Topical Review

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

Ward M. Glasoe, PhD, PT, ATC,[1] and Thomas C. Michaud, DC,[2]

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,[58] Dudley Morton claimed that instability of the first ray altered foot mechanics resulting in weight being transferred from the first metatarsal head toward the central forefoot. Since Morton published this theory, many authors (including Ward Glasoe[29,36] and Thomas Michaud[55-57]) 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.[13,23,35,36,44,54,56,60-62,65,67] Despite evidence of a lateral shift in plantar pressures,[65] cortical hypertrophy of the second metatarsal,[60] and callus formation beneath the central metatarsals,[61] at the present time, surprisingly few studies have linked first ray hypermobility with altered foot mechanics.[29,40] A chief factor limiting this area of research has been the difficulty associated with measuring first ray mobility (FRM).

According to Wanivenhaus,[74] 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.[27,30,31,46,48,49,52,53,71] The methods include serial radiographs,[1,18,49] mechanical devices,[28,52,64] or by means of a

[1]Division in Physical Therapy, Department of Rehabilitation Medicine, Medical School, University of Minnesota, Minneapolis, MN, USA
[2]Michaud Chiropractic Center, Newton, MA, USA

Corresponding Author:
Ward M. Glasoe, PhD, PT, ATC, Division in Physical Therapy, Department of Rehabilitation Medicine, Medical School, University of Minnesota, Mayo Mail Code 388, 420 Delaware St. SE, Minneapolis, MN 55455, USA
Email: glaso008@umn.edu
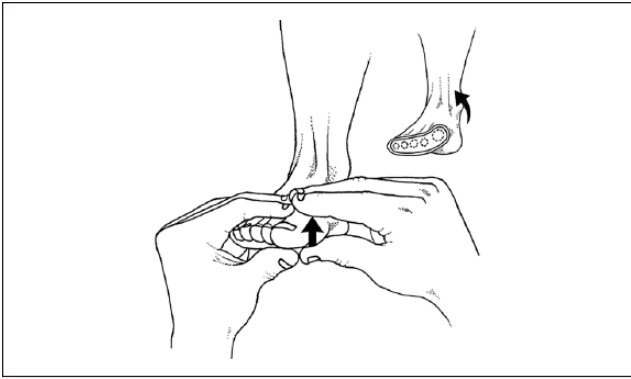
Figure 1. Dorsal (straight arrow) first ray mobility examined manually in isolation to the lesser metatarsals. Dorsiflexion is coupled with inversion (curved arrow) as the load is imposed.

manual stress test examination, which over the past 30 years has morphed into quantifying FRM with a handheld ruler.[41,42,49,53,73] 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.[27,30,31,46,48,49,52,53,71]

Research has reported normative values. Dorsal FRM in healthy adults ranges from 3 to 8 mm.[2,9,12,23-25,27,30,31,39,40,71] Toward the extreme, in women with hallux valgus it averages between 7 and 10 mm.[8,26,40,52,69] In one article, Glasoe and Coughlin[29] made the consensus statement that dorsal FRM averages 5 mm in adults, with values exceeding 8 mm suggesting evidence of hypermobility.[29] A study by Klaue et al[52] defined hypermobility at 9 mm, whereas a study undertaken by Singh et al[69] 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.[2,7,27,28,30,31,37,38,48]

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.

Historical Overview

Manual Examination

Morton introduced the manual examination approach nearly a century ago.[58,59] 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 guidance 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.[13,36]

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[47] 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[66] 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[6,27,36,71] 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.[46,71]

Though simplicity is the requisite element for any clinical test, examining FRM by hand (Figure 1) lacks diagnostic accuracy,[6,27,68] irrespective of the examiner's training or experience.[27] Though research[6,27,68] has repeatedly demonstrated that manual estimates of FRM are unreliable, the examination continues to be performed in the clinic[13,46,53] and in clinic-based studies[17,19,46,72] 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,[18] and researchers use radiographs to validate other methods used to quantify the measure of dorsal FRM.[38,48,49]

The modified Coleman block test is preferred.[1,18,49,62,71] As described by Alexander in 1990,[1] the protocol involves standing a patient on a block to maximally dorsiflex the first
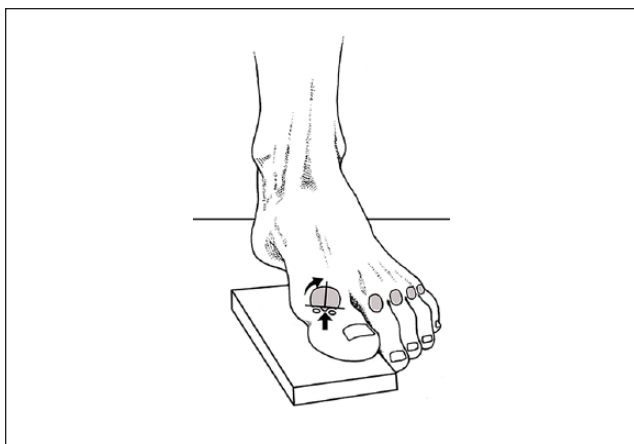
Figure 2. The modified Coleman block test position dorsiflexes (straight arrow) and inverts (curved arrow) the first ray in isolation to the lesser metatarsals. The technique is used to measure displacement of the first ray on a series of standard radiographs. On average, the first ray dorsiflexes 6.5 mm from the neutral position while simultaneously inverting 2.7 degrees.[71]

ray (Figure 2). Change in the sagittal plane position of the first ray is then tracked on sequential lateral view radiographs.[1,18,49,62] Tracking displacement on radiographs has limitations, however, because foot motion is multiplanar, and out-of-plane movement cannot be accurately captured on standard radiographs.[32,33,36] The three-dimensional loading behavior of the first ray has been most studied in women with hallux valgus.[22,34,51,70] In this group, weight acceptance moves the first ray in equal proportions of dorsiflexion and inversion, and to lesser extent, adduction.[22,34,51,70] The modified Coleman block test remains one option for quantifying dorsal FRM,[1,18,49,62] provided the examiner can accept the expected projection error associated with radiographic analysis.[70]

In a study published in 2018, Tavara-Vidalon et al[71] 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.[4] 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[2,3,7,31,39] or handheld rulers.[21,41,42,46,49,53] 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[64] 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.[64] Without validating the measurement, Birke et al[3] used this device to quantify dorsal FRM in a clinical study. Owing to a flaw in the design of the device,[28,37] 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[28] 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.[28] Though this prototype device[64] was never mentioned in the literature again, the concept of measuring dorsal FRM with a mechanical device was soon pursued by others.[37,52]

Klaue and Glasoe introduced their own devices (Figure 3) in the 1990s.[37,52] The design of both devices was published in detail to allow others to build replicas, and many did.[6,7,12,40,48,69] A study by Klaue et al[52] 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.[39,48,69] Basic in design (Figure 3A), Klaue[52] 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 operating 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.[31,39,52,53]
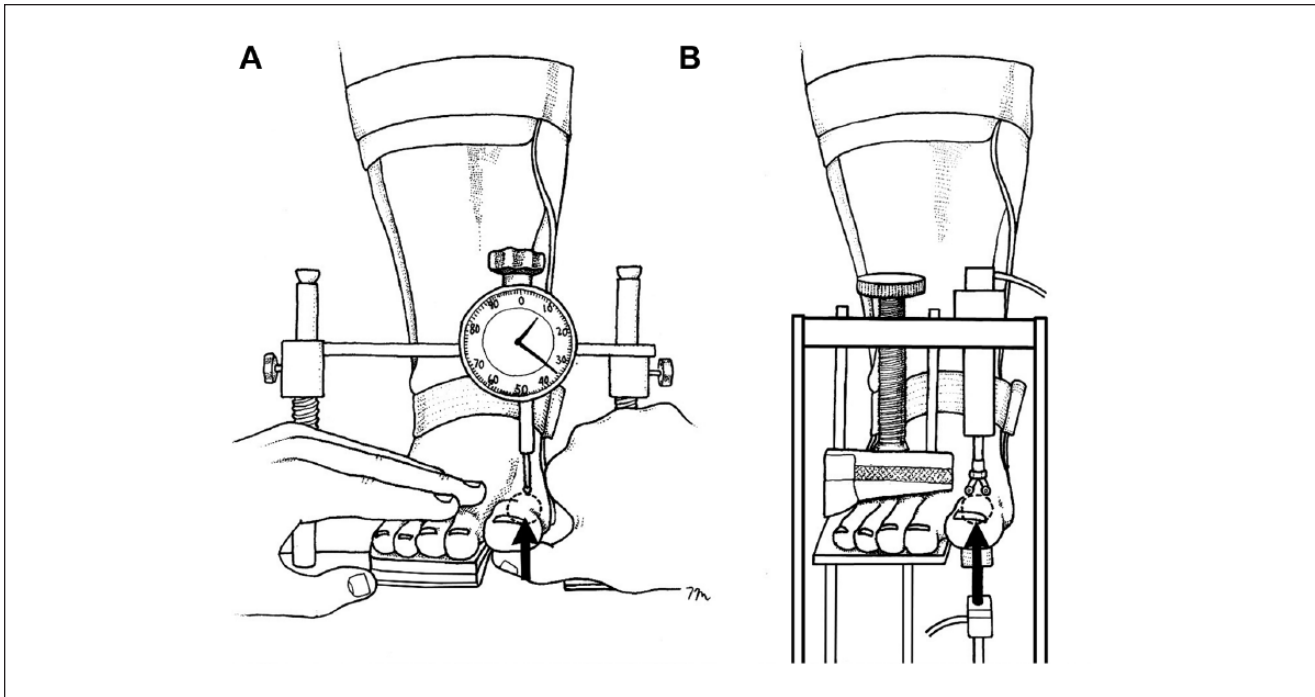
Figure 3. Dorsal first ray mobility measured with a mechanical device. (A) Klaue device records displacement when the first ray is moved manually. (B) Glasoe device records force and displacement when the first ray is moved mechanically with a preplanned load. Panel A was modified from a photograph in Singh et al.[69]

While Klaue did not test reliability, a decade later Jones et al[48] 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[48] 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[52] has been used to measure dorsal FRM in more studies[8-12,31,39,40,48,50,69] than any other single method. Of concern, the experiment by Jones[48] 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.[28] Incorporating the most objectifying features of the 2 previous designs,[52,64] 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.[28] 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,[28,37,38]

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[2,23-28,30,31,37,38] 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.[30,31] Though the device[37] has been replicated by others for use in research,[6,7] its size and technical nature keep it from being routinely used in the clinic.

Both the Klaue[52] and Glasoe[37] mechanical devices (Figure 3) have been used in a number of unaffiliated studies.[2,6-12,23,25-28,30,31,37-40,48,69] These initiatives eventually culminated into a multicenter study that compared measures acquired by 1 examiner using both devices.[31] In preparation for this study, a load of 45 N was determined as the average load exerted to dorsiflex the first ray manually.[30,31] The study itself[31] 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[31] 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
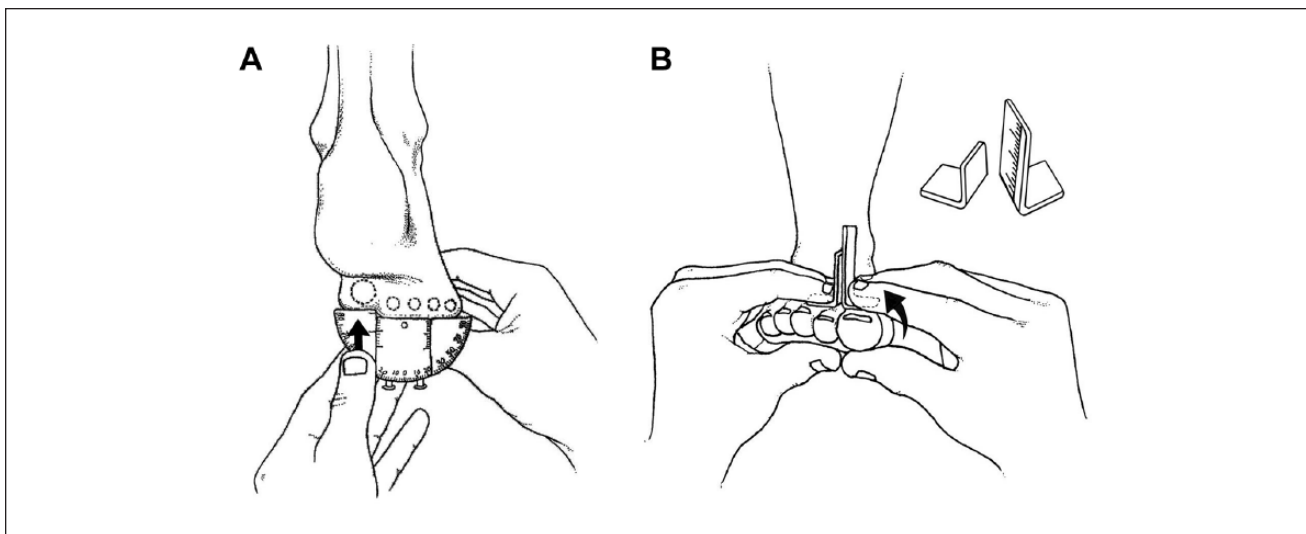
Figure 4. Dorsal first ray mobility examined manually, with displacement measured by (A) holding the Kilmartin Sagittal Raynger[73] on the plantar surface of the foot and (B) holding rulers on the dorsal surface of the foot. With both approaches, the displacement of the first ray is measured relative to second metatarsal, which is held stationary.

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 device[37,52] 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 Kilmartin[73] 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 authors[73] 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 Young[53] reintroduced the handheld ruler approach in 2001 (Figure 4B). Kim joined with Lee[49] 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 2008[49] compared data collected with the handheld ruler to measures acquired with the Klaue device,[52] and serial radiographs.[1,18,49] 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's[49,53] 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 awkard 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[6,24,30,68] 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 Kilmartin[73] had originally instructed, Greisberg[41,42] 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[20,21] 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,[64] 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 Kilmartin[73] 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 Coughlin[39] 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.

Declaration of Conflicting Interests

References

1. Alexander IJ. *The Foot, Examination and Diagnosis*, New York, NY: Churchill Livingstone; 1990.

2. Allen MK, Cuddeford TJ, Glasoe WM, et al. Relationship between static mobility of the first ray and first ray, midfoot, and hindfoot motion during gait. *Foot Ankle Int*. 2004;25(6):391-396.

3. Birke JA, Franks DB, Foto JG. First ray joint limitation, pressure, and ulceration of the first metatarsal head in diabetes mellitus. *Foot Ankle Int*. 1995;16(5):277-284.

4. Brown KM, Bursey DE, Arneson LJ, et al. Consideration of digitization precision when building local coordinate axes for a foot model. *J Biomech*. 2009;42(9):1263-1269.

5. Cerveri P, Quinzi M, Bovio D, Frigo C. A novel wearable apparatus to measure fingertip forces in manipulation tasks based on MEMS barometric sensors. *IEEE Trans Haptics*. 2017;10(3):317-324.

6. Cornwall MW, Fishco WD, McPoil TG, et al. Reliability and validity of the clinically assessing first-ray mobility of the foot. *J Am Podiatr Med Assoc*. 2004;94(5):470-476.

7. Cornwall MW, McPoil TG, Fishco WD, et al. The influence of first ray mobility on forefoot plantar pressure and hindfoot kinematics during walking. *Foot Ankle Int*. 2006;27(7): 539-547.

8. Coughlin M, Jones C, Viladot R, et al. Hallux valgus and first ray mobility: a cadaveric study. *Foot Ankle Int*. 2004;25(8):537-544.

9. Coughlin M, Shurnas P. Hallux rigidus: demographics, etiology, and radiographic assessment. *Foot Ankle Int*. 2003;24(10):731-743.

10. Coughlin MJ, Jones CP. Hallux valgus and first ray mobility. *J Bone Joint Surg Am*. 2007;89(9):1887-1898.

11. Coughlin MJ, Jones CP. Hallux valgus: demographics, etiology, and radiographic assessment. *Foot Ankle Int*. 2007;28(7):759-777.

12. Coughlin MJ, Shurnas PS. Hallux valgus in men part II: first ray mobility after bunionectomy and factors associated with hallux valgus deformity. *Foot Ankle Int*. 2003;24(1):73-78.

13. D'Amico JC. Understanding the first ray. *Podiatry Management*. 2016:109-122. https://www.podiatrym.com/cme/CME1_916.pdf. Accessed March 11, 2019.

14. Daniel DM, Stone ML, Sachs R, Malcom L. Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. *Am J Sports Med*. 1985;13(6):401-407.

15. DiGiovanni CW, Kuo R, Tejwani N, Price R, Hansen ST. Isolated gastrocnemius tightness. *J Bone Joint Surg Am*. 2002;84(6):962-970.

16. Docherty CL, Rybak-Webb K. Reliability of the anterior drawer and talar tilt tests using the LigMaster joint arthrometer. *J Sport Rehabil*. 2009;18(3):389-397.

17. Faber FW, Van Kampen PM, Bloembergen MW. Long-term results of the Hohmann and Lapidus procedure for the correction of hallux valgus: a prospective, randomised trial with eight- to 11-year follow-up involving 101 feet. *Bone Joint J*. 2013;95-B:1222-1226.

18. Faber FWM, Kleinrensink GJ, Mulder PGH, Verhaar JAN. Mobility of the first tarsometatarsal joint in hallux valgus patients: a radiographic analysis. *Foot Ankle Int*. 2001;22(12):965-969.

19. Faber WM, Mulder PH, Verhaar JN. Role of first ray hypermobility in the outcome of the Hohmann and the Lapidus procedure. *J Bone Joint Surg Am*. 2004;86(3):486-495.

20. Fraser JJ, Koldenhoven RM, Jaffri AH, et al. Foot impairments contribute to functional limitation in individuals with ankle sprain and chronic ankle instability [published online ahead of print July 6, 2018]. *Knee Surg Sports Trauma Arthrosc*. doi:10.1007/s00167-018-5028-x.

21. Fraser JJ, Koldenhoven RM, Saliba SA, Hertel J. Reliability of ankle-foot morphology, mobility, strength, and motor performance measures. *Int J Sports Phys Ther*. 2017;12(7): 1134-1149.

22. Geng X, Wang C, Ma X, et al. Mobility of the first metatarsal-cuneiform joint in patients with and without hallux valgus: in vivo three-dimensional analysis using computerized tomography scan. *J Orthop Surg Res*. 2015;10:140.

23. Glasoe WM, Allen MK, Kepros T, Stonewall L, Ludewig PM. Dorsal first ray mobility in women athletes with a history of stress fracture of the second or third metatarsal. *J Orthop Sports Phys Ther*. 2002;32(11):560-567.

24. Glasoe WM, Allen MK, Ludewig PM. Comparison of first ray dorsal mobility across different forefoot alignments. *J Orthop Sports Phys Ther*. 2000;30(10):612-623.

25. Glasoe WM, Allen MK, Ludewig PM, Saltzman CL. Dorsal mobility and passive stiffness in patients with diabetes mellitus. *Foot Ankle Int*. 2004;25(8):250-555.

26. Glasoe WM, Allen MK, Saltzman CL. First ray dorsal mobility in relation to hallux valgus deformity and first intermetatarsal angle. *Foot Ankle Int*. 2001;22(2):98-101.

27. Glasoe WM, Allen MK, Saltzman CL, Ludewig PM, Sublett SH. Comparison of two methods used to assess first ray mobility. *Foot Ankle Int*. 2002;23(3):248-252.

28. Glasoe WM, Allen MK, Yack HJ. Measurement of dorsal mobility in the first ray: elimination of fat pad compression as a variable. *Foot Ankle Int*. 1998;19(8):542-546.

29. Glasoe WM, Coughlin MJ. A critical analysis of Dudley Morton's concept of disordered foot function. *J Foot Ankle Surg*. 2006;45:147-155.

30. Glasoe WM, Getsoian S, Myers M, et al. Criterion-related validity of a clinical measure of dorsal first ray mobility. *J Orthop Sport Phys Ther*. 2005;35(9):589-593.

31. Glasoe WM, Grebing BR, Beck S, Coughlin MJ, Saltzman CL. A comparison of device measures of dorsal first ray mobility. *Foot Ankle Int*. 2005;26(11):957-961.

32. Glasoe WM, Nuckley DJ, Ludewig PM. Hallux valgus and the first metatarsal arch segment: a theoretical biomechanical perspective. *Phys Ther*. 2010;90(1):110-120.

33. Glasoe WM, Pena F, Phadke V, Ludewig PM. Arch height and first metatarsal joint axis orientation as related variables in foot structure and function. *Foot Ankle Int*. 2008;29(6): 647-655.

34. Glasoe WM, Pena FA, Phadke V. Cardan angle rotation sequence effects on first-metatarsophalangeal joint kinematics:

implications for measuring hallux valgus deformity. *J Foot Ankle Res*. 2014;7:29.

35. Glasoe WM, Saltzman CL. Recalcitrant posterior tibialis tendinitis from an unstable first ray. *Foot Ankle Surg*. 2002;8:281-284.

36. Glasoe WM, Yack HJ, Saltzman CL. Anatomy and biomechanics of the first ray. *Phys Ther*. 1999;79(9):854-859.

37. Glasoe WM, Yack HJ, Saltzman CL. Measuring first ray mobility with a new device. *Arch Phys Med Rehabil*. 1999;80(1):122-124.

38. Glasoe WM, Yack HJ, Saltzman CL. The reliability and validity of a first ray measurement device. *Foot Ankle Int*. 2000;21(3):240-246.

39. Grebing BR, Coughlin MJ. The effect of ankle position on the exam for first ray mobility. *Foot Ankle Int*. 2004;25(7):467-475.

40. Grebing BR, Coughlin MJ. Evaluation of Morton's theory of second metatarsal hypertrophy. *J Bone Joint Surg Am*. 2004;42(7):1375-1386.

41. Greisberg J, Prince D, Sperber L. First ray mobility increase in patients with metatarsalgia. *Foot Ankle Int*. 2010;31(11):954-958.

42. Greisberg J, Sperber L, Prince DE. Mobility of the first ray in various foot disorders. *Foot Ankle Int*. 2012;33(1):44-49.

43. Hanlon S, Caccese J, Knight CA, Swanik CB, Kaminski TW. Examining ankle-joint laxity using 2 knee positions and with simulated muscle guarding. *J Athl Train*. 2016;51(2):111-117.

44. Hansen ST. Hallux valgus surgery—Morton and Lapidus were right! *Clin Pod Med Surg*. 1996;13(3):347-354.

45. Heng ML, Chua YK, Pek HK, Krishnasamy P, Kong PW. A novel method of measuring passive quasi-stiffness in the first metatarsophalangeal joint. *J Foot Ankle Res*. 2016;9:41.

46. Heng ML, Krishnasamy P, Kong PW. First ray mobility and posterior tibial tendon dysfunction (PTTD) in persons with flat foot: a case control study. *Foot (Edinb)*. 2018;37:57-60.

47. Hiss J. *Functional Foot Disorders*. Los Angeles, CA: Oxford Press; 1949.

48. Jones CP, Coughlin MJ, Pierce-Villadot R, et al. The validity and reliability of the Klaue device. *Foot Ankle Int*. 2005;26(11):951-956.

49. Kim JY, Hwang SK, Lee KT, Young K, Jung JS. A simpler device for measuring the mobility of the first ray of the foot. *Foot Ankle Int*. 2008;29:213-218.

50. Kim JY, Park JS, Hwang SK, Young KW, Sung IH. Mobility changes of the first ray after hallux valgus surgery: clinical results after proximal metatarsal chevron osteotomy and distal soft tissue procedure. *Foot Ankle Int*. 2008;29(5):468-472.

51. Kimura T, Kubota M, Taguchi T, et al. Evaluation of first-ray mobility in patients with hallux valgus using weight-bearing CT and a 3-D analysis system: a comparison with normal feet. *J Bone Joint Surg Am*. 2017;99(3):247-255.

52. Klaue K, Hansen ST, Masquelet AC. Clinical, quantitative assessment of first tarsometatarsal mobility in the sagittal plane and its relation to hallux valgus deformity. *Foot Ankle Int*. 1994;15(1):9-13.

53. Lee KT, Young K. Measurement of first-ray mobility vs. hallux valgus patients. *Foot Ankle Int*. 2001;22(12):960-964.

54. Meyer M, Tomeno B, Burdet A. Metatarsalgia due to insufficient support by the first ray. *Int Orthop*. 1981;5:193-201.

55. Michaud TC. *Foot Orthoses and Other Forms of Conservative Foot Care*. Baltimore, MD: Williams & Wilkins; 1993.

56. Michaud TC. *Human Locomotion: The Conservative Management of Gait-Related Disorders*, Newton, MA: Newton Biomechanics; 2011.

57. Michaud TC, Nawoczenski DA. The influence of two different types of foot orthoses on first metatarsophalangeal joint kinematics during gait in a single subject. *J Manipulative Physio Ther*. 2006;29(1):60-65.

58. Morton D. Hypermobility of the first metatarsal bone: the interlinking factor between metatarsalgia and longitudinal arch strains. *J Bone Joint Surg*. 1928;10:187-196.

59. Morton DJ. *The Human Foot. Its Evolution, Physiology, and Functional Disorders*, New York, NY: Columbia University Press; 1935.

60. Myerson M, Allon S, McGarvey W. Metatarsocuneiform arthrodesis for management of hallux valgus and metatarsus primus varus. *Foot Ankle Int*. 1992;13(3):107-115.

61. Myerson MS, Badekas A. Hypermobility of the first ray. *Foot Ankle Clin*. 2000;5(3):469-484.

62. Prieskorn DW, Mann RA, Fritz G. Radiographic assessment of the second metatarsal: measure of first ray hypermobility. *Foot Ankle*. 1996;17(6):331-333.

63. Pugh L, Mascarenhas R, Arneja S, Chin PY, Leith JM. Current concepts in instrumented knee-laxity testing. *Am J Sports Med*. 2009;37(1):199-210.

64. Rodgers MM, Cavanagh PR. A device for the measurement of first ray mobility. In: *Proceedings of the North American Congress on Biomechanics*. Montreal, Canada; August 25-27, 1986. Abstract, 205-206.

65. Rodgers MM, Cavanagh PR. Pressure distribution in Morton's foot structure. *Med Sci Sports Exerc*. 1989;21(1):23-28.

66. Root ML, Orien WP, Weed JH. *Normal and Abnormal Function of the Foot*. Los Angeles, CA: Clinical Biomechanics Corp; 1977.

67. Roukis TS, Landsman AS. Hypermobility of the first ray: a critical review of the literature. *J Foot Ankle Surg*. 2003;42(6):377-390.

68. Shirk C, Sandrey MA, Erickson M. Reliability of first ray position and mobility measurements in experienced and inexperienced examiners. *J Athl Train*. 2006;41(1):93-101.

69. Singh D, Biz C, Corradin M, Favero L. Comparison of dorsal and dorsomedial displacement in evaluation of first ray hypermobility in feet with and without hallux valgus. *Foot Ankle Surg*. 2016;22:120-124.

70. Swanson JE, Stoltman MG, Oyen CR, et al. Comparison of 2D-3D measurements of hallux and first ray sagittal motion in patients with and without hallux valgus. *Foot Ankle Int*. 2016;37(2):227-232.

71. Tavara-Vidalon SP, Monge-Vera MA, Lafuente-Sotillos G, Dominguez-Maldonado G, Munuera-Martinez PV. Static range of motion of the first metatarsal in the sagittal and frontal planes. *J Clin Med*. 2018;7(11):1-12.

72. Voellmicke KV, Deland JT. Manual examination technique to assess dorsal instability of the first ray. *Foot Ankle Int*. 2002;23(11):1040-1041.

73. Wallace WA, Kilmartin TE. Predicting hallux abducto valgus. *J Am Podiatr Med Assoc*. 1990;80(9):509-510.

74. Wanivenhaus A, Pretterklieber M. First tarsometatarsal joint: anatomical biomechanical study. *Foot Ankle Int*. 1989;9(4):153-157.