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Diagnostic Evaluation of Mechanical Ankle Instability by Comparing Injured and Uninjured Contralateral Ankles Using Arthrometry

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Context: Individuals with mechanical ankle instability (MAI) have obvious lateral ligament laxity and excessive ankle joint motion beyond the physiological range. Arthrometry has been introduced to quantitatively measure the laxity of the ankle joint. However, the diagnostic accuracy of arthrometry in MAI is still debatable.

Objectives: To (1) evaluate the difference in laxity between bilateral ankles in patients with and those without MAI and (2) calculate the diagnostic accuracy of ankle arthrometry using bilateral comparisons.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: A total of 38 individuals with unilateral MAI (age = 31.24 ± 7.90 years, height = 168.93 ± 7.69 cm, mass = 65.72 ± 10.47 kg) and 38 individuals without MAI (control group; age = 32.10 ± 7.10 years, height = 166.59 ± 7.89 cm, mass = 62.93 ± 10.72 kg).

Main Outcome Measure(s): Bilateral ankle laxity in each participant was quantitatively measured by performing the arthrometric anterior drawer test. Continuous data of loading force and joint displacement were recorded. Data from both ankles were compared for the ankle joint displacement at a loading force of 75 N (D75) and load-displacement ratio from 10 to 40 N (LDR 10–40).

Results: The D75 between injured and uninjured ankles in patients with MAI was different ($t_{37} = 9.78$, $P < .001$). The mean LDR 10–40 in injured ankles was higher than that in uninjured ankles ($t_{37} = 9.80$, $P < .001$). In the control group, no differences were found between the left and right ankles. The MAI group had larger bilateral differences than the control group (t_{37} range = 7.33–8.18; $P < .001$). When LDR 10–40 was used to diagnose MAI, the arthrometer showed sensitivity and specificity of 0.900 and 0.933, respectively, with a cutoff value of 0.0351 mm/N.

Conclusions: An ankle arthrometer can be used to quantitatively measure the difference in bilateral ankle laxity in patients with MAI. Arthrometer-measured LDR 10–40 can be used to diagnose MAI with high diagnostic accuracy.

Key Words: chronic ankle instability, arthrometer, sensitivity, specificity, diagnosis

Key Points

- Bilateral differences in anterior talar translation, which were quantitatively measured via arthrometric stress testing, were larger in patients with mechanical ankle instability than in those without mechanical ankle instability.
- Load-displacement ratios were higher in patients with mechanical ankle instability, indicating that greater laxity of the lateral ankle ligaments was caused by partial or total ligament failure.
- By using load-displacement ratios as a reference standard, we found that ankle arthrometry had high diagnostic accuracy in bilateral comparisons of ankles.

Ankle sprains are one of the most common musculoskeletal injuries, with a high incidence in the general and athletic populations.[1] Researchers[2] have suggested that 30% to 75% of athletes with sprained ankles have long-term impairments, such as recurrent sprains, perceptions of "giving way," pain, and swelling. These symptoms are collectively termed *chronic ankle instability* (CAI). The presence of CAI negatively affects ankle function in athletes.[3] Chronic ankle instability can be subdivided into functional ankle instability (FAI) and mechanical ankle instability (MAI). The former refers to subjectively perceived instability during daily or sport activities, whereas the latter describes obvious lateral ligament laxity and excessive ankle joint motion beyond the physiological range.[4] Ligamentous changes in MAI result in structural instability of the ankle joint, such that talocrural anterior translation and internal rotation are notably increased on the injured side compared with the healthy ankle.[5] Clinically, MAI is assessed by manual examination, stress radiography, and instrumented ankle arthrometry, all of which indicate the laxity of the ankle joint via the stress-strain relationship during an anterior drawer test (ADT) and talar tilt test.[2]

Although manual stress tests via the ADT and talar tilt test[6] are most frequently used in clinical settings to assess MAI, they are subjective methods and depend on the clinician's experience. Arthrometers provide an objective method of measuring the laxity of ankle joints quantitatively, simulating the ADT and talar tilt test of the ankle. However, the diagnostic

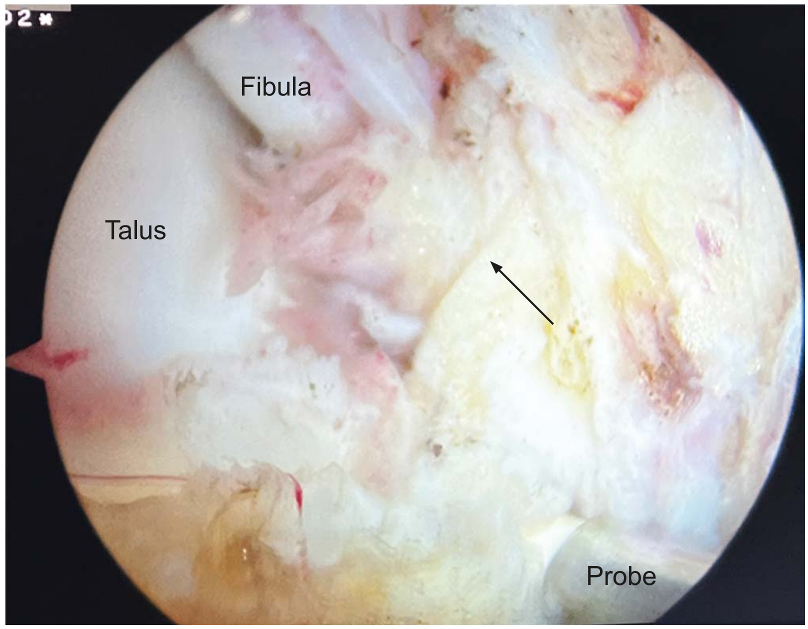

Figure 1. Arthroscopic visualization of complete rupture of the anterior talofibular ligament. The arrow indicates where the anterior talofibular ligament should have been visible, but it was replaced by proliferating synovium after the injury.

accuracy of arthrometry in terms of sensitivity and specificity is still debatable. Croy et al[7] found that the sensitivity and specificity of arthrometric ADT were 0.83 and 0.40, respectively, for differentiating patients with CAI from healthy control individuals. Lohrer et al[8] reported that the sensitivity and specificity of arthrometric ADT were 0.81 and 0.93, respectively, for discriminating between patients with MAI and FAI. In previous work from our institution, Chen et al[9] recruited 160 control individuals and 153 patients with CAI and demonstrated that arthrometric ADT had sensitivity of 0.804 and specificity of 0.863. In all of these studies, investigators only compared individuals with and those without (control group) CAI; yet the threshold for pathologic ankle displacement using arthrometers varied considerably, thereby limiting the use of arthrometers in clinical practice.

Differences in the demographic and clinical features of individuals may play a role in the diverse values seen for the diagnostic accuracy and pathologic threshold of arthrometers. Given that the threshold for pathologic ankle displacement on the arthrometric ADT has not been defined, an uninjured contralateral ankle may serve as the best reference. However, to our knowledge, no researchers have measured the diagnostic accuracy of arthrometers via bilateral comparisons of ankles in patients with MAI.

This study was an extension of earlier work from our institution,[9] which showed that arthrometer measurements could quantify ankle laxity with good diagnostic accuracy. The purpose of our examination was to further assess the diagnostic accuracy of ankle arthrometers by comparing injured ankles with uninjured contralateral ankles in patients with MAI. Our hypothesis was that arthrometers would display better diagnostic accuracy for MAI via side-by-side comparison of both ankles.

METHODS

Design

A cross-sectional study was conducted between February 2022 and August 2022 to quantitatively investigate the bilateral difference in ankle joint laxity between ankles in the MAI and control groups.

Participants

We recruited participants with MAI from our institution, where they were hospitalized and scheduled to undergo ankle arthroscopy after the experiment. All patients provided written informed consent for arthroscopic procedures. A total of 38 participants (age = 31.24 ± 7.90 years, height = 168.93 ± 7.69 cm, mass = 65.72 ± 10.47 kg) with unilateral MAI were enrolled (MAI group). All participants were confirmed to have impaired lateral ankle ligaments via arthroscopic examination (Figure 1). A total of 38 individuals without MAI (age = 32.10 ± 7.10 years, height = 166.59 ± 7.89 cm, mass = 62.93 ± 10.72 kg) were recruited from the local community through advertisements and were matched by age, sex, height, and mass with participants who had MAI (control group). All participants provided written informed consent, and the study was approved by the Huashan Institutional Review Board.

Selection Criteria. Inclusion and exclusion criteria were based on the criteria of the International Ankle Consortium[10] and arthroscopic findings. For the MAI group, the following inclusion criteria were used: (1) age 18 to 50 years, (2) ≥1 episode of substantial unilateral ankle sprain sustained ≥12 months before recruitment, (3) ≥1 interrupted day of desired physical activity due to the ankle injury, (4) a history of ≥2 episodes of unilateral sprains or perceived instability or giving way in the 6 months before the study, (5) a Cumberland Ankle Instability Tool (CAIT) score of <24, and (6) direct visualization of lateral ligament injuries via ankle arthroscopy after arthrometric testing. For the control group, the following inclusion criteria were used: (1) no history of ankle injury, instability, or surgery; (2) normal ankle range of motion and muscle strength; and (3) a CAIT score of 29 or 30. The following exclusion criteria were used for both groups: (1) age not between 18 and 50 years, (2) a history of surgery or fracture in either lower extremity, or (3) a history of acute injury to the lower extremity within 3 months before enrollment.

Sample Size Calculation. We calculated sample size using the following formula: sample size = $(Z_{1-\alpha/2})^2(SD)^2/d^2$,[11] where $Z_{1-\alpha/2}$ is the standard normal variate, which equals 1.96 at 5% type I error; *SD* is the standard deviation of the variable taken from previous work,[9] which was 1.566; and *d* is the absolute error or precision decided in the earlier study,[9] which was set at 0.5 for this investigation. Thereafter, the sample size was calculated to be at least 37 ankles in each group.

Experimental Procedure

Two researchers (Y.C. and S.C.) who were experienced in use of the arthrometer and were blinded to the conditions of participants, including group, injured side, and CAIT score, performed instrumented ADT using the Ligs Digital Arthrometer (Innomotion Software Technologies). All participants in the MAI and control groups completed the arthrometric testing in a treatment room. All data were transferred to a laptop computer and were processed by a third researcher (C.W.). In the MAI group, this test was performed 1 day before the arthroscopic procedure. All arthroscopic procedures were to be performed by a senior surgeon (X.W.), who was blinded to the results of the arthrometric testing. The arthrometer consisted of a motor unit and a sensor unit. A researcher (C.Z.) demonstrated the use of the arthrometer to participants and assisted them in maintaining the position of the tested lower limb. The knee was flexed to 90°, and the ankle was placed in a neutral position (0° of flexion angle) using a goniometer. The neutral position was measured from the plantar surface of the foot relative to the anterior tibia. With the participant's calf and heel fixed, the motor unit pushed the anterior tibia posteriorly at a constant speed of 3 N/s until the maximum loading force of 75 N was reached. Loading force and joint-displacement data were recorded continuously at a frequency of 30 Hz by the sensor unit. To reduce the influence of the calf musculature, the recording started the moment after the load exceeded 10 N. The load is accurate to 1 N, and displacement is accurate to 0.1 mm.[9]

All participants underwent testing of both ankles. For the MAI group, the differences between the injured and uninjured ankles were calculated. For the control group, the differences between the left and right ankles were calculated and recorded as absolute values. Ankle arthrometer calculations were based on the average values of 3 consecutive measurements. The arthrometer has been shown to have excellent test-retest and intertester reliability.[9]

Outcome Measures

Traditionally, static measures are used to assess the laxity of the ankle joint by measuring the anterior translation of the talus with a maintained loading force applied by an arthrometer.[7,12] However, more recently, researchers[8,9] have suggested that dynamic measures using load-displacement curves might better reflect the difference in laxity between injured and uninjured ankles. Chen et al[9] reported that the arthrometer could best distinguish an injured from an uninjured ankle using displacement at a loading force of 75 N (D75) as a static reference standard. When using dynamic measurement by depicting load-displacement curves, Chen et al showed that the difference in the load-displacement ratio (LDR) at 10 to 40 N (LDR 10–40)

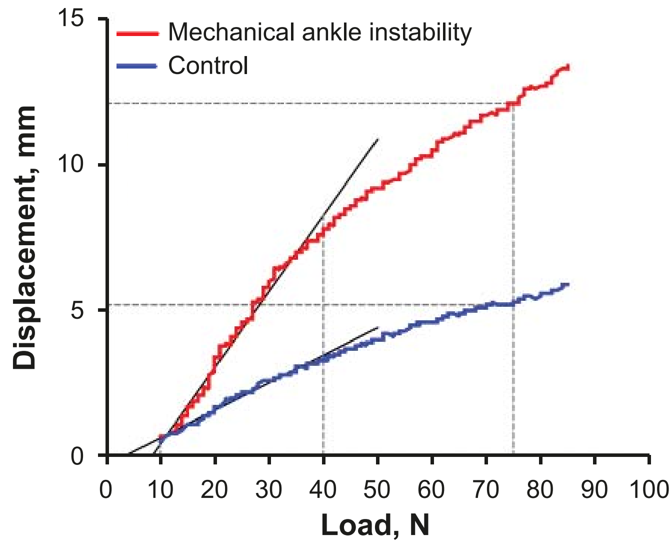

Figure 2. Two typical load-displacement curves of the arthrometric anterior drawer test. For the static reference, displacement was recorded when the loading force was maintained at 75 N. For the dynamic reference, the slopes of linear regression were used to calculate load-displacement ratios at 10 to 40 N.

had the largest effect size (ES) between mechanically stable and unstable ankles (Figure 2).[9] The LDR 10–40 was the slope of the linear regression between 10 and 40 N on the load-displacement curve. Therefore, D75 and LDR 10–40 were used for further analysis.

Statistical Analysis

Characteristics of the 2 groups were compared using 2-tailed paired *t* tests. Differences in D75 and LDR 10–40 between bilateral ankles of participants in the 2 groups were calculated using a 2-tailed paired *t* test. We used subtraction to establish absolute differences between ankles in each participant and a 2-tailed between-subjects *t* test to examine between-groups absolute limb differences in D75 and LDR 10–40. The Cohen *d* was used to compute ESs, which were interpreted as *small* (0.20), *medium* (0.50), or *large* (0.80).[13] A receiver operating characteristic (ROC) curve analysis was generated to identify the cutoff points that discriminated between the control and MAI groups for bilateral absolute differences in D75 and LDR 10–40. The upper left coordinate of each ROC curve was the cutoff point. The area under the ROC curve (AUC) value was calculated to reflect the diagnostic accuracy of D75 and LDR 10–40. Sensitivity and specificity were determined. The α level was set a priori at .05. Statistical analyses were performed using SPSS (version 24.0; IBM Corp).

RESULTS

Patient Characteristics

Characteristics of the MAI and control groups are shown in Table 1. We observed differences in CAIT scores between the groups ($t_{37} = 10.96$, $P < .001$).

Bilateral Comparisons of Ankles

In the MAI group, the mean D75 of injured ankles was 11.32 ± 1.93 mm, and the mean D75 of uninjured ankles was

Table 1. Participants' Characteristics

Characteristic	Group, Mean ± SD: Mechanical Ankle Instability (n = 38)	Control (n = 38)	t_{37} Value	P Value
Age, y	31.24 ± 7.90	32.10 ± 7.10	0.50	.19
Height, cm	168.93 ± 7.69	166.59 ± 7.89	1.31	.21
Mass, kg	65.72 ± 10.47	62.93 ± 10.72	1.15	.11
Body mass index, kg/m^2	22.91 ± 2.41	22.54 ± 2.40	0.67	.21
Cumberland Ankle Instability Tool score	20.17 ± 5.51	29.97 ± 0.19	10.96	<.001

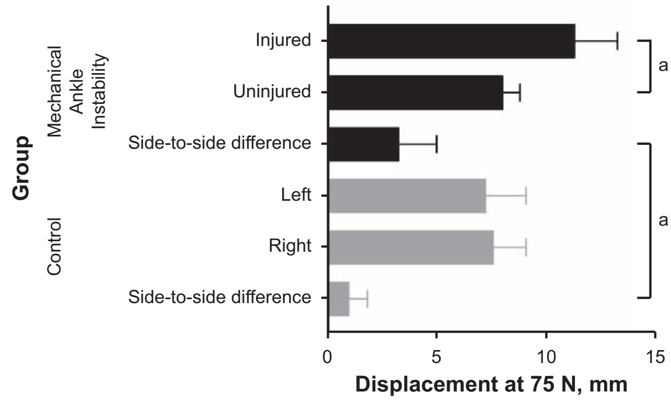

Figure 3. Arthrometric anterior drawer test measurement outcomes of displacement at a loading force of 75 N (displacement at 75 N) for ankles in the mechanical ankle instability and control groups. [a] Indicates a difference ($P < .001$).

8.03 ± 0.76 mm ($t_{37} = 9.78$, $P < .001$, ES = 2.24; Table 2). The mean LDR 10–40 of injured ankles was higher than that of uninjured ankles (0.222 ± 0.046 mm/N versus 0.138 ± 0.026 mm/N, respectively; $t_{37} = 9.80$, $P < .001$, ES = 2.25). In the control group, no differences were found between the left and right ankles in either D75 ($t_{37} = 0.92$, $P = .14$) or LDR 10–40 ($t_{37} = 1.16$, $P = .07$).

Absolute differences between each participant's ankles were also calculated using subtraction. The difference in D75 was larger in the MAI group than in the control group (3.28 ± 1.72 mm versus 1.02 ± 0.81 mm, respectively; $t_{37} = 7.33$, $P < .001$, ES = 1.68; Figure 3). The difference in LDR 10–40 was also larger in the MAI group than in the control group (0.084 ± 0.048 mm/N versus 0.018 ± 0.013 mm/N, respectively; $t_{37} = 8.18$, $P < .001$, ES = 1.88; Figure 4).

Diagnostic Accuracy

The results of the ROC curve analysis of bilateral absolute differences in ankle D75 and LDR 10–40 are presented in Table 3. When the cutoff value of D75 was set at 1.85 mm, the highest AUC value was derived (0.914 [95% CI = 0.844, 0.984]), and the sensitivity and specificity were 0.800 and 0.933, respectively. For LDR 10–40, the highest AUC value was 0.959 (95% CI = 0.907, 1.000) when the cutoff value was set at 0.0351 mm/N, and the sensitivity and specificity were 0.900 and 0.933, respectively. The ROC curves are displayed in Figure 5.

DISCUSSION

Our most important finding was that ankle arthrometry had excellent diagnostic accuracy for MAI when comparing injured and uninjured contralateral ankles. Compared with static measurement using D75, dynamic measurement using LDR 10–40 provided superior diagnostic accuracy based on the higher sensitivity and specificity.

We observed that arthrometric stress testing had sensitivity and specificity of 0.900 and 0.933, respectively, when using LDR 10–40 for bilateral comparisons. A dynamic reference standard using LDR 10–40 was more sensitive than a static reference standard using D75 for diagnosing MAI (Table 3). The diagnostic accuracy of arthrometric stress testing is superior to that of manual ADT.[6] The clinical practice of manual ADT is highly dependent on the tester's subjectivity and experience. In a recent meta-analysis of 885 cases, the researchers[14] reported that manual ADT had a sensitivity of only 54%, despite a relatively high specificity of 87%. Li et al[15] noted a difference in the diagnostic performance of manual ADT between a junior and a senior examiner: sensitivity was only 5.3% for the junior examiner but 39.5% for the senior examiner. By contrast, arthrometric ADT has the advantage of objectively quantifying the test results, and sensitivity has been described as ranging from 74% to 91.7%.[7–9,16]

The load-displacement curves reflected the laxity of the ankle joints under arthrometric loading (Figure 2). Under a lower loading force (10–40 N), patients with MAI had a steeper slope than the control individuals, indicating a greater extent of anterior talar translation caused by lateral ligament failure.[8] However, when the loading force was increased (>40 N), the curves of patients with MAI and control individuals tended to be parallel and have decreased slopes, which suggested that the talus was being forced to the end position and soft tissues around the ankle caused further displacement.

In previous studies related to the diagnostic accuracy of ankle arthrometry, the authors compared patients with CAI

Table 2. Bilateral Comparisons of Ankles by Group

Group	Variable	Ankle, Mean ± SD: Injured (n = 38)	Uninjured (n = 38)	T_{37} Value	P Value	Effect Size
Mechanical ankle instability	D75, mm	11.32 ± 1.93	8.03 ± 0.76	9.78	<.001	2.24
	LDR 10–40, mm/N	0.222 ± 0.046	0.138 ± 0.026	9.80	<.001	2.25
		Left (n = 38)	Right (n = 38)			
Control	D75, mm	7.25 ± 1.82	7.60 ± 1.47	0.92	.14	0.21
	LDR 10–40, mm/N	0.105 ± 0.030	0.112 ± 0.022	1.16	.07	0.27

Abbreviations: D75, displacement at a loading force of 75 N; LDR 10–40, load-displacement ratio at 10 to 40 N.

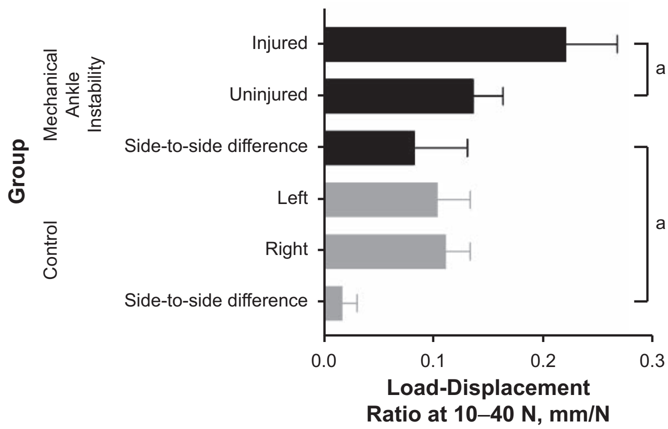

Figure 4. Arthrometric anterior drawer test measurement outcomes of load-displacement ratio at 10 to 40 N (LDR at 10–40) for ankles in patients with mechanical ankle instability and controls. [a] Indicates a difference ($P < .001$).

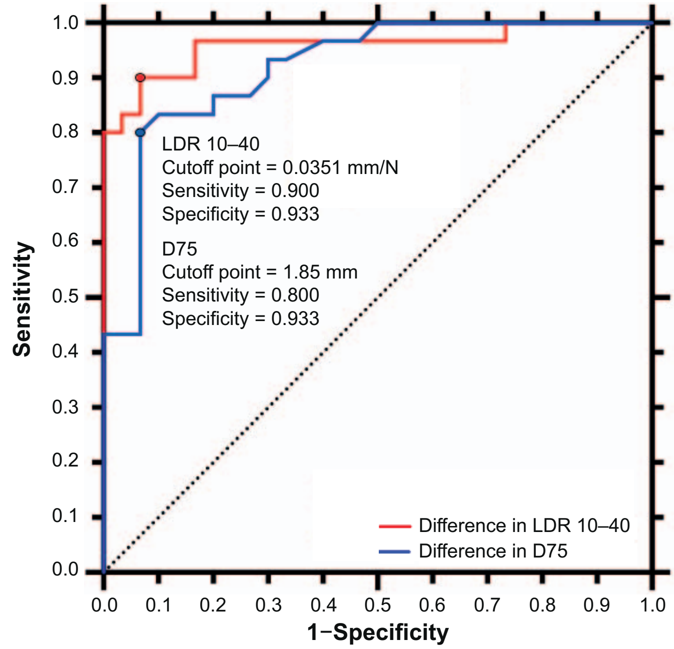

Figure 5. Receiver operating characteristic curve of differences in D75 and LDR 10–40. Abbreviations: D75, displacement at a loading force of 75 N; LDR 10–40, load-displacement ratio at 10 to 40 N.

and a healthy control group.[7,17,18] Yet factors such as sex, foot size, local anatomy of the ankle, and soft tissue elasticity vary when performing the ADT.[19] Eliminating all of these potentially confounding factors that may affect the results of ankle stress testing is not possible, but a bilateral ankle comparison is not influenced by these factors. Chen et al[9] compared 153 ankles with CAI and 160 uninjured ankles and found sensitivity of 0.804 and specificity of 0.863 using LDR 10–40 as a dynamic reference standard. Nonetheless, Chen et al compared only CAI and uninjured ankles and did not assess bilateral differences between the CAI and control groups. Using the same experimental procedure and device, we found sensitivity and specificity of 0.900 and 0.933, respectively, using LDR 10–40 for bilateral comparisons. Thus, the ankle arthrometer displayed superior diagnostic accuracy for bilateral comparisons when only 1 ankle had MAI.

Differences between injured and uninjured contralateral ankles in the ADT results have varied among studies. Liu et al[20] demonstrated mean increased laxity of 12.8% in injured ankles compared with uninjured contralateral ankles. Tourné et al[21] reported that the average bilateral difference in patients with MAI was 2 mm. Hubbard and Cordova[22] observed an average difference of 5.5 mm between the injured and uninjured contralateral ankles of patients with CAI. These investigators used different methods to measure the change in anterior talofibular ligament (ATFL) length, including displacement of the arthrometer transducers,[20,22] stress radiography,[21] stress ultrasonography,[19] and stress magnetic resonance imaging.[23] Different standards for representing ATFL lengthening led to various results. Transducer displacement essentially reflected translation of the ankle complex rather than the ATFL. Cho et al[6] used stress radiography to define displacement as the distance between the posterior malleolus and the talus, whereas ultrasonography and stress magnetic resonance imaging were used to directly measure the distance between the origin and insertion of the ATFL. Cho et al described the sensitivity of stress radiography as 86%, whereas that of stress ultrasonography was as high as 100%. Moreover, ATFL examination depends on the examiner's experience and positioning of the participant's foot,[24] which were markedly diverse in different studies. For example, Iwata et al[25] found that the variability of stress ultrasonography between the experienced and beginner groups was too high to be clinically acceptable. Regarding foot positioning, the anterolateral drawer test allowed more internal rotation of the ankle than the ADT and detected more subtle degrees of ankle instability.[15] However, the instrumented anterolateral drawer test was only performed in a cadaveric study, and its clinical use requires further development of ankle arthrometers.[26] Some authors have classified MAI as a difference of >3 mm of anterior displacement between the involved and uninvolved ankles,[27] whereas other researchers have used a difference of 2 mm[28–31]; these thresholds were set arbitrarily. Croy et al[7] demonstrated that different thresholds yielded different sensitivity and specificity, even if the arthrometric testing procedures were identical. For the proper diagnosis of MAI via an arthrometer, the best approach might be bilateral comparisons with a standardized testing procedure and a reasonable diagnostic threshold, which should be derived from calculation. In our work, the average bilateral difference was 3.28 mm. Furthermore, we determined that the 1.85-mm threshold for the bilateral difference in anterior D75 offered the highest sensitivity and specificity.

In this study, we calculated the AUC of 2 reference standards, D75 and LDR 10–40. The LDR had a higher AUC,

Table 3. Receiver Operating Characteristic Curve Analysis of D75 and LDR 10–40

Bilateral Difference	Area Under the Receiver Operating Characteristic Curve (95% CI)	Cutoff Value	Sensitivity (95% CI)	Specificity (95% CI)
Displacement at loading force of 75 N	0.914 (0.844, 0.984)	1.85 mm	0.800 (0.627, 0.905)	0.933 (0.787, 0.988)
Load-displacement ratio at 10–40 N	0.959 (0.907, 1.000)	0.0351 mm/N	0.900 (0.744, 0.965)	0.933 (0.787, 0.988)

indicating superior diagnostic accuracy. The LDR 10–40 is an emerging reference standard that may have an advantage in reflecting ATFL laxity. Among the researchers who used arthrometer-measured LDR, Lohrer et al[8] measured the LDR between 40 and 60 N to represent the laxity of the ankle joint, and the resulting sensitivity and specificity were 0.81 and 0.93, respectively. However, Chen et al[9] demonstrated that LDR 10–40 had a larger ES and AUC according to the load-displacement curves of the arthrometers. This might explain why we observed higher sensitivity and specificity. Nauck et al[16] also used LDR to analyze ankle stiffness and reported sensitivity of 0.917 and specificity of 0.625. Nauck et al tested cadaveric ankles; some with intact lateral ligaments might have had structural changes resulting in increased laxity, which would have been misdiagnosed by the arthrometer (false positive). This could explain the relatively low specificity they identified. Chen et al[9] showed that arthrometer-measured LDR 10–40 had sensitivity and specificity of 0.804 and 0.863, respectively; however, they did not further subdivide participants with CAI into MAI and FAI groups. Patients with FAI have intact ankle ligaments, which might have influenced the arthrometric measurements and decreased the sensitivity compared with other studies.

We recognize that many factors affect the diagnostic accuracy of ankle arthrometers. Differences in outcome measures yield different sensitivity and specificity values. Reviewing the literature on the sensitivity and specificity of ankle arthrometry, we found that dynamic measures, such as LDR, generally had better sensitivity and specificity than static measures using anterior displacement.[7–9,17] Dynamic measures reflected the entire process when the lateral ligaments of the ankle joints were being stretched during the ADT, whereas static measures represented only the ending status. Moreover, the setup and participants also played roles in the outcomes of different investigations. In a cadaveric study, the researchers[32] easily controlled the damage to ankle ligaments by severing $\geq$1 lateral ligament. However, participants with MAI from in vivo studies sustained ligament failure due to recurrent sprains that stretched their ligaments, which was different from cutting of the structures.[33] Another factor was that the loads differed greatly among the different arthrometers, and the resulting anterior displacement ranged widely from 3.2 ± 2.8 mm to 21 ± 2.5 mm.[34] In addition, the methodologic approaches to recruiting patients with MAI were diverse, including questionnaires, sonography, stress radiographs, magnetic resonance imaging, and clinical examination, all of which had different validities in assessing MAI.[34]

We acknowledge several limitations of our work. First, we did not include patients with FAI. Differentiating the diagnosis between FAI and MAI using arthrometers may be useful because the interventions for these conditions differ. Second, the arthrometric talar tilt test was not performed. Future authors should assess diagnostic accuracy in bilateral comparisons.

CONCLUSIONS

The ankle arthrometer quantitatively measured the difference in bilateral ankle laxity in patients with MAI. An absolute difference of $>$1.85 mm in D75 or $>$0.0351 mm/N in LDR 10–40 for bilateral ankles suggests the diagnosis of MAI. Using LDR 10–40, the arthrometer had high diagnostic accuracy with sensitivity and specificity of 0.900 and 0.933, respectively. The arthrometer could be a useful tool for diagnosing patients with MAI in clinical settings.

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