat pad. This error was discovered after Birke’s paper was published, when Glasoe et al identified that compression of the fat pad during the loading process introduced as much as 3 mm of error. Conversely, measures taken on the dorsum of the first metatarsal eliminated this error. Though this prototype device was never mentioned in the literature again, the concept of measuring dorsal FRM with a mechanical device was soon pursued by others.

Klaue and Glasoe introduced their own devices (Figure 3) in the 1990s. The design of both devices was published in detail to allow others to build replicas, and many did. A study by Klaue et al. found that the measure of dorsal FRM increased in patients with hallux valgus, and after this seminal publication, the Klaue namesake was adopted to describe this type of device when replicated by others. In operating this device (Figure 3A), Klauer attached a frame to an ankle-foot orthosis (AFO) and from the frame suspended a caliper so that it rested on the first metatarsal. The caliper recorded motion as the examiner dorsiflexed the first ray through its full range of motion. In testing this device (Figure 3A), both the start point of measurement and the amount of the force exerted to dorsiflex the first ray are noncontrolled variables, left to the discretion of the examiner. To reduce variability, the measure is repeated multiple times, with the average recorded for analysis.
While Klaue did not test reliability, a decade later Jones et al. evaluated the reliability and validity of measurements acquired with the device (Figure 3A) on cadavers. They found that measures recorded by 2 examiners were not statistically different (P = .99) or different (P = .83) from measures made on serial radiographs. Though this study demonstrated good internal consistency, the result mostly gives testament to the skills of the examiners and not necessarily to the reliability of the device. Without question, the Klaue device has been used to measure dorsal FRM in more studies than any other single method. Of concern, the experiment by Jones stands as the only study to test reliability with statistical means. Before the Klaue device can be fully embraced, the reliability of the measure needs to be consistently demonstrated in clinical trials. Further research is warranted.

The Glasoe device was introduced in 1998. Incorporating the most objectifying features of the 2 previous designs, this device (Figure 3B) stabilized the hindfoot with an AFO, was instrumented to output a force-displacement measurement, and recorded movement from a probe placed on the first metatarsal. During data collection, the patient sat with their ankle and forefoot fixed in a neutral position; a separate platform held the first metatarsal level with the lesser metatarsals to mark the start point of measurement. In preliminary studies, measures recorded with the device at loads between 20 and 55 N were judged to be reliable (ICC ≥ 0.98) and not different (P ≥ .21) than radiographs. The device was then used in a variety of clinical trials, and in each study the measure was demonstrated to be reliable (ICC ≥ 0.90; SEM ≤ 0.40 mm). In 2005, the device was interfaced with a computer. This update allowed for the storage, retrieval, and time-based analysis of the data. Though the device has been replicated by others for use in research, its size and technical nature keep it from being routinely used in the clinic.

Both the Klaue and Glasoe mechanical devices (Figure 3) have been used in a number of unaffiliated studies. These initiatives eventually culminated into a multicenter study that compared measures acquired by 1 examiner using both devices. In preparation for this study, a load of 45 N was determined as the average load exerted to dorsiflex the first ray manually. The study itself found no difference (P = .12) in measures of dorsal FRM recorded at 45 N with Glasoe’s device compared with Klaue’s device, and a correspondingly good level of agreement (ICC = 0.70) between device measurements (Figure 3). Further, this collaborative investigation afforded the team of researchers opportunity to directly compare and contrast the devices. The Klaue device was portable (Figure 3A), and dorsiflexing the first ray by hand permits the examiner to make judgments about the quality

Figure 3. Dorsal first ray mobility measured with a mechanical device. (A) Klaue device records displacement when the first ray is moved manually. (B) Glasoe device records force and displacement when the first ray is moved mechanically with a preplanned load. Panel A was modified from a photograph in Singh et al.69
of the tissue resistance. This perception of stiffness cannot, however, be objectified with the Klaue device. By contrast, the Glasoe device (Figure 3B) outputs both force (N) and displacement (mm) measurements. Recording both allows the mechanical properties of stiffness to be calculated by dividing the measurement of force with the change in displacement over time. As an example, in one study Glasoe et al.25 identified stiffness and reduced FRM ($P < .05$) to be associated risk factors of plantar ulcer formation in patients with diabetes. Unfortunately, neither device37,52 has been deemed to have enough commercial value to warrant widespread use as a clinical tool. As a result, clinician-based researchers have opted to measure FRM with handheld rulers (Figure 4).21,41,42,46,49,53

**Handheld Rulers**

Three different ruler techniques have been published, but for practical purposes the measure of dorsal FRM can be quantified on either the plantar or the dorsal surface of the foot (Figure 4). Wallace and Kilmartin73 developed the “Kilmartin Sagittal Raynger” in 1990 (Figure 4A). This innovative tool comprising 2 side-by-side moveable rulers quantified displacement as an examiner dorsiflexed the first ray. Although the authors73 suggested that their patent-pending ruler would be sold as a clinical tool, it was never described in the literature again.

Failing to credit Wallace and Kilmartin, Lee and Young53 reintroduced the handheld ruler approach in 2001 (Figure 4B). Kim joined with Lee49 and a team of clinicians to publish a second paper in 2008 whereby they claimed rulers provided “a simple, fast, and easy way” to measure dorsal FRM.49 Calling it the Euliji Medical Center (EMC) ruler,49,53 the tool was a 2-piece ruler set marked in 1-mm gradations (Figure 4B). The measurement was made by balancing the ruler on the dorsum of the first and second metatarsals while delivering a manual force to dorsiflex the first ray. Lee et al.53 did not test reliability in 2001, though a follow-up study in 200849 compared data collected with the handheld ruler to measures acquired with the Klaue device,52 and serial radiographs.1,18 Measures obtained with the ruler were not different ($P = .12$) from measures acquired with the device, but were different ($P < .05$) from radiographs, demonstrating partial agreement across methods.

Seeing handheld rulers as a practical substitute for measuring dorsal FRM, a study by Glasoe et al.30 compared data collected with Lee’s49,53 ruler approach (Figure 4B) to measures collected with his device (Figure 3B). In this examiner-blinded trial,30 the ruler measures were found to be unreliable (ICC = 0.05; SEM = 1.23 mm), whereas device measures were demonstrated to be highly reliable (ICC = 0.98; SEM = 0.15 mm). Additionally, there was no agreement (ICC ≤ −0.06) between the device and ruler measurements of dorsal FRM. Empirically, the rulers were described as awkward to handle and hindered the delivery of the stress-force. The study put forth recommendations for improving the ruler approach. First, a full-length AFO could be incorporated into the procedure to ensure that the foot is held stationary. Second, the force delivered to dorsiflex the first ray could be quantified and standardized. To date, neither recommendation has been acted on by those who continue to promote rulers as a viable option for measuring dorsal FRM.21,41,42,46,49
Despite research that calls into question the veracity of measuring dorsal FRM with any sort of manual technique, Greisberg et al.41,42 offered another handheld ruler approach in 2010,41 and again in 2012.42 Like Wallace and Kilmartin73 had originally instructed, Greisberg41,42 placed his ruler on the plantar surface of the foot. As previously described, measures acquired on the plantar surface (Figure 4A) introduce error due to compression of the fat pad.28 Despite this error issue, studies continue to measure dorsal FRM from the plantar surface of the foot in peer review articles.

To summarize, this review of the literature found no strong evidence to support any single method for measuring dorsal FRM. Radiographs objectify first ray displacement but are subject to projection error when tracking out-of-plane motion and introduce the added risk of radiation exposure. Mechanical devices offer potential, but at present, no commercial devices are being marketed for the purpose of measuring FRM. Finally, handheld rulers are prone to the same subjective error attributed to the manual examination procedure.

Commentary

This article concludes by making recommendations for standardizing the testing procedures, and advances ideas toward the development of a new device for measuring dorsal FRM.

Standardization of Procedures

Three recommendations are offered for standardizing the measurement of dorsal FRM. First, the motion detector, whether it be an electronic sensor, a probe,6,37,48,52,69 or a handheld ruler,42,46,49,53,73 must be placed on the dorsum of the foot. Second, the measure should be made with the ankle aligned in the neutral position.39 Third, the force imposed on the first ray should be quantified, and a research-based guideline should govern the magnitude of the load.

With regard to the placement of the motion detector, the problem with the Rodgers and Cavanagh mechanical device,64 and the ruler approaches advocated by Wallace and Kilmartin73 and more recently by Greisberg et al.42 was that measures acquired on the plantar surface of the foot do not differentiate motion from compression of the plantar fat pad. If motion is restricted, the amount the fat pad compresses under an imposed load could exceed movement of the first ray.28

Joint motion should always be measured from a consistent body position. In the case of FRM, any change in ankle position changes the tension in the plantar fascia and motion of the first ray. Grebing and Coughlin15 reported measures of dorsal FRM to be reduced from 9.3 to 4.9 mm when the measure was obtained with the ankle plantarflexed compared with in the neutral position. On the basis of this finding, the neutral ankle position (0 degrees of dorsiflexion) should be adopted as the standard for measuring dorsal FRM.39 Additionally, since 25% of adults cannot attain a neutral ankle position with the knee extended,15 the knee should also be flexed.39

To quantify the manual delivery of force, researchers have turned to wearing a tactile pressure sensor.5,45 A sensor placed on the thumb or inside a glove could record the perpendicular force applied by the examiner when dorsiflexing the first ray during operation of the Klaue device (Figure 3A) or a handheld ruler (Figure 4B). Though the optimal force required to measure FRM has not been established, Glasoe et al.30,31 found 45 N to be the average load exerted with the thumb when assessing FRM by hand (Figure 1). This amount of force could serve as a baseline for future research that is undertaken to advise testing protocol guidelines.

Future Development

A variety of special tests have been developed to diagnose joint instability (laxity), and from these tests, handheld arthrometers have evolved. Laxity at the knee and ankle is assessed with the anterior drawer test. While this special test is well accepted, the delivery of force is an unknown variable that negatively influences the quantification of results. Therefore, use of an arthrometer is preferred to quantify the measure of anterior displacement.14,16,43,63 Likewise, it would seem logical to model the next-generation device for quantifying FRM after arthrometers that already exist and are being used in the clinic to measure displacement (translation) at the knee and ankle.

Conclusion

There currently are no uniform standards that govern and guide the measurement of dorsal FRM. This is troubling because the measurement informs surgical decisions, orthotic prescriptions, and group assignments in research. This review found sufficient support for the continuation of measuring dorsal FRM with radiographs and mechanical devices, whereas manual examination and handheld ruler methods should be subjected to further testing. Since testing procedures are still evolving, this article made recommendations for how the measurement could be standardized across methods, and advances ideas toward the development of a portable arthrometer to measure FRM. The information presented has potential to improve how the measurement of dorsal FRM is acquired in patients and interpreted in the literature.

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