Test-retest reliability of a clinical foot assessment device for measuring first metatarsophalangeal joint quasi-stiffness

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Abstract

Background: The stiffness of the first metatarsophalangeal joint (MTPJ) is of interest in cases such as hallux rigidus and apropulsive gait. Subjective rating of joint mobility as 'hypermobile, normal, or stiff' is an unreliable method. Previous instruments for the assessment of first MTPJ stiffness can be too hard and uncomfortable for test subjects. Recently, a new device using a load cell and optical fiber with fiber Bragg grating (FBG) sensors was developed to provide a comfortable means of clinical foot assessment. This study aimed to evaluate the test-retest reliability of this FBG-load cell device in measuring the first MTPJ quasi-stiffness.

Methods: The left foot of 13 female subjects were measured twice for their first MTPJ quasi-stiffness, approximately seven days apart. The FBG-load cell device measured the MTPJ range of motion from a resting position to maximum dorsiflexion and then returning to the resting start-position. The force applied by a clinician to displace the toe was simultaneously recorded using a load cell. The quasi-stiffness over the "working range" in loading and unloading directions were determined from the slope of the torque-angular displacement graph. The test-retest reliability of the MTPJ quasi-stiffness was evaluated using intra-class correlation coefficient [ICC (2,1)].

Results: The reliability was almost perfect for MTPJ quasi-stiffness over the loading phase (ICC = 0.814), moderate for MTPJ quasi-stiffness over the unloading phase (ICC = 0.477) and moderate for MTPJ maximum range (ICC = 0.486).

Conclusion: The foot assessment device based on FBG and load cell was able to reliably measure the first MTPJ quasi-stiffness in a clinical setting. The measurement reliability was higher during the loading phase than the unloading phase.

Word Count: 270

Keywords: hallux, toe joint, range of motion, torque

1. Introduction

Examining the mobility of the first metatarsophalangeal joint (MTPJ) of the foot can guide clinical decision making and inform orthotic prescription [1]. In the literature, MTPJ range of motion have been used in the evaluation of hallux valgus [2], diabetic foot ulceration risks [3], and plantar fasciitis [4]. Typical convenient methods used in clinic to assess first MTPJ mobility include subjectively rating the joint as 'hypermobile, normal or stiff' [1,5] and visually estimating MTPJ range of motion [2,4,6]. These convenient methods are often subjective or not sufficiently accurate and reliable, especially among less experienced examiners [7]. Furthermore, 'hypermobility' in the first metatarsal is still being debated today. Measurement of the first MTPJ range of motion using goniometric devices can be problematic because there is no standardization of the baseline reference or the amount of force applied to move the toe, resulting in a very large range of first MTPJ dorsiflexion between 65° and 110 ° reported in literature [6,8–10]. Passive range of motion alone does not fully represent the mobility of a joint because the amount of force the tester applies also needs to be taken into consideration. For instance, the first MTPJ of two patients may dorsiflex equally to 60 °, however one only requires 7 N of force while the other requires 12 N to achieve the same displacement. To overcome this weakness, the concept of measuring joint quasi-stiffness can be applied. Another term commonly used to describe joint quasi-stiffness is joint flexibility. Quantification of stiffness or flexibility is derived from both force and joint displacement [1,11,12]. First MTPJ flexibility or stiffness, has been of a factor interest in conditions such as hallux rigidus [11,13] and low foot arch profile [12]. In hallux rigidus, scarring affects joint flexibility and stiffness. First MTPJ flexibility have functional consequences such as increased hallux loading during walking and running economy [12,14]. As described by Rao et al [12], first MTPJ flexibility is able to give information on the joint movement throughout the range of motion. Quantification of joint flexibility or stiffness would give clinicians further information on the joint function.

In the past decade, new instrumentation has been developed to objectively quantify MTPJ stiffness or quasi-stiffness by measuring the force and motion of the joint [1,12,15–17]. For example, mechanical devices have been used to measure the applied torque and resulting first MTPJ angular excursion to reflect the stiffness of the joint [12,15,16]. Others have used more portable systems such as a pressure sensor worn on the clinician's thumb and video analysis for MTPJ motion measurement [1].

Recently, a new clinical system based on optical fiber technology was developed to measure MTPJ quasi-stiffness in loading and unloading directions [17]. In this system, a fiber Bragg grating (FBG) sensor coupled with a load cell was used to measure the MTPJ motion and applied force simultaneously. The FBG embedded optical fiber is small, thin, and malleable such that it can be fitted into garments discretely. This new method has been validated by laboratory experiments and successfully trialed in a hospital setting, operated by a clinician to measure the first MTJP quasi-stiffness on human subjects [17]. The test-retest reliability of the system, however, has not been previously evaluated. A good test-retest reliability signifies the internal validity of a test and assures that patients are assessed and monitored using a consistent method.

The aim of this study was to assess the test-retest reliability of the clinical system comprising FBG sensor and load cell for measuring MTPJ quasi-stiffness. It was hypothesized that the method would display good reliability for MTPJ quasi-stiffness in both loading and unloading directions.

2. Materials and methods

2.1. Subjects

Ethical approval was received from the Singhealth Centralised Institutional Review Board (IRB reference 2017/2559). Thirteen female participants were recruited from convenience sampling based on a larger study conducted in the podiatry department of local tertiary hospital [mean (standard deviation), age 29.8 (7.1) years, height 169.9 (5.6) cm, body mass 59.2 (11.6) kg]. All participants provided written informed consent to participate in the study. Female participants were targeted because hallux valgus deformity, a foot condition associated with MTPJ mobility [18], is more prevalent in women [19]. Participants were excluded if they (1) had any foot injury which resulted in seven or more days of rest in the last six months; (2) had previous foot surgery; (3) had any rheumatology or connective tissue conditions; or (4) were pregnant at the time of the study.

2.2. Procedures

This study adopted a within-subject test-retest design. Each participant reported twice to the hospital for repeated tests, separated by approximately seven days apart. The study procedures were carrried out in a clinical examination room, by a qualified podiatrist with nine years of clinical experience.

During each visit, the MTPJ quasi-stiffness of the participant's left foot was measured using the FBG-load cell device (Figure 1) [17]. This system measures MTPJ range of motion using FBG sensor constructed within an optical fiber, and simultaneously records the force applied by a clinician using a load cell (Sensorcraft Technology (S), Pte Ltd, Singapore). The load cell weighs less than 1.50 kg and can be easily operated by the clinician.

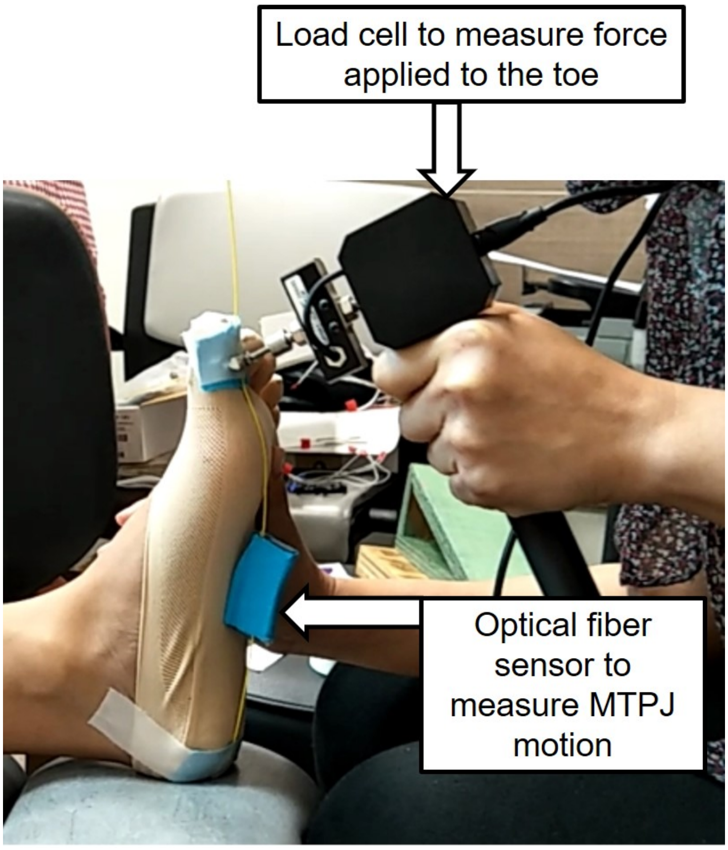

Figure 1. Foot assessment device comprising fiber Bragg grating (FBG) sensor embedded in an optical fiber and a light-weight load cell to measure first metatarsophalangeal joint (MTPJ) quasi-stiffness.

For hygiene reasons, the participant first wore a disposable sock before the start of the test. The participant laid supine on an examination table and had her left foot measured under a non-weightbearing condition which was similar to normal clinical examination practice [1,17]. To ensure consistency, the same podiatrist performed all preparation and test procedures following a set of guidelines. With the foot resting in a neutral position, the optical fiber sensor was attached on the disposable sock garment using dressing tape to ensure tautness (Figure 1). This was achieved by first having one end of the sensor anchored on the plantar first proximal phalanx, followed by the other end of the sensor attached to the plantar heel. The tester would ensure that the FBG sensor was placed in the middle of both the planar hallux and the plantar heel. The plantar heel was the best anchoring point because it is not affected by the hallux displacement. To measure MTPJ quasi-stiffness, the clinician secured the foot in its neutral position by holding at the ankle with the non-working hand [1]. Once the foot was stabilized, the clinician used the working hand to control the load cell and slowly dorsiflexed the first toe to maximum range before returning to the resting position (Figure 2). This movement series is the usual approach a clinician would test the big toe joint mobility in a clinical setting. The dorsiflexing (loading) and returning (unloading) motion were repeated three times continuously while data was acquired from the load cell and optical fiber sensor using a custom software. The clinician applied force slowly via the load cell at the distal edge of the first proximal phalanx to carefully induce sagittal plane motion and was cautious to avoid unwanted abduction/adduction movements. The amount of force applied was measured by the load cell.

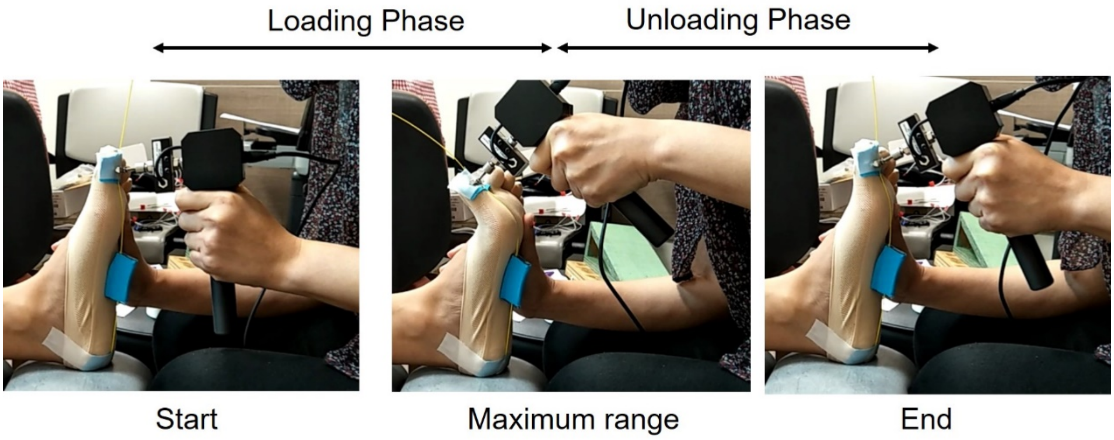

Figure 2. A clinician used the load cell to dorsiflex the first toe to maximum range (loading phase) and then returned to the resting position (unloading phase).

2.3. Data Processing

The moment arm of the first toe was measured (in mm) from the tuberosity of the first metatarsal head to just beneath the tuberosity of the first distal phalange on the medial aspect of the foot [1]. With participant-specific moment arm values, the force (in N) measured from the load cell can be converted to torque (in Nmm) for each participant to calculate rotational stiffness. By plotting the torque versus MTPJ angular displacement, the quasi-stiffness over the "working range" in the loading and unloading directions can be calculated as the slope of the graph (Figure 3). It is well established that the torque versus angular displacement plots are non-linear in human joints [20,21]. For the MTPJ, previous work proposed to use the middle "working range" where the quasi-stiffness was rather linear [1]. In the present study, the middle "working range" was defined as 25% to 75% of the maximum MTPJ range.

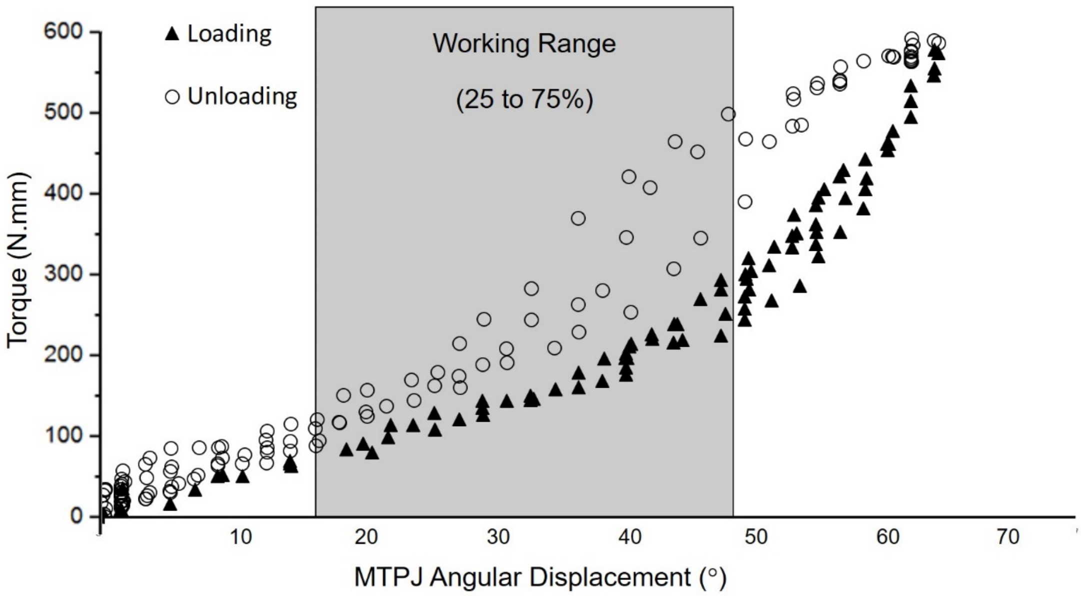

Figure 3. First metatarsophalangeal joint (MTPJ) quasi-stiffness over the middle "working range" was calculated as the slope of the torque-angular displacement graph. Data displayed are three repetitions of dorsiflexing (loading) and returning (unloading) of the first toe in one subject.

2.4. Statistical Analyses

Statistical analyses were performed using SPSS version 25.0 (SPSS Inc, IL, Chicago). The variables of interest were MTPJ maximum range and MTPJ quasi-stiffness over the loading and unloading phases. To evaluate the test-retest reliability, repeated measurements were assessed using Bland-Altman plots and intra-class correlation coefficient [ICC (2,1)]. The ICC results were interpreted as *slight* (0 to 0.20), *fair* (0.21 to 0.40), *moderate* (0.41 to 0.60), *substantial* (0.61 to 0.80), and *almost perfect* (0.81 to 1.00) [22]. Based on the ICC values, the corresponding standard error of measurement (SEM) was also computed. In addition, data from session 1 and session 2 were compared using paired-sample *t*-tests. The mean difference between sessions, together with 95% confidence intervals (CI), were also calculated. Data are expressed as mean (standard deviation). Statistical significance was set at 0.05 level.

3. Results

There were no statistically significant differences in any MTPJ variables between session 1 and session 2 (Table 1). The reliability was *almost perfect* for MTPJ quasi-stiffness over the loading phase (ICC = 0.814), *moderate* for quasi-stiffness over the unloading phase (ICC = 0.477) and *moderate* for MTPJ maximum range (ICC = 0.486).

*** Table 1 goes here ***

Visual inspection of the Bland-Altman plots suggested that the data were randomly scattered without systematic bias for the MTPJ maximum range and the quasi-stiffness during the unloading phase (Figure 4). There was, however, an outlier with exceptionally high value in the data of the MTPJ quasi-stiffness during the loading phase.

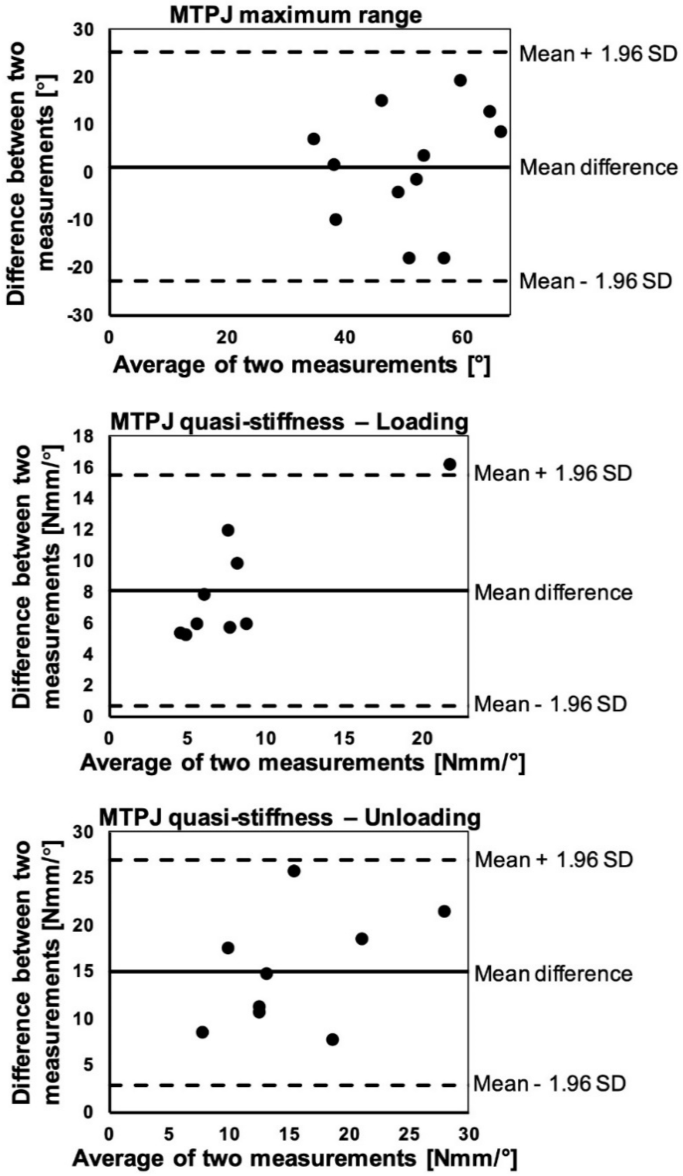

Figure 4. Bland-Altman plots for the measurements of the first metatarsophalangeal joint (MTPJ) maximum displacement, quasi-stiffness during loading phase, and quasi-stiffness during unloading phase.

4. Discussion

This study aimed to assess the test-retest reliability of a new clinical foot assessment system comprising optical fiber sensors and a load cell to measure MTPJ quasi-stiffness. It was found that MTPJ maximum range and quasi-stiffness measured using the new system showed *moderate to almost perfect* reliability in female participants tested over two sessions on different days. The MTPJ quasi-stiffness over the loading phase has higher reliability and lower measurement error than that over the unloading phase.

4.1. First MTPJ quasi-stiffness

In the present study, the first MTPJ quasi-stiffness was consistently higher in the unloading phase than the loading phase in both test sessions and this observation parallels previous findings using the same clinical foot assessment device [17]. In a video-based study, Heng et al [1] determined the first MTPJ quasi-stiffness during the unloading phase. In their study, the reported mean quasi-stiffness over the working range of the unloading phase ranged from 14.2 to 14.9 Nmm/° and this range was similar to the mean values of 14.99 to 15.50 Nmm/° found in the present study (Table 1). It is promising that both studies, despite using different measurement techniques, reported comparable range of MTPJ quasi-stiffness of approximately 15 Nmm/°. While there is no data of the loading phase from the work by Heng et al [1], it can be expected that both methods are generally comparable in measuring quasi-stiffness of the first big toe.

When comparing between two test sessions, the reliability of the first MTPJ quasi-stiffness over the unloading phase was *moderate* in the current study (ICC = .477) and also the study by Heng et al (ICC = .568) [1]. For the loading phase, *almost perfect* reliability was observed among the 13 subjects tested in the present study (ICC =.813, Table 1). Using a mechanical device to measure the first MTPJ stiffness on 28 subjects, Farhadi et al [16] reported a Cronbach alpha of 0.84 (right feet) and 0.92 (left feet) which overall can be interpreted as *almost perfect* reliability. This high repeatability could be attributed to the ergonomics and design of their device which directs force to move the big toe, rather than relying on a tester to manually control the movement.

The torque-angular displacement characteristics over working range in the unloading phase was less consistent than that over the loading phase (Figure 3; Table 1). This could be related to the wrist-ergonomics associated with the use of the load cell by the clinician. In the loading direction, the hand and wrist moved easily while keeping the loading force perpendicular to the toe; however, in the unloading direction the tester’s wrist rotated slightly in order to keep the load cell as perpendicular as possible. This inadvertent wrist rotation may affect the test-retest repeatability of the unloading phase. Future improvement in the design of the load cell with more consideration of the hand and wrist ergonomics may contribute to better and more repeatable measures. Nevertheless, the overall reliability of the clinical assessment device was acceptable and comparable to other available technologies. The advantages of this device were that the optical fiber is malleable and comfortable on the test subject, and the operation of the load cell is intuitive for the tester. Thus, the device has good potential to support clinicians in the evaluation of foot function by providing objective measurements of toe joint quasi-stiffness.

4.2 Maximum joint range of motion

The maximum joint range of motion of the first MTPJ achieved *moderate* repeatability (ICC = .486). This is likely due to the difficulty in standardizing a tautness of the optical fiber. If the fiber was too taut, it could snap. Under situations where the optical fiber had even a little too much slack, the first part of the joint range of motion could not be adequately captured by the FBG sensors due to insufficient tension. Finally, the assessor may push the toe with different amount of force each time, resulting in slightly different end points. Traditional goniometric measurements may be more suited for clinicians and researchers who are interested in measuring MTPJ range of motion only, without the need for information on the joint stiffness [6,7].

4.3 Limitations

There are several limitations to the present study. Firstly, this study only examined the female feet because hallux valgus conditions are associated with female sex [19]. In future, studies on males will be necessary to understand their toe joint stiffness and if sex differences exist. Secondly, this study only looked at the test-retest reliability of a single tester who is an experienced podiatrist. It will be interesting to explore the inter-rater reliability of testers with varied clinical experience. Thirdly, this study examined the passive movement of the big toe joint under a non-weightbearing condition. Although this test position is clinically meaningful and commonly used in routine practice, the stiffness characteristics of the big toe joint under weightbearing and dynamic movements such as standing and walking may better reflect functional conditions.

5. Conclusions

This study demonstrated that the new clinical foot assessment device based on optical fiber technology and load cell was able to measure the first MTPJ quasi-stiffness with *almost perfect* reliability over the loading phase and *moderate* reliability over the unloading phase. Given that the optical fiber is malleable and comfortable for the participants, and the operation of the load cell is intuitive for the tester, this device has good potential to support clinicians in the evaluation of foot function, by providing objective measurements of toe joint quasi-stiffness.

Word Count = 2,591

Declarations of Interest

None

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Brief Summary

What Is Already Known?

- First metatarsophalangeal joint (MTPJ) mobility subjectively rated as ‘hypermobile’, ‘normal’, and ‘stiff’ are unreliable
- First MTPJ quasi-stiffness can be quantified using various instrumentation
- Previous methods include mechanical device, pressure sensor, or video analysis

What This Study Adds?

- Reliable first MTPJ quasi-stiffness can be objectively measured using optical fiber technology and a load cell
- Quasi-stiffness over the loading phase has higher reliability and lower measurement error than the unloading phase
- Ergonomics and handling of the load cell device may affect the unloading phase readings

Figure Captions

Figure 1. Foot assessment device comprising fiber Bragg grating (FBG) sensor embedded in an optical fiber and a light-weight load cell to measure first metatarsophalangeal joint (MTPJ) quasi-stiffness.

Figure 2. A clinician used the load cell to dorsiflex the first toe to maximum range (loading phase) and then return to the resting position (unloading phase).

Figure 3. First metatarsophalangeal joint (MTPJ) quasi-stiffness over the middle "working range" was calculated as the slope of the torque-angular displacement graph. Data displayed are three repetitions of dorsiflexing (loading) and returning (unloading) of the first toe in one subject.

Figure 4. Bland-Altman plots for the measurements of the first metatarsophalangeal joint (MTPJ) maximum displacement, quasi-stiffness during loading phase, and quasi-stiffness during unloading phase.

Table 1 Test-retest reliability statistics of the first metatarsophalangeal joint (MTPJ) in female participants (n = 13). Data are expressed as mean (standard deviations).

Variable	Session 1	Session 2	Mean Difference [95% CI]	p-value	ICC	SEM
MTPJ maximum range [°]	51.7 (13.0)	50.5 (10.7)	1.3 [-6.5, 9.0]	0.729	0.486	8.4
MTPJ quasi-stiffness – Loading [Nmm/°]	8.14 (3.78)	8.22 (4.99)	-0.28 [-2.52, 1.97]	0.784	0.813	1.88
MTPJ quasi-stiffness – Unloading [Nmm/°]	14.99 (6.14)	15.50 (6.21)	-0.51 [-5.49, 4.48]	0.821	0.477	4.34

P-values are determined from paired-sample t-tests. CI – confidence intervals, ICC – Intraclass correlation coefficients, SEM – Standard error of measurement.

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