

Using surface markers to describe the kinematics of the medial longitudinal arch

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Abstract

Background

Static and dynamic assessment of the medial longitudinal arch (MLA) is an essential aspect for measuring foot function in both clinical and research fields. Despite this, most multi-segment foot models lack the ability to directly track the MLA. This study aimed to assess various methods of MLA assessment, through motion capture of surface markers on the foot during various activities.

Methods

Thirty general population participants (mean age 20 years) without morphological alterations to their feet underwent gait analysis. Eight measures, each representing a unique definition of the MLA angle using either real only, or both real and floor-projected markers, were created. Participants performed tasks including standing, sitting, heel lift, Jack's test and walking, and had their Arch Height Index (AHI) measured using callipers. Multiple-criteria decision analysis (MCDA) with 10 criteria was utilised for selecting the optimal measure for dynamic and static MLA assessment.

Results

In static tasks, the standing MLA angle was significantly greater in all measures but one when compared to sitting, Jack's test and heel lift. The MLA angle in Jack's test was significantly greater than in heel lift in all measures. Across the compared dynamic tasks, significant differences were noted in all measures except one for foot strike in comparison to 50% gait cycle. All MLA measures held significant inverse correlations with MLA measured from static and dynamic tasks. Based on MCDA criteria, a measure comprising the first metatarsal head, fifth metatarsal base, navicular and heel markers was deemed the best for MLA assessment.

Significance

This study aligns with the current literature recommendations for the use of a navicular marker for characterising the MLA. It contrasts with previous recommendations and advocates against the use of projected markers in most situations.

Keywords: navicular marker, multi-segment foot model, medial longitudinal arch, arch height index, multicriteria decision analysis

USING SURFACE MARKERS TO DESCRIBE THE KINEMATICS OF THE MEDIAL LONGITUDINAL ARCH

Background

Static and dynamic evaluation of clinical foot and ankle disorders is regularly performed with three-dimensional gait analysis, including the use of marker-based multi-segment foot models (MFMs). Over forty MFMs have been reported in the literature and used across multiple pathologies [1] to inform and evaluate treatment options and management in clinical practice [1,2]. The modelling approach varies significantly between these models, at least in part because they are often designed for specific purposes or populations.

These differences in modelling approach are particularly evident when considering the midfoot. In some MFMs, the midfoot is represented as a single rigid 3D segment, with Euler angles used to describe its orientation in relation to other segments [3–4, 6]. However, it is questionable whether this is the best approach, as the midfoot is composed of multiple, cube-shaped bones in which it is not easy to define anatomically or kinematically meaningful axes. Another approach, such as in the Oxford Foot Model, is to output the linear distance between the apex of the MLA and the forefoot plane. The main limitation of this method is the translation into clinical applicability. The most important element of midfoot function is the medial longitudinal arch (MLA), which is also the structure that is most frequently assessed in relation to lower limb complaints [7,8]. Therefore, to provide detailed insight on pathologies pertaining to the midfoot, direct MLA measurement would hold greater utility than assessment of the midfoot segment as a whole.

To characterise the MLA, an understanding of its anatomy is essential. One approach is to approximate the arch as a triangle when viewed medially, with two points forming the base of the MLA and the other the apex. This principle has been used in previous studies, where these three points have been used to calculate the MLA angle [9]. Furthermore, to improve measurement repeatability, the incorporation of virtual markers projected to the floor was introduced by Caravaggi et al. [9]. Of the midfoot bones, the navicular is generally accepted to form the apex of the MLA. However, there is a lack of evidence on which to make decisions about what other points should be used, meaning a single optimal method has not been identified in the literature.

An approach that has been used in several healthcare fields is multiple-criteria decision analysis (MCDA) [10]. MCDA defines the desired properties and incorporates these into a decision model to rank the options using multiple criteria [10]. In context of the MLA, the desired properties pertain to accuracy and reliability of MLA measurement. Accuracy can be defined as demonstrating the known biomechanical principles of MLA deformation when exposed to bodyweight and other forces, resulting in a flattening of the arch. Therefore, comparisons of static and dynamic tasks in which there are varying levels of bodyweight force exertion on the foot should elicit differences in MLA angles [11]. In addition, MLA measurement accuracy can be demonstrated by comparing it against a known gold standard. Currently, radiographic measurements are deemed the gold standard due to direct visualisation of anatomy [12]. Validated clinical methods such as the Arch Height Index (AHI) can also be used as comparators [13], particularly when exposure to ionising radiation is problematic.

The aim of this study was to use MCDA to rank various methods of MLA representation using motion capture of surface markers on the foot during different activities.

Methods

Subjects

This study assessed 60 feet from 30 healthy participants (17 females and 12 males, age range 8-25 years). Informed consent was sought from parents/guardians for participants aged below 16 years and from the participants themselves for those aged 16 years and above. The inclusion criteria for this study were: age between 8 and 25 years (to exclude young children where the arch has not yet developed), and no recent injuries or previous surgery or excessive trauma to the foot arches. The study was approved by the local research ethics committee (Reference: R74434/RE002).

Measures

Eight measures were implemented using markers on the head of the 1st metatarsal (D1M), the proximal 1st metatarsal (P1M), the navicular tuberosity (NAV), the proximal 5th metatarsal (P5M), the sustentaculum tali (STL), and the posterior middle of the calcaneus (HEE), (all but P5M shown in Figure 1). Of these, four MLA measures (Measure 1, Measure 2, Measure 3, Measure 4) were established to reflect radiographically derived angles. The other four MLA measures (Measure 1p, Measure 2p, Measure 3p, Measure 4p) were created using a combination of real markers and virtual markers (projected to the ground during static standing). Caravaggi et al. [14] advocated the latter to improve repeatability in the vertical position of the markers.

For each measure, the MLA angle was calculated as the angle between the unit normal vectors of two planes ('anterior' and 'posterior'). Each plane was defined by three points: one at the apex of the arch (either NAV or P1M), one at P5M, and one other. For the anterior plane, the third point was D1M. For the posterior plane, the third point was either HEE or STL.

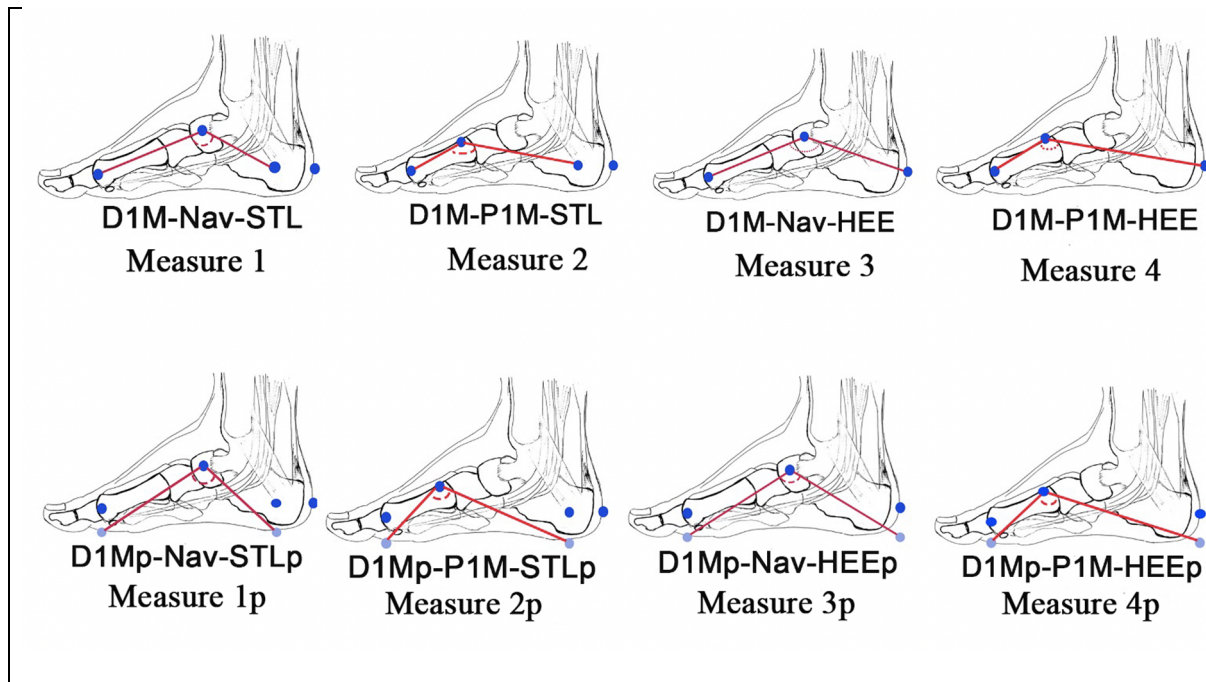


Figure 1. The eight measures reflecting distinct MLA angle definitions. D1M- head of 1st metatarsal, Nav- navicular tuberosity, P1M – proximal 1st metatarsal, STL- sustentaculum tali, HEE-posterior middle of the calcaneus. The subscript p indicates that marker is projected to the floor to create a virtual marker.

Desired property	Criterion
Sensitivity to characterising MLA shape - which measure can best detect changes in the shape of the MLA that are known to occur in specific stances/movements	a1 Ability of the measure to detect a flatter arch (greater MLA angle) while standing with the feet flat on the floor compared to during Jack's test (in accordance with the windlass mechanism).
	a2 Ability of the measure to detect a flatter arch (greater MLA angle) while standing with the feet flat on the floor compared to during the heel lift test (in accordance with the windlass mechanism).
	a3 Ability of the measure to detect a flatter arch (greater MLA angle) during Jack's test compared to during the heel lift test (in accordance with the windlass mechanism).
	a4 Ability of the measure to detect a flatter arch (greater MLA angle) while standing with the feet flat on the floor compared to when seated with the feet flat on the floor but with minimal load through them (reflecting the change in MLA when loaded compared to unloaded)
	a5 Ability of the measure to be able to detect a flatter arch (greater MLA angle) at midstance (50% stance), in comparison to that at initial contact - foot strike (0-3% of the gait cycle), as expected in typically developed feet.
	a6 Ability of the measure to be able to detect a flatter arch angle (greater MLA angle) at toe off (62% of GC) in comparison to midstance (50% stance), as expected in typically developed feet.
	a7 Ability of the measure to be able to detect differences between the maximum and minimum arch angle values.
	a8 Ability of the measure to distinguish between populations with different arch types, by detecting a greater MLA angle while standing with feet flat on the floor in children/adults with flat feet compared to those with typically developed feet, as expected.
Alignment with known MLA assessment methods	b1 Correlation between the measure's static standing MLA angle and the Arch Height Index during static standing.
	b2 Correlation between the measure's MLA angle at 50% stance and the Arch Height Index static standing.
Repeatability	c1 Strength of intra-rater reliability of measurement.
Adaptability for use	d1 Adaptability of the measure for use on different foot sizes (adults, children aged 8-16 and children under the age of 8 with small feet).
	d2 Adaptability of the measure for use on different foot arch types (rigid flat foot, flexible flat foot, cavus).
Ease of use	e1 Level of ease of marker placement, with emphasis on ensuring ease of palpation of any new markers added to already existing OFM set.
	e2 Ability to facilitate timely marker placement, thereby ensuring that if new markers are added to the already existing OFM set, their placement does not extend the current marker placement time.
	e3 Level of ease of implementation, with emphasis on ensuring analysis and the interpretation of the collected data can be conducted without the need for additional software or extensive alteration from the existing OFM data analysis protocol.
	e4 Ability to facilitate timely data processing and data extraction, thereby ensuring that their data processing does not extend the current processing time.
	e5 Ability to facilitate ease of interpretation of the results, in a manner that is comparable to the already existing OFM set.
Clinical utility	f1 Ability to generate data output that can be interpreted and applied to clinical practice.

Table 1. MCDA criteria (only the non-shaded questions were evaluated for this publication).

Data collection

Motion capture data was collected using a standardised protocol (Plug-in-Gait with Oxford Foot Model) [15] with an additional marker on the navicular bone. Marker data was collected with a 16 infra-red camera system (Vicon MX/T40, Vicon, Oxford UK, 100 Hz sample rate). For static assessment, the four tasks of standing, sitting, heel lift and Jack's test were conducted (Appendix A). For dynamic assessment, the participants were asked to walk at a self-selected speed along a 10-m long level walkway, to enable capture of a minimum of six clean foot strikes per foot.

The MLA angles from the static and dynamic tasks were assessed for correlation with the clinical measure of Arch Height Index (AHI), which was derived using standard techniques involving callipers and graph paper [16]. Repeatability of each MLA measure was assessed by conducting two sessions, one week apart, by the same person conducting marker placement on a sub-set of four participants.

Data processing

Data processing included gap filling in marker data using cubic spline interpolation and trajectory filtering using the Woltring algorithm. Dedicated pipelines were used to compute lower limb kinematic quantities (Vicon Nexus, v.2.12). For dynamic movement tasks, the most representative trial was calculated for each of the left and right feet, by choosing the trial with the lowest root mean square (RMS) error compared to the mean of all six trials. MLA angle at initial contact, midstance (50% stance phase), and toe off, along with the maximum and minimum values of the MLA angle, were identified.

Multi-criteria decision analysis

MCDA was used to objectively define which MLA measure was optimal [17,18]. The criteria for MCDA were first proposed via a consensus meeting of 15 participants including orthopaedic surgeons, a podiatrist, physiotherapists, biomechanical engineers and clinical scientists. This culminated in the formation of 26 questions that were later tested by two rounds of online questionnaires. Such Delphi work initially resulted in the determination of 18 criteria (Table 1). Ten of these criteria were utilised in this study. The criteria in sections d and e will be assessed in future work.

To conduct MCDA, relative ranking scores for each measure for each criterion were calculated. The measures were scored based on the mean difference in MLA angle across the tasks (a1 – a5), correlation with AHI (b1-b2) and mean difference in MLA angle between the repeated measurement attempts (c1). The best measure in each instance scored 8 and the worst 1. Scores were awarded irrespective of the statistical significance of each result (see next sub-section). The measure with the most points in total was selected as the best overall measure. No weightings were applied as there were no clear criteria for making one criterion more important than another.

Statistical analysis

Since this study evaluated a novel method for characterising the MLA, with no previous data available, a formal *a priori* sample size calculation could not be performed. However, the

sample size used in this study (60 feet from 30 participants) is in agreement with comparable studies in the literature [9,19–21].

SPSS v27 was used to perform the statistical tests. The data was assessed for normality using the Shapiro-Wilk test, following which all datasets were deemed as being parametric. Z-scores were calculated to identify outliers.

MLA angle change detection is presented in the form of mean differences between the compared tasks (e.g. sitting and standing), which were assessed for significance using repeated measures ANOVA. The data is also presented with box and whisker plots. Correlation of the static (standing) and dynamic (50% stance phase) movement tasks with the AHI, for all MLA measures, was assessed by calculating Pearson correlation coefficients. Repeatability of each of the measures during the static standing task was presented in the form of mean differences between the two measurement sessions.

Results

The total scores from the MCDA (Table 2) are collectively greater in the measures which exclusively used real markers in comparison to the measures which used a combination of real markers and markers projected to the floor. In terms of individual measure performance, Measure 3 was deemed as most optimal by virtue of having the highest overall score.

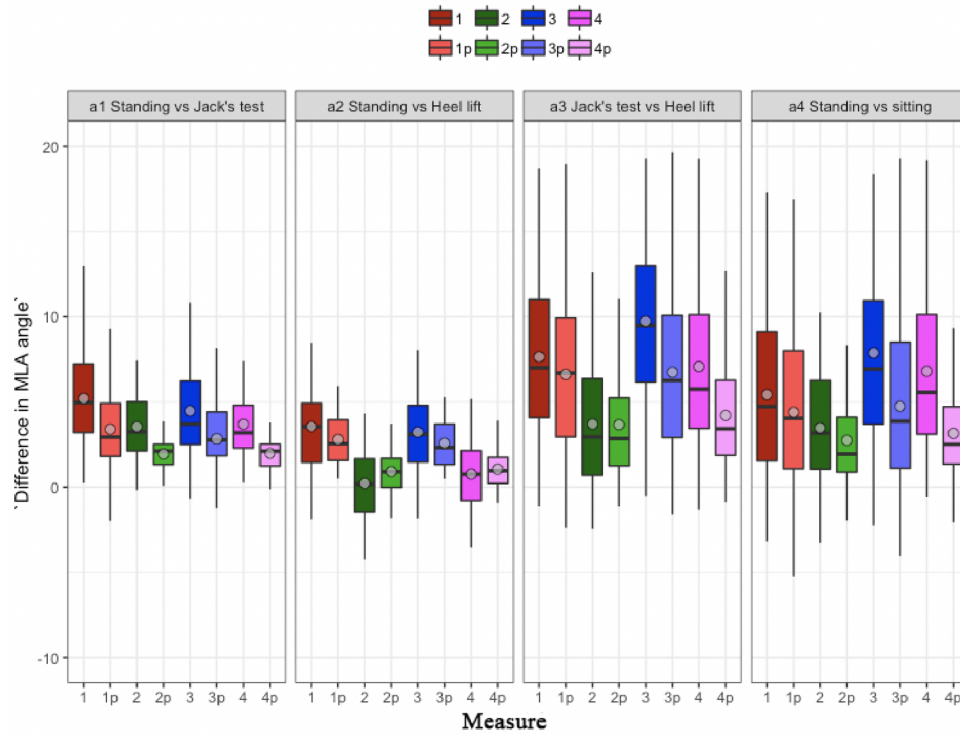
Desired property	Criterion	MLA measure scores							
		1	1p	2	2p	3	3p	4	4p
MLA change detection	a1 standing vs Jack's test	8	6	1 ^{NS}	2	7	5	3	4
	a2 standing vs heel lift	7	6	2	1	8	5	4	3
	a3 Jack's test vs heel lift	6	5	3	1	8	4	7	2
	a4 standing vs sitting	8	4	5	1	7	3	6	2
	a5 foot strike vs 50% stance	4	5	1 ^{NS}	6	3	7	2	8
	a6 50% stance vs Toe off	7	6	1	2	8	5	4	3
	a7 max vs min vale in GC	6	8	1	2	7	5	4	3
Alignment	b1 correlation with AHI vs static	7	5	1	3	8	6	2	4
	b2 correlation with AHI vs 50%GC	7	4	1	3	8	6	2	5
Repeatability	c3 intra-rater reliability	4	6	3	1	7	8	5	2
Total score		64	54	19	22	71	54	39	36

Table 2. - Scores for each measure based on the MCDA criteria.

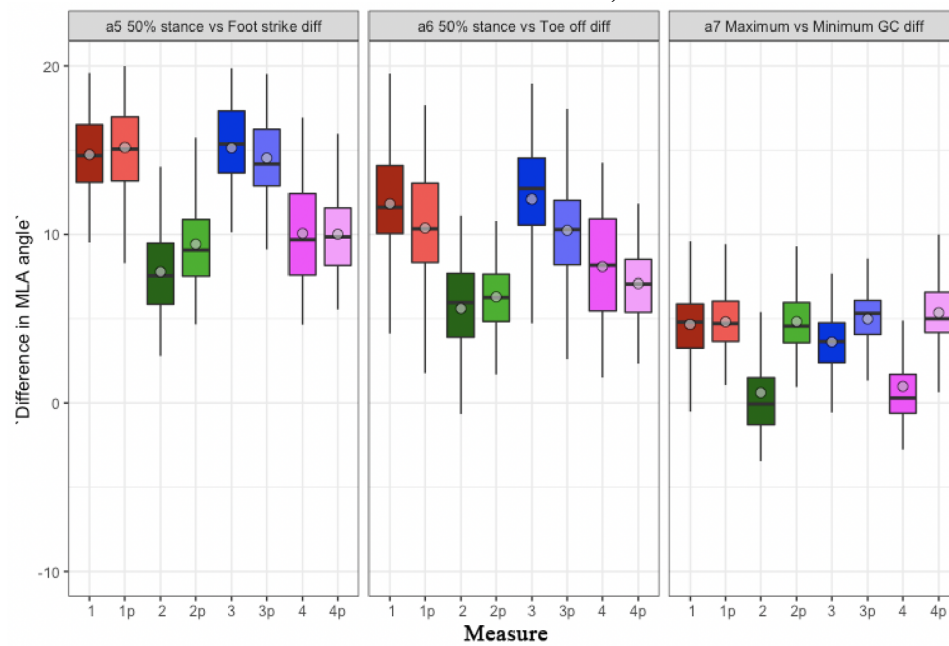
NS indicates not significant

Differences in the MLA angle between tasks were detected by the measures (Figure 2).

Amongst the static movement tasks of standing, sitting, Jack's test and heel lift, significant mean differences were found in all measures except for Measure 2 upon comparison of standing with Jack's test. The largest mean difference in MLA angle between standing and each of sitting and Jack's test was detected by Measure 1. For comparisons in MLA angle between heel lift and each of standing and Jack's test, Measure 3 demonstrated the largest mean difference.



a)



b)

Figure 2: Differences in MLA angles across a) static and b) dynamic tasks. The box represents the interquartile range, the tails represent the minimum and maximum values without outliers, the thick black line in the middle of the box represents the median and the circle in the middle of the box represents the mean.

Among the dynamic movement tasks of foot strike and 50% gait cycle, alongside the minimum and maximum MLA angles between foot strike and toe off, significant mean differences were found in all measures except for Measure 2 upon comparison of foot strike with 50% stance phase). The largest mean difference in MLA angle was observed in Measure 4p for between foot strike and 50% stance phase, Measure 3 for between 50% stance phase and toe off, and Measure 1p for between the minimum and maximum MLA angles within the gait cycle.

There were significant inverse correlations between the standing MLA angle and AHI across all MLA measures. However, high inverse correlations, defined as 0.7 or greater [22], were only observed in Measures 3, 1 and 3p, with the highest in Measure 3. As for between the 50% gait cycle MLA angle and AHI across all MLA measures, there were significant inverse correlations. However, high inverse correlations were only observed in Measures 1 and 3, with the highest in Measure 3.

Measure	1	1p	2	2p	3	3p	4	4p
Standing vs AHI correlation (r) – MDCA b1	-0.71	-0.65	-0.48	-0.59	-0.73	-0.70	-0.56	-0.64
50% GC vs AHI correlation (r) – MDCA b2	-0.70	-0.64	-0.50	-0.61	-0.71	-0.68	-0.57	0.66

Table 3: Correlations between AHI and each of standing and 50% stance MLA angles across the measures.

Measure	1	1p	2	2p	3	3p	4	4p
Mean MLA angle difference as attempt 1 -attempt 2 (°)	- 1.5	2.6	-10.1	-6.0	1.3	-1.2	-9.7	-5.2

Table 4. Difference in MLA angles across repeated standing measurements for each measure.

Discussion

The purpose of this study was to determine which measure most meaningfully and reliably characterised the MLA angle across static and dynamic tasks. From this study's MCDA criteria, the results demonstrated that the use of real markers is preferred in terms of measurement accuracy, and Measure 3 (P1M-NAV-HEE) was the best of the eight measures for characterising the MLA based on static and dynamic MLA arch angle assessments.

This is the first study that has incorporated the use of MCDA to facilitate objective decision-making for the optimal method for MLA assessment in gait tasks. The conclusion of Measure 3 being the best is strengthened by the evidence that it consistently obtained the highest scores in each of the desired properties, alongside having the greatest average score. Nevertheless, for the property of repeatability, Measure 3p which incorporated projected markers was superior. Therefore, depending on the relative importance of accuracy and repeatability to the research application, the optimal choice may be different.

From this study's results on MLA change detection, it can be observed that most of the static task comparisons yielded significant differences irrespective of the MLA measure used. The standing MLA angles were significantly greater than the sitting across all eight measures, due to comparatively greater bodyweight force exertion on the foot resulting in a flatter arch with a larger MLA angle. For the tasks of heel lift and Jack's test, each had lower MLA angles in comparison to standing, which may be explained by the activation of two mechanisms to elevate the MLA – the windlass and calcaneocuboid locking mechanisms. Jack's test involves passive dorsiflexion of the big toe, which activates the windlass mechanism due to increased tension in the plantar aponeurosis leading to pulling of the calcaneus towards the metatarsal

heads, culminating in an upward force in the MLA that elevates it [11]. For the heel raise, this causes supination of the foot which leads to convergence of the talonavicular and calcaneocuboid joint axes, resulting in locking of the transverse tarsal joint and elevation of the MLA in a process known as the calcaneocuboid locking mechanism [23]. Additionally, the plantarflexion at the ankle joint and dorsiflexion of the toe which occur upon doing the heel lift also activate the windlass mechanism, thereby providing an extra form of foot stabilisation to elevate the MLA [24].

In the dynamic tasks, the MLA angle at 50% stance phase was significantly greater than both foot strike and toe off angles. Relatively greater bodyweight force is exerted onto the MLA to flatten it to a greater extent in the former task than the latter, as this point represents single limb support. In toe off, foot supination and toe dorsiflexion with the shifting of the bodyweight force forward to the contralateral leg activate the calcaneocuboid locking and windlass mechanisms, to elevate the MLA [25]. Upon comparison of the differences between foot strike and at 50% stance phase, it was noticed that Measure 3 did not perform as well as measures with projected markers. This is likely due to small changes in MLA angle between these two time points, resulting in only small differences between the measures.

Furthermore, the MLA angles were correlated against clinically assessed AHI as this comparator has been previously validated against radiographic measurements [13]. All MLA measures showed significant inverse correlations with AHI for both standing and 50% stance. However, there was notable disparity in the correlation strengths. Interestingly, MLA measures 3, 1 and 3p which sequentially had the highest correlations between standing and AHI, also had the highest respective correlations between 50% stance and AHI. A similar trend

between standing and 50% stance phase was also noted for the lowest correlations with AHI, namely Measures 2, 2p and 4. This suggests the accuracy to which a measure assesses the MLA during static tasks may be indicative of its ability to assess the structure during dynamic ones as well.

It is well recognised that the navicular plays a key role in the anatomy and function of the MLA. Several other studies have reported the use of the navicular marker as a useful means of characterising the MLA in MFMs [9,26–28]. This is due to the natural anatomical position of the navicular marker and the particular role it holds in MLA function [25]. It is also known to have a low rate of measurement error including marker misplacement and soft tissue artifacts [21]. Additionally, the use of the navicular marker for representing the MLA has been confirmed in studies using plain x-rays [14] and biplanar fluoroscopy [29,30]. Therefore, together with the results from this study's MCDA, it can be suggested that using a measure with a navicular marker is an optimal way of characterising the MLA.

The incorporation of projected markers onto the floor was based on the study by Caravaggi et al. [14], which suggested that projection of the metatarsal bone marker helps to increase repeatability. The results of this study corroborate this finding, with Measure 3p holding the best MCDA score for the repeatability property. Although, it must also be acknowledged that Caravaggi et al. [14] used the Rizzoli foot measure in contrast to the modified OFM used in this study, and that different variations of static and dynamic tasks were conducted amongst the studies. Therefore, the results cannot be directly compared or used interchangeably.

Limitations

Only eight MLA definitions were assessed, therefore, there is the possibility that another MLA measure beyond those assessed in this study would yield more optimal results. However, to minimise this limitation, the latest recommendations from the literature were assimilated, including the addition of a navicular marker to the original OFM. This posed the second and third limitations of an increased risk of placement error and increased marker placement time. However, from this study's intra-rater repeatability assessment, it can be observed from Table 3 that navicular marker placement repeatability is consistent with the error posed when using the other markers. Furthermore, there is a fourth limitation with regards to the use of clinically assessed AHI to assess the accuracy of the MLA measures. It may be argued that the use of radiographic measurements would be better suited for this role due to being able to accurately visualise the MLA. However, the clinical AHI assessment method used in this study has previously been validated against radiographic measures in different populations [13] and meant participants were not unnecessarily exposed to radiation. Additionally, there is a potential fifth limitation, where there could be skin movement artefacts, especially at initial foot contact. With regards to the MCDA, all criteria were given equal weighting on the final score. However, it is possible that some criteria have a relatively greater importance in determining how best to characterise the MLA.

Conclusion

The MCDA results suggest the optimal measure for characterising the MLA across both static and dynamic settings uses real markers on heel, navicular, head of the first metatarsal and

base of the fifth metatarsal. This study did not find the use of projected markers to improve measurement accuracy, but may improve repeatability.

Conflict of interest statement

To the best of our knowledge, none of the authors have any conflict of interest, financial or otherwise. This study was funded by Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences (NDORMS), Oxford University as part of the primary author's doctoral studies. There was no involvement in this study by the funder.

Appendix A. Detailed description of movement tasks used in this study

Task	Description of the task
AHI weightbearing	To obtain weightbearing AHI, the measurements of full foot length, truncated foot length and dorsum height at 50% foot length were taken using callipers, with the participant standing on both legs on graph paper with full weightbearing.
Standing static *	This entailed the participant standing still with their feet about 10 cm apart, in a natural position, with their arms crossed and hands positioned on opposite shoulders, while standing on a force plate.
Jack's test *	This involved the participant standing still on the force plate, with their feet shoulder width apart and bodyweight equally distributed between both feet. In this stance, a researcher passively dorsiflexed the participant's toe to activate the Windlass mechanism and held it in this position for 10 s.
Heel rise*	This involved the participant standing with their feet about 10 cm apart. In this position, the participant slowly raised their heels off the floor as far as possible, while keeping their knees straight. They were expected to hold this position for a count of 8 and then slowly lower their heels to the floor.
Sitting *	This involved participants sitting on a stool, with their arms crossed, hands positioned on opposite shoulders and knees flexed to 90°. Their feet were placed on the force plate to check that minimal weight was through the feet.
Dynamic walking trials*	This entailed the participant walking across a 10 m walkway within the motion capture volume at a self-selected speed, for 6 trials per foot.

*Represents trial that have used the 3D gait analysis marker set

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