Journal of Biomechanics 88 (2019) 180–185

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Reliability of medial-longitudinal-arch measures for skin-markers based kinematic analysis

Paolo Caravaggi [a,*], Alessandra B. Matias [b], Ulisses T. Taddei [b], Maurizio Ortolani [a], Alberto Leardini [a], Isabel C.N. Sacco [b]

[a] Laboratorio di Analisi del Movimento, IRCCS Istituto Ortopedico Rizzoli, Via di Barbiano 1/10, 40136 Bologna, Italy
[b] Physical Therapy, Speech and Occupational Therapy Dept., School of Medicine, University of Sao Paulo, SP, Brazil

A R T I C L E I N F O

Article history:
Accepted 12 March 2019

Keywords:
Medial longitudinal arch
Skin-markers
Foot kinematics
Walking
Running
Reliability

A B S T R A C T

The medial-longitudinal arch (MLA) is perhaps the most important feature characterizing foot morphology. While current skin-markers based models of the MLA angle used in stereophotogrammetry allow to estimate foot arch shape and deformation, these do not always appear consistent with foot anatomy and with standard clinical definitions. The aim of this study was to propose novel skin-markers based measures of MLA angle and investigate their reliability during common motor tasks.

Markers on the calcaneus, navicular tuberosity, first metatarsal head and base, and on the two malleoli were exploited to test eight definitions of MLA angle consistent with foot anatomy, both as angles between two 3-dimensional vectors and as corresponding projections on the sagittal plane of the foot. The inter-trial, inter-session and inter-examiner reliability of each definition was assessed in multiple walking and running trials of two volunteers, tested by four examiners in three sessions.

Inter-trial variability in walking was in the range 0.7–1.2 deg, the inter-session 2.8–7.5 deg, and the inter-examiner in the range 3.7–9.3 deg across all MLA definitions. The Rizzoli Foot Model definition showed the lowest inter-session and inter-examiner variability. MLA measures presented similar variability in walking and running.

This study provides preliminary information on the reliability of MLA measurements based on skin-markers. According to the present study, angles between 3-dimensional vectors and minimal marker sets should be preferred over sagittal-plane projections. Further studies should be sought to investigate which definition is more accurate with respect to the real MLA deformation in different loading conditions.

1. Introduction

The Medial-longitudinal Arch (MLA) is perhaps the single most important feature used to describe foot morphology and mechanics. In addition to the weight-bearing properties in static postures, the skeletal and ligamentous structures comprising the MLA are an important elastic storage-return mechanism (Hicks, 1954; Ker et al., 1987), and have a major role in transferring and dampening forces through the foot during dynamic tasks (Caravaggi et al., 2009; Nachbauer and Nigg, 1992; Saltzman and Nawoczenski, 1995; Stearne et al., 2016). Morphology and mechanics of the MLA are multidisciplinary topics, relevant to human anthropology (Bennett et al., 2009; Griffin et al., 2015), to sport and footwear biomechanics (Lin et al., 2012; Perl et al., 2012), and to foot pathologies associated to alterations of MLA shape (Pfeiffer et al., 2006; Tome et al., 2006). In postural control, decreased mobility of the MLA was found to increase sway even after small perturbations (Birinci and Demirbas, 2017) further emphasizing the importance of accurate measurement of MLA dynamics and its relationships with foot functionality.

Although no consensus has been reached in the literature, the most widely-used clinical measures to quantify objectively MLA posture and deformation are the *arch height index* (Williams and McClay, 2000), the *relative arch deformation* (Nigg et al., 1998), and the *navicular drop index*. (Saltzman et al., 1995). The latter, still rather common in the clinical practice, has been shown to be correlated with rearfoot pronation (Boozer et al., 2002), which is suggested to be associated to the stability of the MLA. In addition, footprint-based parameters such as the *arch index* (Cavanagh and Rodgers, 1987), the *arch-length index* (Hawes et al., 1992) and the *Staheli's index* (Staheli et al., 1987) have also been devised. In

* Corresponding author.
E-mail address: paolo.caravaggi@ior.it (P. Caravaggi).

https://doi.org/10.1016/j.jbiomech.2019.03.017
0021-9290/

particular, it has been shown that the arch index can explain 50% of variance in MLA height (McCrory et al., 1997). Scores based on visual observation and manual palpation, such as the *Foot Posture Index*, have also been proposed (Redmond et al., 2006), but this is associated more with the foot pronation/supination posture which is not strictly related to MLA shape.

Stereophotogrammetry, in combination with multisegment foot models, allow to replicate the aforementioned clinical definitions also in dynamic tasks (Hunt et al., 2000; Jenkyn and Nicol, 2007) and to track the MLA angle over time. Most of current geometrical approximations of the MLA angle reported in multisegment foot protocols entail the use of anatomical landmarks on the calcaneus, on the navicular bone and on the first metatarsal head (Bandholm et al., 2008; Simon et al., 2006; Tome et al., 2006). MLA posture is generally calculated as the angle between two 3-dimensional vectors bounded by those markers, with no particular assumptions on their orientation with respect to foot anatomy. In an effort to better replicate the anatomical shape of the MLA, a parabola (Perl et al., 2012) and an ellipse (Ikeda et al., 2014), which best interpolate the position of those skin-markers, have also been proposed. In order to improve the consistency with traditional clinical measures of MLA based on lateral x-ray images, the Rizzoli Foot Model (RFM) is currently the only multisegment foot model approximating the MLA arch as the angle between the projections on the sagittal plane of the foot of two line segments connecting at the sustentaculum tali (Leardini et al., 2007; Portinaro et al., 2014).

While the importance for measuring the MLA is generally recognized, no consensus has thus far been reached on which MLA model better represents the foot medial longitudinal arch shape and deformation. Some of the current definitions used in gait analysis, based on skin-markers, do not appear consistent with foot anatomy and mechanics. Furthermore, despite the importance of MLA biomechanics across several disciplines, a thorough investigation of the error in the calculation of MLA deformation during common motor tasks has yet to be performed. The aim of this study was to compare eight skin-markers based definitions of MLA angle, both as angles between 3-dimensional vectors and as angles between corresponding projections on the sagittal plane of the foot, in terms of inter-trial, inter- and intra-examiner reliability during walking and running.

2. Methods

2.1. Skin-markers based definitions of MLA

The eight geometrical definitions of MLA were based on skin-markers located on the calcaneus (CA: upper central ridge of the calcaneus posterior surface), sustentaculum tali (ST: most medial apex), talo-navicular tuberosity (TN: most medial apex of the navicular tuberosity), the two malleoli (distal apex of the medial and lateral malleolus), base of the first metatarsal bone (FMB: dorso-medial aspect of the first metatarso-cuneiform joint) and head of the first metatarsal bone (FMH: dorso-medial aspect of the first metatarso-phalangeal joint) (Fig. 1), as described in (Leardini et al., 2007; Portinaro et al., 2014). These MLA definitions aim at mimicking the Moreau-Costa-Bertani angle (Moreau and Costa-Bertani, 1943) and the angle between rearfoot inclination and first metatarsal inclination described by Saltzman et al. (1995). All MLA measurements were calculated: (1) as angles between two 3-dimensional vectors (here called 3D angles), and (2) as angles between the projections of those vectors on the sagittal plane of the foot (here called 2D angles, α in Eq. (1)). This is defined as the plane orthogonal to the transverse plane (through CA, FMH and head of the fifth metatarsal bone), and passing through CA and head of the second metatarsal bone (Cappozzo et al., 1995).

$$\alpha = \cos^{-1}\left(\vec{u} \cdot \vec{v}\right) \tag{1}$$

where u and v are two unit vectors, the directions of which are established by real markers on anatomical landmarks or by "virtual" markers constructed from a set of real and virtual points.

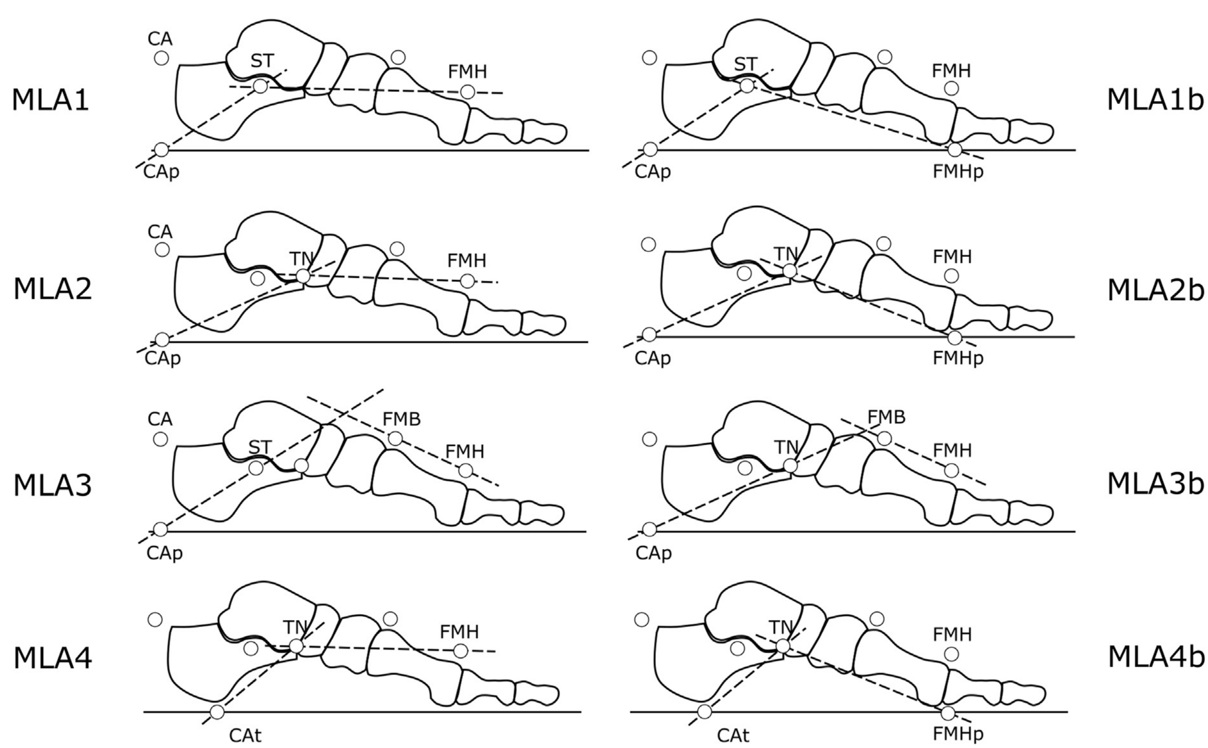

Fig. 1. Left (top to bottom), four skin-markers based measures of medial longitudinal arch angle. Right, four variations using either the projection of FMH on the ground (MLA1b, MLA2b and MLA4b) and using TN instead of ST (MLA3b).

A detailed description of each marker-based MLA measure follows (see Fig. 1).

- **MLA1 - or RFM definition:** the vector on the proximal segment is bounded by marker CA_p and ST, where CA_p is the projection of CA on the x-y plane of the laboratory reference frame (i.e. the ground). The vector on the distal segment is bounded by markers FMH and ST.
- **MLA1-b:** as MLA1 by replacing FMH with FMH_p, where FMH_p is the projection of FMH on the ground.
- **MLA2 - or talo-navicular apex definition:** the vector on the proximal segment is bounded by marker CA_p and by TN. The vector on the distal segment by FMH and TN.
- **MLA2-b:** as MLA2 by replacing FMH with FMH_p.
- **MLA3 - or first metatarsal bone orientation definition:** the vector on the proximal segment is bounded by markers CAp and ST. The vector on the distal segment by FMH and FMB.
- **MLA3-b:** as MLA3 by replacing ST with TN.
- **MLA4 - or calcaneal tuberosity definition:** the vector on the proximal segment is bounded by CA_t and TN, where CA_t is the projection of CA_m - midpoint between CA and the midpoint between peroneal tubercle and ST - on the ground plane. The vector on the distal segment is bounded by FMH and TN.
- **MLA4-b:** as MLA4 by replacing FMH with FMH_p

Each of the above MLA angles was calculated both as the 3D and 2D angles, for a total of 16 MLA measures.

The virtual markers' positions (such as CA_p) were established with the subject in static bipedal standing posture. During kinematic analysis, the trajectory of virtual markers was rigidly fixed to that of the relevant segment local reference frame.

2.2. Repeatability study

A repeatability study was performed to evaluate the inter-trial, inter- and intra-examiner error in calculating MLA angle according to the 16 definitions. The study entailed measuring MLA angle during static bipedal standing posture, and temporal profiles during walking and running in two subjects (subject A: female; 30 years; 57 kg; 1.54 m; Arch Index = 0.22; Foot Posture Index = +2; subject B: male; 26 years; 74 kg; 1.76 m; Arch Index = 0.26; Foot Posture Index = +3). The shank and foot of these subjects were instrumented with reflective skin-markers by four examiners in three sessions, one week apart (Schwartz et al., 2004). An 8-camera motion analysis system (Vero Vicon; sampling rate = 100 Hz) was used to track 16 markers, according to the RFM (Leardini et al., 2007; Portinaro et al., 2014). Markers trajectories were filtered with a Woltring low-pass filter (cutoff frequency = 10 Hz) and imported as .c3d files in Visual3D (Visual3D, C-Motion, Germantown, MD) for angles calculation. The variability of MLA measures was computed as the average of the standard deviation over the gait cycle (AVG-SD), across a number of walking trials pooled according to Schwartz et al. (2004). Accordingly, the variability was determined from the average of this error as follows: inter-trial, across 24 groups (4 examiners*2 subjects*3 sessions) of 5 trials; inter-session, from 8 groups (4 observers * 2 subjects) of 15 trials; inter-examiner, from 2 groups (2 subjects) of 60 trials.

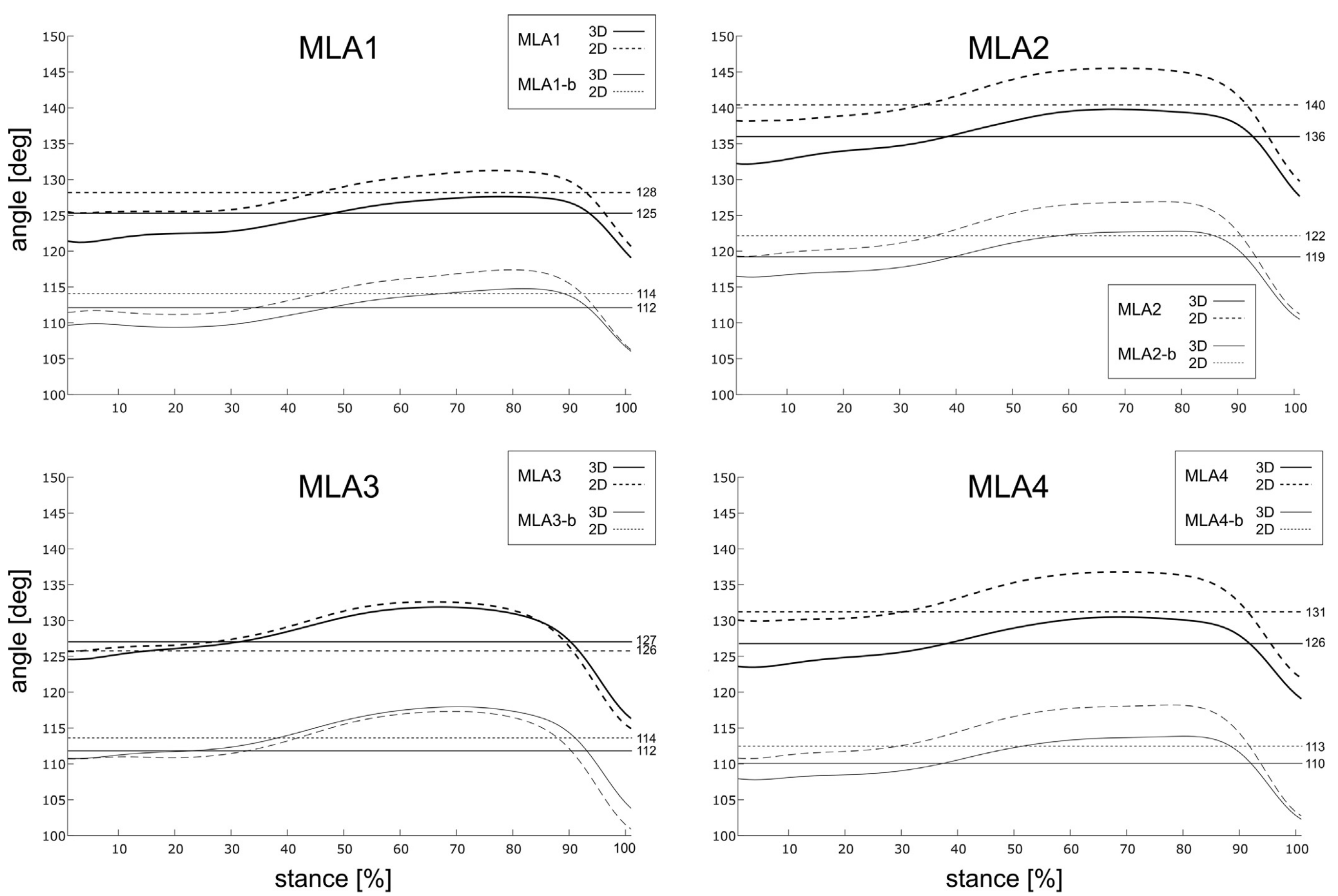

Fig. 2. Mean temporal profiles of MLA angles during normalized stance phase duration for one of the two subjects across 60 walking trials. MLA angles are shown as continuous bold line (3D angle), dotted bold line (2D angle), continuous thin line (3D angle, *b* variation) and dotted thin line (2D angle, *b* variation). For each definition, straight lines are showing the mean MLA angle in bipedal standing posture. See Fig. 1 for measures description.

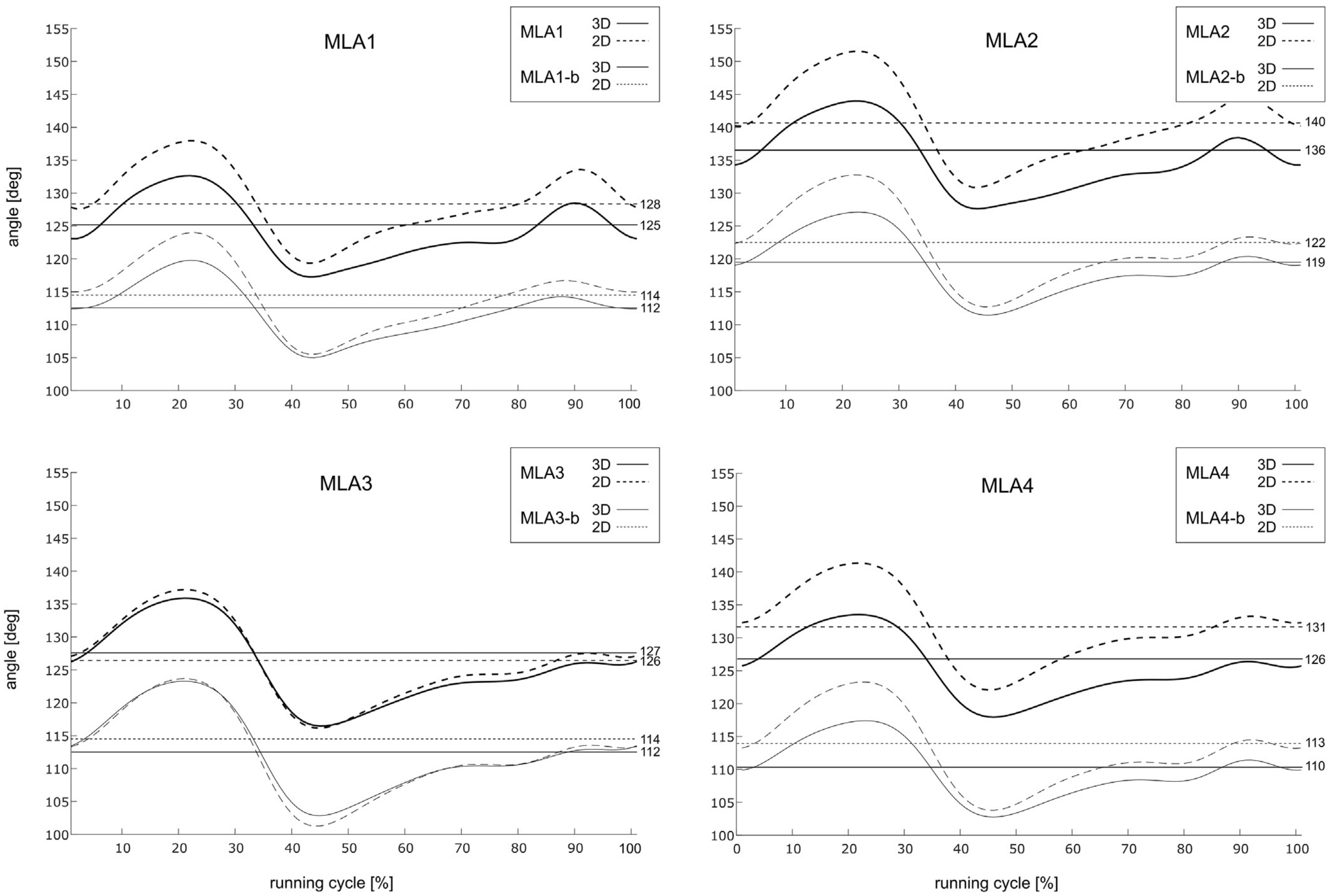

Fig. 3. Mean temporal profiles of MLA angles during normalized running cycle for one of the two subjects across 60 walking trials. MLA angles are shown as continuous bold line (3D angle), dotted bold line (2D angle), continuous thin line (3D angle, *b* variation) and dotted thin line (2D angle, *b* variation). For each definition, straight lines are showing the mean MLA angle in bipedal standing posture. See Fig. 1 for measures description.

Table 1
Inter-trial, inter-session and inter-examiner variability [deg] of MLA measures in walking and running. Variability data are reported for each of the eight measures calculated both as angles between 3-dimensional vectors (3D), and as angles between corresponding projections on the sagittal plane of the foot (2D). See Fig. 1 for details.

MLA definition		Variability – AVG-SD [deg]					
		Inter-trial		Inter-session		Inter-examiner	
		Walking	Running	Walking	Running	Walking	Running
MLA1	3D	0.7	0.7	2.8	3.0	3.7	4.0
	2D	0.8	1.0	3.6	3.3	4.8	4.6
MLA1-b	3D	0.7	0.7	3.7	3.5	5.1	5.2
	2D	0.8	0.9	4.3	4.0	6.0	5.8
MLA2	3D	0.8	0.7	3.4	3.3	4.2	4.2
	2D	1.1	1.0	5.2	4.9	6.9	6.6
MLA2-b	3D	0.8	0.7	4.5	4.3	5.9	6.1
	2D	1.0	0.9	5.7	5.1	7.7	7.6
MLA3	3D	0.9	0.8	5.4	4.2	6.5	5.4
	2D	1.2	1.1	7.5	6.2	9.3	7.9
MLA3-b	3D	0.9	0.8	4.2	3.8	5.7	5.1
	2D	1.1	1.1	6.2	5.5	8.2	7.3
MLA4	3D	0.7	0.7	3.9	3.4	4.8	4.4
	2D	1.1	1.0	5.9	5.4	8.1	7.3
MLA4-b	3D	0.7	0.7	4.9	4.5	6.6	6.5
	2D	1.1	1.0	6.4	5.8	8.9	8.5

3. Results

Mean temporal profiles of MLA angles across 60 walking and 60 running trials for one of the two subjects, along with mean MLA angles during static bipedal standing posture, are shown in Fig. 2 and Fig. 3, respectively. In general, the 2D angles were larger than the corresponding 3D angles.

The inter-trial variability in walking was in the range 0.7–1.2 deg, the inter-session 2.8-7.5 deg, and the inter-examiner in the range 3.7–9.3 deg across all MLA definitions (Table 1). MLA1,

Table 2
For each MLA definition, the inter-trial median [25–75%] ROM [deg] in walking and running for the two subjects. ROM data are reported for each of the 8 measures calculated both as angles between 3-dimensional vectors (3D), and as angles between corresponding projections on the sagittal plane of the foot (2D). See Fig. 1 for details.

MLA definition		ROM [deg]			
		Walking		Running	
		Subject 1	*Subject 2*	*Subject 1*	*Subject 2*
MLA1	3D	9 [8 11]	7 [6 7]	16 [15 17]	15 [12 19]
	2D	11 [10 12]	10 [9 11]	19 [18 21]	22 [20 26]
MLA1-b	3D	9 [8 10]	7 [6 7]	15 [14 16]	15 [12 19]
	2D	12 [10 13]	10 [9 11]	19 [18 20]	21 [19 26]
MLA2	3D	13 [11 15]	9 [9 11]	17 [16 19]	17 [14 20]
	2D	16 [15 18]	16 [15 18]	21 [20 24]	28 [25 30]
MLA2-b	3D	13 [11 14]	9 [10 12]	17 [15 17]	17 [14 18]
	2D	16 [15 17]	16 [14 17]	20 [19 22]	24 [22 26]
MLA3	3D	17 [15 18]	14 [12 16]	20 [19 21]	19 [18 24]
	2D	18 [17 20]	17 [16 20]	21 [20 24]	26 [25 31]
MLA3-b	3D	15 [13 17]	12 [10 14]	21 [20 23]	21 [17 24]
	2D	17 [15 19]	16 [13 18]	22 [21 25]	27 [25 31]
MLA4	3D	12 [10 13]	10 [9 11]	16 [15 18]	14 [13 18]
	2D	15 [14 17]	15 [14 18]	20 [18 22]	24 [22 27]
MLA4-b	3D	12 [11 13]	11 [10 12]	15 [14 16]	16 [14 18]
	2D	16 [15 17]	16 [15 17]	20 [18 22]	24 [22 26]

and its variation MLA1-b, showed the lowest inter-session and inter-examiner variability in both walking and running. MLA measures showed similar variability in walking and running. For each MLA definition, the variability of the 3D angles was always smaller than the corresponding 2D angles.

In walking, the inter-trial (n = 60) median range of motion (ROM) ranged between 9 and 18 deg for subject 1 and 7–17 deg for subject 2, across the MLA definitions (Table 2). In running, ROM ranged between 15 and 22 deg for subject 1, and between 14 and 28 deg for subject 2. MLA1 showed the lowest ROM in both walking and running. For each MLA definition, ROM of the 3D angles in walking and running was lower than that for the corresponding 2D angles.

4. Discussion

The main objective of this study was to establish a set of possible geometrical definitions of the MLA angle based on skin-markers, and to assess their repeatability during common locomotor activities with respect to traditional definitions. In order to be consistent with clinical/radiological measures, these were calculated both as angles between 3-dimensional vectors and as angles between the projected vectors on the sagittal plane of the foot. For each MLA definition, variability and ROM in walking and running of the 3D angles were always lower than the corresponding 2D angles. This could be accounted for to the additional error in the definition of the sagittal plane of the foot, on which markers' positions are projected. For the same reason, larger variability was also detected for MLA definitions based on larger number of real and virtual markers, such as MLA3 and MLA4. As expected, the inter-examiner variability was larger than the inter-session and this was larger than the inter-trial across all MLA measurements. Despite the larger accelerations the foot is subjected to in running, no differences in variability were detected with respect to the corresponding errors in walking. While the present inter-trial and inter-session variability of MLA measurements is rather consistent with those previously reported, the average inter-examiner repeatability is slightly lower than what calculated for other foot joints during walking (range 2.7–11.5 deg, from Caravaggi et al. (2011)). This result is remarkable considering the larger angles and overall motion measured with the present MLA definitions, and further stresses the need for experienced operators in markers positioning as those recruited in the present investigation.

This study allows quantifying the systematic errors in MLA measurements that should be accounted for when assessing differences between groups involving more than one observer in the data collection. The present results may help choosing the measure with higher reliability which will give greater statistical power to detect differences between groups, for a given sample size. While knowledge of the inter-trial and inter-examiner reliability of MLA measures based on skin-markers allows assessing the robustness of the measurements, no information can be inferred on the accuracy of the real MLA posture and deformation in dynamic activities. The rather small variability and range of motion detected for MLA1 does not necessarily imply that the model is well replicating the mechanics of the medial arch. Therefore, while the present study is indicating that MLA angle definitions based on minimal marker sets should be pursued to improve reliability of measurements, further analysis on the accuracy of current MLA definitions with respect to standard imaging-based measures are necessary and should be sought in future investigations.

Acknowledgements

The National Council for Scientific and Technological Development (CNPq) funded I.C.N. Sacco (Process: 305606/2014-0), and the State of São Paulo Research Foundation (FAPESP) funded the fellowship of Paolo Caravaggi (2017/23975-8) during the execution of the present investigation.

Conflict of interests

This study has not received any funding/assistance from commercial organizations that could lead to a conflict of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.03.017.

References

Bandholm, T., Boysen, L., Haugaard, S., Zebis, M.K., Bencke, J., 2008. Foot medial longitudinal-arch deformation during quiet standing and gait in subjects with medial tibial stress syndrome. J. Foot Ankle Surg. 47, 89–95.

Bennett, M.R., Harris, J.W., Richmond, B.G., Braun, D.R., Mbua, E., Kiura, P., Olago, D., Kibunjia, M., Omuombo, C., Behrensmeyer, A.K., 2009. Early hominin foot morphology based on 1.5-million-year-old footprints from Ileret, Kenya. Science 323, 1197–1201.

Birinci, T., Demirbas, S.B., 2017. Relationship between the mobility of medial longitudinal arch and postural control. Acta orthopaedica et traumatologica turcica 51, 233–237.
Boozer, M., Finch, A., Waite, L., 2002. Investigation of the relationship between arch height and maximum pronation angle during running. Biomed. Sci. Instrum. 38, 203–207.
Cappozzo, A., Catani, F., Croce, U.D., Leardini, A., 1995. Position and orientation in space of bones during movement: anatomical frame definition and determination. Clin. Biomech. (Bristol, Avon) 10, 171–178.
Caravaggi, P., Benedetti, M., Berti, L., Leardini, A., 2011. Repeatability of a multi-segment foot protocol in adult subjects. Gait Posture 33, 133–135.
Caravaggi, P., Pataky, T., Goulermas, J.Y., Savage, R., Crompton, R., 2009. A dynamic model of the windlass mechanism of the foot: evidence for early stance phase preloading of the plantar aponeurosis. J. Exp. Biol. 212, 2491–2499.
Cavanagh, P.R., Rodgers, M.M., 1987. The arch index: a useful measure from footprints. J. Biomech. 20, 547–551.
Griffin, N.L., Miller, C.E., Schmitt, D., D'Août, K., 2015. Understanding the evolution of the windlass mechanism of the human foot from comparative anatomy: Insights, obstacles, and future directions. Am. J. Phys. Anthropol. 156, 1–10.
Hawes, M.R., Nachbauer, W., Sovak, D., Nigg, B.M., 1992. Footprint parameters as a measure of arch height. Foot ankle 13, 22–26.
Hicks, J.H., 1954. The mechanics of the foot. II. The plantar aponeurosis and the arch. J. Anat. 88, 25–30.
Hunt, A.E., Fahey, A.J., Smith, R.M., 2000. Static measures of calcaneal deviation and arch angle as predictors of rearfoot motion during walking. Aust. J. Physiother. 46, 9–16.
Ikeda, A., Kasuga, T., Ogasawara, T., Kosugi, S., Tanaka, Y., 2014. Three-Dimensional Analysis Method for Longitudinal Arch Deformation, Orthopaedic Research Society, 60th Annual Meeting.
Jenkyn, T.R., Nicol, A.C., 2007. A multi-segment kinematic model of the foot with a novel definition of forefoot motion for use in clinical gait analysis during walking. J. Biomech. 40, 3271–3278.
Ker, R.F., Bennett, M.B., Bibby, S.R., Kester, R.C., Alexander, R.M., 1987. The spring in the arch of the human foot. Nature 325, 147–149.
Leardini, A., Benedetti, M.G., Berti, L., Bettinelli, D., Nativo, R., Giannini, S., 2007. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. Gait Posture 25, 453–462.
Lin, Y.H., Chen, C.Y., Cho, M.H., 2012. Influence of shoe/floor conditions on lower leg circumference and subjective discomfort during prolonged standing. Appl. Ergon. 43, 965–970.
McCrory, J., Young, M., Boulton, A., Cavanagh, P., 1997. Arch index as a predictor of arch height. The Foot 7, 79–81.
Moreau, M., Costa-Bertani, G., 1943. Roentgen study of flat foot. Year Book Radiol. 81, 82.
Nachbauer, W., Nigg, B.M., 1992. Effects of arch height of the foot on ground reaction forces in running. Med. Sci. Sports Exerc. 24, 1264–1269.
Nigg, B.M., Khan, A., Fisher, V., Stefanyshyn, D., 1998. Effect of shoe insert construction on foot and leg movement. Med. Sci. Sports Exerc. 30, 550–555.
Perl, D.P., Daoud, A.I., Lieberman, D.E., 2012. Effects of footwear and strike type on running economy. Med. Sci. Sports Exerc. 44, 1335–1343.
Pfeiffer, M., Kotz, R., Ledl, T., Hauser, G., Sluga, M., 2006. Prevalence of flat foot in preschool-aged children. Pediatrics 118, 634–639.
Portinaro, N., Leardini, A., Panou, A., Monzani, V., Caravaggi, P., 2014. Modifying the Rizzoli foot model to improve the diagnosis of pes-planus: application to kinematics of feet in teenagers. J. Foot Ankle Res. 7, 754.
Redmond, A.C., Crosbie, J., Ouvrier, R.A., 2006. Development and validation of a novel rating system for scoring standing foot posture: the Foot Posture Index. Clin. Biomech. (Bristol, Avon) 21, 89–98.
Saltzman, C.L., Nawoczenski, D.A., 1995. Complexities of foot architecture as a base of support. J. Orthop. Sports Phys. Ther. 21, 354–360.
Saltzman, C.L., Nawoczenski, D.A., Talbot, K.D., 1995. Measurement of the medial longitudinal arch. Arch. Phys. Med. Rehabil. 76, 45–49.
Schwartz, M.H., Trost, J.P., Wervey, R.A., 2004. Measurement and management of errors in quantitative gait data. Gait Posture 20, 196–203.
Simon, J., Doederlein, L., McIntosh, A.S., Metaxiotis, D., Bock, H.G., Wolf, S.I., 2006. The Heidelberg foot measurement method: development, description and assessment. Gait Posture 23, 411–424.
Staheli, L.T., Chew, D.E., Corbett, M., 1987. The longitudinal arch. A survey of eight hundred and eighty-two feet in normal children and adults. J. Bone Joint Surg. Am. 69, 426–428.
Stearne, S.M., McDonald, K.A., Alderson, J.A., North, I., Oxnard, C.E., Rubenson, J., 2016. The Foot's arch and the energetics of human locomotion. Sci. Rep. 6, 19403.
Tome, J., Nawoczenski, D.A., Flemister, A., Houck, J., 2006. Comparison of foot kinematics between subjects with posterior tibialis tendon dysfunction and healthy controls. J. Orthopaed. Sports Phys. Ther. 36, 635–644.
Williams, D.S., McClay, I.S., 2000. Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. Phys. Ther. 80, 864–871.