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ISB recommendations for skin-marker-based multi-segment foot kinematics

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ABSTRACT

The foot is anatomically and functionally complex, and thus an accurate description of intrinsic kinematics for clinical or sports applications requires multiple segments. This has led to the development of many multi-segment foot models for both kinematic and kinetic analyses. These models differ in the number of segments analyzed, bony landmarks identified, required marker set, defined anatomical axes and frames, the convention used to calculate joint rotations and the determination of neutral positions or other offsets from neutral. Many of these models lack validation. The terminology used is inconsistent and frequently confusing. Biomechanical and clinical studies using these models should use established references and describe how results are obtained and reported.

The International Society of Biomechanics has previously published proposals for standards regarding kinematic and kinetic measurements in biomechanical research, and in this paper also addresses multi-segment foot kinematics modeling. The scope of this work is not to prescribe a particular set of standard definitions to be used in all applications, but rather to recommend a set of standards for collecting, calculating and reporting relevant data.

The present paper includes recommendations for the overall modeling and grouping of the foot bones, for defining landmarks and other anatomical references, for addressing the many experimental issues in motion data collection, for analysing and reporting relevant results and finally for designing clinical and biomechanical studies in large populations by selecting the most suitable protocol for the specific application.

These recommendations should also be applied when writing manuscripts and abstracts.

1. Introduction

The foot is a very complex structure comprised of 28 bones, 33 joints, and about 100 ligaments, controlled by extrinsic and intrinsic muscle–tendon units. Many pathologies of the foot involve one or multiple segments (e.g., tibia-fibula, hindfoot, midfoot, forefoot, and hallux) but not necessarily the entire foot. Clinicians diagnose and treat foot and ankle pathologies based on the anatomical location of the disease or injury, corresponding pathophysiology, and scoring systems such as patient-reported outcome measures. Kinematic assessments limited to one degree-of-freedom (e.g., hinge-like rotation about the intermalleolar axis), cannot provide the kinematic detail required for diagnosis, treatment planning and prognosis of pathologies of this anatomically and functionally complex structure. Multi-segment foot models (MFM) are therefore necessary to advance our understanding of physiological function and disease onset and progression, as well as the effects of treatments. To date, about 40 MFM have been described in the literature (Leardini et al., 2019). A number of these models have been used to successfully distinguish pathological from asymptomatic feet and have demonstrated differences between foot types, but only a few have undergone a thorough reliability assessment. The MFM does not assume the foot is a rigid body – only that each segment, as defined in the model, behaves as a rigid body under dynamic conditions. For example, when a surgeon plans an arthrodesis (joint fusion) to minimize

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pain in an arthritic joint, an MFM affords the opportunity to see the changes pre- and post- operatively in the involved segments and if any compensations have resulted in adjacent segments as a result of the fusion.

A review of MFM described a substantial diversity of systems based upon the anatomy and segment motions tracked (Leardini and Caravaggi, 2016). Four of the most widely published MFM are: the Milwaukee Foot Model (Kidder et al., 1996), the Oxford Foot Model (Carson et al., 2001), the Rao Foot Model (Rao et al., 2006) and the Rizzoli Foot Model (Leardini et al., 1999, 2007; Portinaro et al., 2014). All of these models comprise a tibia, rearfoot, forefoot and hallux. The Milwaukee foot model employs an X-ray based method for establishing segment alignment while the Rao model seeks to establish subtalar neutral to define the reference foot and ankle alignment. The Rao model separates the first metatarsal from the second through fifth metatarsals to model the forefoot as two segments. The Rizzoli Foot Model has a midfoot segment, which the vast majority of MFM do not include. Most MFM use a double leg standing posture to provide reference orientations of the foot and lower limb segments. Bone grouping (i.e., the identification of the foot segments), as well as the definition of a possible 'neutral position' of the foot and ankle for possible off-set removal, are two important factors that can result in large differences between MFM. Several investigators (Dixon et al., 2012; Pothrat et al., 2015) have compared the Oxford Foot Model to a lower limb model where the foot is modeled as one rigid segment. Ankle kinematics were strongly affected by the foot model chosen and ankle power was 40% larger in the plug-in gait model. The authors suggested caution be taken when reporting results from a single segment foot model.

There is substantial clinical (Yan et al., 2020), biomechanical (Hillstrom et al., 2013; Mootanah et al., 2013; Rao et al., 2011; Shultz et al., 2017; Song et al., 1996) and epidemiological (Galica et al., 2013; Golightly et al., 2019, 2014; Hagedorn et al., 2013; McLean et al., 2014; Menz et al., 2013; Nguyen et al., 2013; Riskowski et al., 2013; Song et al., 2018) evidence that there is more than one 'normal' or 'control' foot. There are asymptomatic feet but they may have a planus, rectus or cavus morphology with tendencies towards three-dimensional (3D) pronation, neutral or supination posture. This concept is known as foot type. Differences in foot function between foot types have been determined with a plantar pressure measuring device to assess peak pressure in masked regions of the foot. Multi-segment foot kinematics are also affected by foot type (Buldt et al, 2015; Kerr et al, 2015; Portinaro et al, 2014; Krzak et al, 2015; Cobb et al, 2009), which confirms the distinctions between foot structure and function that have been made with plantar pressure and arch height and malleolar valgus-based studies (Song et al, 1996; Hillstrom et al, 2013). Multi-segment foot kinetics have not been evaluated across foot types to date.

The objective of this paper is to present a number of recommendations that may be useful for researchers, clinicians and lecturers in the field of foot kinematic analysis using skin marker based stereophotogrammetry. These suggestions from the International Society of Biomechanics (ISB) concern several relevant aspects of MFM: (Section 2) modeling of foot segments, (Section 3) anatomical references and frames, (Section 4) experimental issues, (Section 5) data analysis and reporting, (Section 6) clinical and other applications in large populations, and (Section 7) final ISB recommendations. Given how complexity of the foot, and the diversity of its functional roles, the recommendations are based on principles rather than recommending one specific way of modeling the foot.

2. Modeling the foot segments

The foot encompasses many bones in close proximity making a complete kinematic model for every joint with skin mounted markers virtually impossible (Fig. 1). 3D kinematic analysis of individual bones is valid and reliable only via invasive approaches such as intracortical pins (Arndt et al., 2007; Lundgren et al., 2008; Westblad et al., 2002),

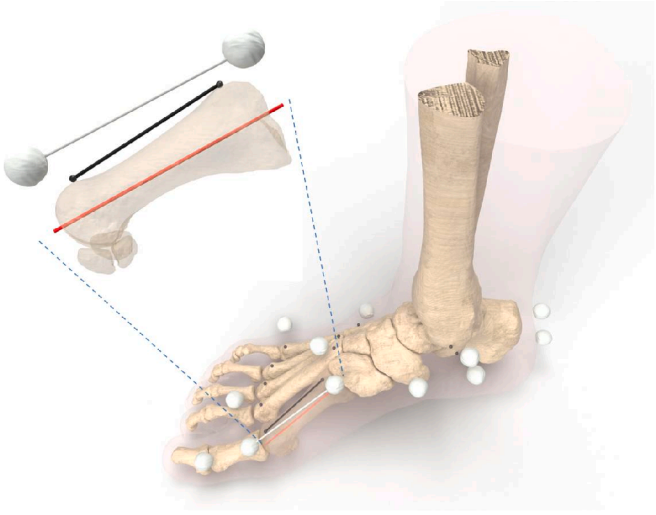

Fig. 1. Diagrammatic representations of possible technical and anatomical references in MFM, taken from a real case; in the top-left, a zoomed-in diagram of the first metatarsal. The longitudinal (i.e., mid-diaphyseal) axis of the bone (in red) can be represented as the line (black) joining two relevant anatomical landmarks (black circles); these landmarks are tracked by the external skin markers (grey spheres and axis).

actuator-controlled gait simulators in vitro (McKearney et al., 2019; Nester et al., 2007; Okita et al., 2013; Saito et al., 2019), quasi-dynamic radiostereometric analysis (RSA) which involves insertion of intracortical markers (Lundberg, 1989; Lundberg et al., 1989a, 1989b, 1989c) and bi-planar video fluoroscopy (Komistek et al., 2000; Lenz et al., 2021). Intracortical pins, actuator controlled gait simulators and RSA methods all track bones very precisely by utilizing at least three non-collinear markers inserted surgically into each bone segment of interest. Bi-planar video fluoroscopy methods either with invasively inserted intracortical markers or using marker-less tracking have shown great potential (Balsdon et al., 2019; Iaquinto et al., 2014), but are at present limited by the radiation exposure, equipment and personnel costs, and tracking volumes. The recommendations presented here are therefore restricted to MFM implemented with video-based tracking of skin-mounted markers.

With the exception of the calcaneus and maybe the first metatarsal, foot bones are generally difficult to track individually using surface markers. These two bones are large, superficial and present easily palpable landmarks and offer ample space for marker attachment. The definition of other segments requires bone grouping. This can range from a single foot segment to 26 different segments (Glasgow-Maastricht foot model in Oosterwaal et al., 2016). The segments chosen should be defined based on anatomical and functional relevance, in addition to being appropriate for the clinical issue addressed in the study.

Bone grouping can be determined based on relative motion of the different bones during the functional task being assessed. For example, using intracortical pin data, it was found that only two functional units consistently rotated in phase during walking; these were a medial ray segment comprising the navicular, medial cuneiform and first metatarsal and another segment comprising the navicular and cuboid (Wolf et al., 2008). It was concluded that a relevant marker set should define four segments: calcaneus, navicular–cuboid, medial cuneiform–first metatarsal and fifth metatarsal. However, only a few studies have implemented this suggestion, presumably because of the difficult association of skin markers with these specific segments.

Grouping foot bones in segments to be tracked requires an appropriate design of the relevant marker set. Marker placement varies with each segment and a small error can result in a relatively large error in embedded axes and overall segment orientation. Marker misplacement can cause an overall displacement of the kinematic waveforms, although

tends to have limited effect on general patterns or the range of motion (Deschamps et al., 2012b, 2012a). It is important to be aware of the effect of bone grouping and landmark-to-marker association when using a MFM, to appropriately interpret the final kinematic results. It is also important to be aware that axis alignment based on skin markers may not necessarily correspond to underlying skeletal anatomy (Fig. 1; Zavatsky et al., 2019) and that misalignment is likely to be compounded in cases of foot deformity. Marker placement is generally associated with bony prominences, but given the variety of individual bone shapes, particularly when pathology is present, it cannot always be assumed that surface anatomy relates well to overall bone or segment orientation. It is also important to determine a 'neutral position' for the foot and ankle, which defines an offset for the joint kinematics, and to establish the foot type of the reference cohort. Attention to these details is necessary for comparing 'absolute' kinematic data (i.e., without removing the neutral position offset) from different MFM (Schallig et al., 2020). Otherwise, one may need to settle for comparing 'relative' motion (i.e., after removal of the neutral position offset) for each joint. An operating protocol for marker placement and a careful assessment of relevant reliability is thus recommended. Eventually, it is important for each laboratory to establish their own database of normal participants to provide a common reference and minimize inter-rater variability.

A review (Bishop et al., 2012) revealed that only 9 out of 26 articles reported coefficients of multiple correlation or intra-class correlation to support the reliability or repeatability of the MFM developed. Only one study directly validated a marker-set with intracortical pins (Nester et al., 2007). At present, there are only a few validated skin marker based MFM and further research in this field is required.

It is necessary to distinguish between 3D joint rotations and planar angles. The former are the three independent rotations according to a kinematics convention (Grood and Suntay, 1983; Wu et al., 2002). Planar angles are calculated as line segments projected into an anatomical plane, and were introduced by a few MFM to describe global orientations of isolated bones or more complex functional concepts (e.g., forefoot-to-rearfoot alignment, longitudinal and transverse arches, metatarsal bone orientations). For both three- and two-dimensional rotations, the joints can also be defined for adjacent segments (e.g., tibiotalar, mid-tarsal or Chopart, tarso-metatarsal or Lisfranc, metatarso-phalangeal) or for non-adjacent segments (e.g., forefoot with respect to rearfoot).

3. Anatomical references

To report motion of a body segment in clinical terms, anatomical reference frames must be defined based on anatomical landmarks. These can be bony prominences, or geometrical points. These landmarks (see Fig. 1 for an example) should be a) tracked by means of corresponding direct markers attached on the skin, b) identified with a pointer with respect to a relevant rigid cluster of markers (Buldt et al., 2015; Carson et al., 2001; Houck et al., 2006; Hyslop et al., 2010; Leardini et al., 1999; Nester et al., 2014; Raychoudhury et al., 2014; Souza et al., 2014), or c) defined as virtual points (e.g., projection points, mid-points or centroids or pivot points of joint motion). When the entire foot is assumed to be a single rigid body, three or four landmarks suffice, but in MFM each segment must have its own anatomical references. A large number of landmarks, axes and reference frames have been proposed, as addressed in a recent review (Leardini et al., 2019), but common references that apply to all protocols have not been established. Modern motion capture systems now allow a large number of single skin markers to be tracked on the dorsal aspect of the foot (Oosterwaal et al., 2016; Raychoudhury et al., 2014), thus marker clusters, and relevant anatomical landmark calibrations, previously introduced for better marker visibility (Leardini et al., 1999) are no longer necessary. For most of the proposed techniques, and according to previous ISB recommendations (Grood and Suntay, 1983; Wu et al., 2002), kinematic analysis of the foot joints should be in 3D (i.e., three independent rotations about three different axes of the joint); this 3D motion can be calculated between the two segments of the joint, but also between a single segment and a global reference frame, either rigid with a laboratory frame or a global anatomical reference frame.

The number and location of reference landmarks are decided according to the MFM adopted and, where relevant, to the specific clinical or scientific investigation. Among all possible palpable landmarks, selection should be based according to the following: a) minimize skin motion artifact due to gliding of the skin with respect to the underlying bone; b) avoid muscles, tendons, fat pads and other soft tissues in close proximity for the same reason; c) represent relevant anatomical axes or planes and d) allow natural execution of the motor task without disturbing the participant under analysis. The full marker-set should be visible to the cameras and have appropriate inter-marker distances to maintain separate trajectories during motion capture. This process is not trivial, as foot bones are small and encapsulated in thick tissues. In particular, the talus has no clear palpable landmarks, thus making it nearly impossible to be tracked in 3D space non-invasively, unless strong assumptions are made (Birch and Deschamps, 2014). This implies that in vivo skin-marker-based analyses, tibio-calcaneal motion cannot be differentiated into tibiotalar and subtalar joint motion.

An alternative to calculation of joint rotations in the 3D space by coordinate reference axes is to use planar angles, as mentioned above. With this approach, line segments determined by the position of two markers are projected at each time sample onto an anatomical or other relevant planes (e.g., the ground) (Fischer et al., 2017; Leardini et al., 2007; Portinaro et al., 2014; Simon et al., 2006). These planar measures are appropriate to report angles and deformations at the foot, as has been traditionally performed in static radiographical measurements, such as inclination of the metatarsal bones, the medial longitudinal and other arches of the foot, the varus/valgus of the calcaneus or of the first metatarso-phalangeal joint, and many other standard 2D angles (e.g., Hibb, Meary or Kite angles; see also Carrara et al., 2020). However, these planar angles can provide erroneous measurements in extreme 3D conditions (e.g., between bones with large ranges of relative motion in all three anatomical planes, or in feet with large deformities), though these errors can be estimated easily by 3D trigonometry.

In order to limit subjective factors, the landmark identification must have adequate intra- and inter-rater consistency and repeatability of the measurements (Arnold et al., 2013; Caravaggi et al., 2011; Carson et al., 2001; Curtis et al., 2009; Deschamps et al., 2012a, 2012b; Long et al., 2010; McCahill et al., 2018). A clear goal of these repeatability analyses is often to compare foot joint kinematics longitudinally (i.e., at various follow-up time points or before and after treatment). In these studies, it is particularly recommended that bony prominences are used for anatomical landmark and frame definitions, rather than by assumed anatomical planes of the body. Optical techniques (Kalkum et al., 2016) and plaster molds (Saraswat et al., 2013, 2012) have also been used for landmark identification and relevant marker mounting, but these are likely biased by the associated experimental maneuvers, which may suffer from a lack of inter-rater repeatability. To increase repeatability, it has also been recommended that experienced raters with extensive knowledge of MFM and foot anatomy and practice in marker attachment are involved (Caravaggi et al., 2011; Deschamps et al., 2012b). There is general agreement that careful training of raters and direct skin mounted markers maximize repeatability of the measurements (Novak et al., 2014).

Establishing specific recommendations on anatomical landmarks and segment reference frames that are generally applicable is perhaps unrealistic due to the large spectrum of clinical questions and scientific aims claimed in MFM papers in the literature. Still, it is recommended that the information provided for a study is sufficient to enable other investigators to replicate the data collection and analysis (Deschamps et al., 2011), and yield comparable results. Particularly for those working in a clinical context, where comparisons between populations and follow-up must be performed, it is also recommended that co-

ordinate reference frames are based on anatomical landmarks, whose identification is more repeatable than functional axes or generic global reference planes (e.g., the ground or the anatomical planes of the leg). It is suggested that skin markers directly represent the corresponding anatomical references, rather than being used for technical reference frames requiring additional calibration procedures.

4. Experimental issues

Most studies have used passive motion analysis systems consisting of 4 to 15 cameras, though a precise description of the camera layout is generally lacking in the majority of the studies. Changing the camera layout for tasks other than walking (e.g., jumping) is often not necessary since the capture volume of interest generally remains small. The bilateral measurement of foot kinematics creates additional technical challenges often necessitating more cameras since marker visibility (e.g., those on the medial side of the foot) might be affected in the swing or flight phase of gait. Faster kinds of motor tasks (e.g., running) may also require additional cameras, as well as increased measurement frequencies up to 500 Hz (Deschamps et al., 2011; Leardini et al., 2019). However, most of the past problems in marker tracking have been overcome by modern motion capture systems.

The accuracy of the motion analysis system is an important experimental factor, although it is rarely reported. Excellent accuracy, about 0.1% of the largest dimension of the calibrated field of view, was reported in both static and dynamic conditions since the 1990 s (Kidder et al., 1996), and satisfactory accuracy with the smallest recorded range of motion being seven times larger than the mean motion measurement error (Rattanaprasert et al., 1999) were also claimed. Clearly, a highly accurate, properly set-up and calibrated motion analysis system is necessary in order to quantify reliably and precisely the relatively small displacements of the segments and the small joint rotations which occur in the foot during locomotion. Today this is guaranteed by most of the motion capture systems when used cautiously.

The diameter of skin markers used in MFM have ranged from 4 to 16 mm (Deschamps et al., 2011; Eichelberger et al., 2018; Leardini et al., 2019; Oosterwaal et al., 2016). The choice for a specific marker size seems to be driven by experience rather than empirical data. From a technical viewpoint, one may prioritize larger markers since more pixels can be processed to determine the centroid of a marker, however, this advantage may be potentially offset by a greater distance between the center of the marker and the underlying anatomical landmark. Moreover, larger markers might hamper the natural motion of a participant, cause accidental collisions with other markers or even interfere with the local skin rigidity. To the best of our knowledge, only one recent study (Ebrecht and Sichting, 2020) addressed these issues for MFM.

Accurate marker placement may be challenging, particularly when studying patients with foot deformities due to anatomical landmark variations or even missing anatomical landmarks in cases of certain surgical interventions (e.g., midfoot arthrodesis, amputations) (Deschamps et al., 2011; Novak et al., 2014). Marker placement guided by radiographic or ultrasound imaging could be considered the gold standard, however, this may involve radiation exposure and is difficult to implement in most clinical gait laboratories (Myers et al., 2004; Ness et al., 2008). Marker clusters are also used, but these may be perceived as uncomfortable and require time-consuming anatomical landmark calibration (Deschamps et al., 2012b; Leardini et al., 2019; Novak and Riener, 2015).

Considering the importance of skin motion artifacts in MFM, these have received surprisingly little attention. A study quantifying this artifact using single-plane fluoroscopy showed that the translational effect at the calcaneus and navicular was greater than the rotational effect (Shultz et al., 2011). It was concluded that the effect of skin movement on both marker placement and calculated joint rotations was minimal (Birch and Deschamps, 2011; Shultz et al., 2011). Original studies claimed that the rotational artifact is below three degrees (Reinschmidt et al., 1997; Tranberg and Karlsson, 1998; Umberger et al., 1999). On the other hand, more reliable studies measuring trajectories with skin-, plate- and bone- mounted markers shown that 73% of the range of motion calculated throughout six sub-phases of the stance has differences greater than five degrees (Nester et al., 2007; Shultz et al., 2011). Research is still ongoing to analyze and limit the effects of soft tissue artifact (Camomilla et al., 2017). Finally, the effect of local or general skin rigidity remains uncertain, particularly considering a number of relevant physiological and pathological conditions of the foot (e.g., diabetes mellitus, scar tissue, surgery and edema).

A key issue with skin marker based MFM is the definition of a neutral (or reference) position of the foot joints (Houck et al., 2008; Leardini et al., 1999). Several methods (Houck et al., 2008; Leardini et al., 1999; Levinger and Gilleard, 2006) use a reference position (e.g., resting calcaneal stance position, neutral calcaneal stance position, alignment to an external frame, alignment of the rearfoot to the tibia and reference to the foot position during the stance phase of gait). Subtalar neutral position was found to be more reliable as a reference position than resting calcaneal stance position, enabling comparisons across participants with different foot postures (Houck et al., 2008). Intra-class correlation coefficients of the subtalar neutral position were found to be above 0.95 for all segments and the standard error of the mean predicted errors less than 1.4–2.5 deg in 96% of the cases (Deschamps et al., 2011). In some cases, pathological conditions, surgery or non-reducible foot and leg deformities may render the collection of a neutral/reference position inappropriate. As this could lead to altered interpretations when analyzing pathological gait, future research should investigate potential solutions for this experimental challenge.

It is clinically relevant to measure MFM kinematics also during motor tasks other than walking such as running, jumping, turning, landing and stair ascent/descent. A number of studies have reported consistent and clinically valuable waveform patterns during these tasks (De Ridder et al., 2015; Deschamps et al., 2012b).

In vivo studies using bone pins have also addressed the multi-segment foot kinematics during walking and running conditions. The results of these studies showed that the majority of the foot joints demonstrate a decreased range of motion (Arndt et al., 2007; Lundgren et al., 2008) and greater variability during running (Nester, 2009) compared to walking.

5. Data analysis and reporting

The standard process of checking the continuity and managing gaps in marker trajectories is particularly important in MFM because most of foot joints have small ranges of motion. If gaps cannot be avoided, techniques that utilize complete trajectories on the same rigid segment are recommended, ideally using the average of multiple markers. A secondary preference is to use a linear or spline interpolation (Lewkowicz and Delevoye-Turrell, 2016). However, full reliance on automatic gap-filling techniques is discouraged, and the result of any data interpolation should always be verified, at least with visual inspection, as large inter-subject variability was reported (Carson et al., 2001; Wright et al., 2011; Matias et al., 2020). Measurements presenting large gaps in marker trajectories, should be discarded. Local protocols should specify a priori which data can acceptably be interpolated and which must be discarded.

Smoothing and low-pass filtering are often used to reduce high-frequency noise due to marker oscillation, especially when tracking high-velocity tasks. This may significantly change the marker trajectory and thus the calculated kinematics. Since the maximum frequency content in the foot is about 10 Hz during normal walking (Angeloni et al., 1994; Winter et al., 1974), using cut-off frequencies lower than 10 Hz when applying low-pass filters is discouraged. In general, for any specific motor task to be analyzed, a Fast Fourier transform can be applied to the kinematic data to determine the −3 dB point (or half-power bandwidth) of the frequency spectrum. This would be a

reasonable cut-off frequency for the low pass filter.

Once the marker trajectory data have been pre-processed, kinematic outputs can be computed according to the chosen MFM. Commercial software, such as Visual3D (C-Motion, Canada), and software associated with common stereophotogrammetry camera systems already include some widely used MFM. Matlab, Python or other programming software can be used to calculate joint kinematics directly from the marker trajectories; however, it is recommended that the outputs of custom scripts be compared with those from validated programs. When such scripts are intended to be used for clinical decision-making, the operator should always be aware of national and international health regulations.

Kinematic data for MFM are generally reported as a time history normalized to the stance phase or the entire gait cycle. Kinematics should be reported for motion about a medio-lateral, a vertical and an antero-posterior axis of the joint coordinate system as plantar/dorsiflexion, external/internal rotation and inversion/eversion motion respectively (Wu et al., 2002). Since this terminology is not consistent across studies, every manuscript should clearly report what is meant by these joint rotation terms. Depending upon the scientific question, finite helical axes can also be used (Zavatsky et al., 2019), though it should be noted that for some foot joints movement does not occur solely about one axis. When interpreting kinematic measures, range of motion has been demonstrated to be the most robust discrete parameter and it is among the most used in the assessment of clinical populations (Leardini et al., 2019). Minimum and maximum values can be more sensitive to marker positioning, and errors between three to six degrees should be accounted for when comparing kinematic time-histories acquired in different sessions (Caravaggi et al., 2011). Indices or scores that summarize kinematic abnormalities have also recently been developed for the foot and may be useful as a relevant outcome measure (McCahill et al., 2019).

More complex techniques have also been proposed to analyze coordination of the foot joints, such as the vector coding technique (Sparrow et al., 1987). This may be used to gain insight into the relationship between motion of different foot joints or segments (Arnold et al., 2017; Chang et al., 2008; Pohl and Buckley, 2008; Needham et al., 2020). The technique is, however, very sensitive to small ranges of motion and low angular velocities, thus caution should be used when interpreting these coordination patterns. Statistical parametric mapping (Friston, 1995) has become another popular method for assessing differences between foot kinematic time histories during dynamic tasks (Pataky, 2010; Pataky et al., 2013). One-dimensional statistical parametric mapping can be implemented in Python and Matlab via freeware available at http://spm1d.org. More in general, the choice of the most appropriate statistical analysis should be hypothesis-driven, and clearly justified in the manuscript.

6. Clinical and other applications in large populations

A tool to accurately measure dynamic foot function is needed to improve management of foot and ankle pathology. To fulfill this purpose, the tool needs to be accurate, reliable, sensitive, fit for purpose, practical and user friendly. Therefore, the question is whether currently available MFM fulfill these criteria, and can safely be used to answer clinical questions.

A recent review (Leardini et al., 2019) summarized the evidence for the clinical use of MFM. It was found that the majority of studies were cross-sectional in nature, comparing pathological to typically developing feet. In every reported study, at least one statistical difference was found between the control group and the pathological group. Although several studies have reported on the repeatability of MFM, few have used a pathological cohort in this context (Carter et al., 2018; Deschamps et al., 2012b; Hyslop et al., 2010; McCahill et al., 2018; Sawacha et al., 2009). Only a handful of studies have used a longitudinal design to assess the outcome of interventions, so the evidence for their use in this context is limited. In addition, only a few studies have successfully classified different types of foot pathology using MFM. In summary, there is evidence that MFM are sensitive enough to distinguish pathological from control feet, and have comparable repeatability when applied to pathological feet compared to typically developing feet. There is only limited evidence regarding the ability of MFM to detect change following intervention and their effectiveness in planning treatment.

Clinical, biomechanical and epidemiological data suggest that several foot pathologies are related to foot type, especially on the more severe ends of the spectrum of structure and function. Early work in MFM demonstrated large standard deviations for many of the angular excursions in the hindfoot, midfoot and forefoot (Myers et al., 2004). We now know that much of that variability was due to the inclusion of individuals with different foot types in the analysis in combination with marker placement inaccuracy (Amene et al., 2019; Buldt et al., 2015; Kruger et al., 2019). If a cohort of flexible planus feet were compared to a cohort of well aligned rectus feet, several differences would be expected (e.g., greater eversion in the hindfoot of the planus feet compared with rectus). If these data are pooled, then greater variability for eversion will result. The Oxford and Rizzoli foot models for example are both capable of distinguishing between high and low arched feet (Powell et al., 2013). Since MFM are sensitive to foot type, it is important when comparing groups of patients that they have comparable foot types at baseline to avoid confounding effects. If studies are not stratified by foot type, a large variance is to be expected in the data.

Another important aspect when using an MFM in a clinical context is that the model needs to be able to measure the motion of interest in order to be able to answer the clinical question. For example, if the question regards motion of the medial longitudinal arch in a flat foot population, then the MFM should measure the arch reliably and accurately. Other important considerations include whether the model can cope with the size (for example, small children) and shape (for example, significant deformity) of the feet of interest, and if the model can practically be applied in the desired context (for example, can participants stand for long enough if the MFM adopted requires marker placement during standing?). When applying an MFM in a clinical context, it is also important to understand the limitations associated with these models in general, as well as any limitations specific to the model chosen.

Another factor that drives utility of gait analysis is the time required to collect and analyze the data and hence cost. By definition MFM will incorporate three or more markers per segment. These are also close to each other and therefore a bipedal MFM analysis can be more time consuming than standard lower limb gait analysis. This may explain the paucity of longitudinal analyses using MFM. Based upon a variety of recent technological advances (inertial measurement units, weight bearing computed tomography, markerless motion capture, machine learning and dynamic radiostereometric analysis) improvements are anticipated based upon current research.

In summary, it is becoming increasingly common to use MFM in clinical applications. Evidence suggests they provide adequate sensitivity for distinguishing pathological from typically developing feet, but there is limited evidence in other contexts. It is important that the model is well understood in order to generate accurate results and interpret the findings appropriately.

7. Final recommendations

Several recommendations have emerged throughout this manuscript, and these are summarized below. These add of course to standard advice recommended for all skin-marker-based motion capture analyses, such as: careful selection of the most appropriate number, location and quality of cameras, and of a suitable marker size; routine check of the set-up and calibration of the system; and optimal marker tracking and gap filling.

In the first Section, 7.1, the recommendations are primarily intended

for those wishing to use a previously published MFM, either in its original format or as a slightly modified version. The recommendations in the second Section, 7.2, are intended for those who want to design a new MFM, to address unique issues or to add original measurements not included in those MFM already provided in the literature. In Section 7.3, topics for future basic research are recommended.

7.1. Using an established MFM

a) Define a standard operating protocol, preferably in your own language, for skin marker placement, consistent with the MFM used.
b) Assess reliability of skin marker placement, in particular to establish your own intra-rater and inter-rater repeatability; this should be quantified both in normal and pathological populations analyzed.
c) Define a standard and repeatable procedure for raw data processing, including the extent of permissible gap filling, the smoothing and filtering parameters, etc.
d) Clearly report whether you refer to bony segment motion relative to a global reference system or joint motion between body segments; distinguish also between 3D joint rotations and two-dimensional projection angles.
e) For 3D joint rotations, use the terminology recommended previously in Wu et al. 2002; in any case report clearly the anatomical axes or planes your joint rotations refer to.
f) Collect a static trial in bipedal up-right posture, in the participant's natural (i.e., resting), hindfoot stance position – this serves also as a metric for the deformity based deviation from the position as in the next recommendation, which some patients cannot be placed in.
g) Collect a second static trial, when possible, when the foot is in 'subtalar neutral position' – this serves as a weight-bearing anatomical reference alignment, that the participant is placed into by the rater while in bipedal upright posture. Both of these positions can be used as off-sets for establishing an origin for the MFM kinematic graphs.
h) Determine the foot type of your cohort(s) – if all foot types are included, expect large variability in pooled analyses.
i) Compare your final kinematic results, from a single participant or a population, with corresponding results from the literature, to prescreen for isolated outliers, evident errors (e.g., signs) or aberrant biomechanics. If large differences are noted, check again carefully or else justify why these differences are seen.
j) In your final report, discuss comprehensively the issues mentioned above and specify how these may have affected your results.

7.2. Designing a novel MFM

a) Before designing a new specific MFM, consider and evaluate previous published MFM.
b) Carefully consider and report the reasons why the published MFM are not suitable for your application.
c) Define and clearly report the segments analyzed and which bones each segment represents, to ensure anatomical relevance and full clinical comprehension.
d) Use skin markers in correspondence of anatomical landmarks; avoid using clusters of markers.
e) Define skin marker positions such that: (i) there is a minimum amount of soft tissue artifact (gliding of the skin with respect to the underlying bone); ii) unwanted motion from soft pads, muscles and tendons in close proximity are avoided; iii) relevant anatomical axes or planes are represented; iv) natural execution of the motor task is possible without disturbing the participant under analysis.
f) Report precise marker locations and determine marker placer reproducibility.
g) Test the overall reliability of the MFM.

7.3. Topics requiring further investigation

a) Define new graphical representations of the kinematic measurements, toward better and quicker clinical interpretation.
b) Develop technology that can measure the deviation from a patient's specific deformity to their true anatomical neutral joint position even if they cannot be placed in that position.
c) Define composite indexes (e.g., Gait Deviation Index), to assess the quality of multi-segment foot kinematics with one or a few parameters; it is likely that these will be specific to the pathology or condition under analysis.
d) Support clinical decisions through integration of complementary types of data, combine MFM with plantar pressures, ground reaction forces, medical imaging, electromyography, 3D foot scans, etc.
e) Contribute with additional validation studies to new and published MFM.
f) Investigate the use of more appropriate kinematic description approaches (e.g., different joint conventions, Euler sequences, anatomical axes), that are explicitly more suitable for foot and ankle segments and joints.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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