Journal of Biomechanics 45 (2012) 2041–2045

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

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

Short communication

A comparison between joint coordinate system and attitude vector for multi-segment foot kinematics

H. Rouhani [a,*], J. Favre [a], X. Crevoisier [b], B.M. Jolles [b], K. Aminian [a]

[a] Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Movement Analysis and Measurement, CH-1015 Lausanne, Switzerland
[b] Centre Hospitalier Universitaire Vaudois and University of Lausanne (CHUV), Department of Orthopaedic Surgery and Traumatology, CH-1011 Lausanne, Switzerland

ARTICLE INFO

Article history:
Accepted 13 May 2012

Keywords:
Multi-segment foot and ankle complex
Sensitivity to experimental errors
Joint angle
Kinematics
Gait

ABSTRACT

The joint angles of multi-segment foot models have been primarily described using two mathematical methods: the joint coordinate system and the attitude vector. This study aimed to determine whether the angles obtained through these two descriptors are comparable, and whether these descriptors have similar sensitivity to experimental errors.

Six subjects walked eight times on an instrumented walkway while the joint angles among shank, hindfoot, medial forefoot, and lateral forefoot were measured. The angles obtained using both descriptors and their sensitivity to experimental errors were compared.

There was no overall significant difference between the ranges of motion obtained using both descriptors. However, median differences of more than 6° were noticed for the medial–lateral forefoot joint. For all joints and rotation planes, both descriptors provided highly similar angle patterns (median correlation coefficient: $R > 0.90$), except for the medial–lateral forefoot angle in the transverse plane (median $R = 0.77$). The joint coordinate system was significantly more sensitive to anatomical landmarks misplacement errors. However, the absolute differences of sensitivity were small relative to the joints ranges of motion.

In conclusion, the angles obtained using these two descriptors were not identical, but were similar for at least the shank–hindfoot and hindfoot–medial forefoot joints. Therefore, the angle comparison across descriptors is possible for these two joints. Comparison should be done more carefully for the medial–lateral forefoot joint. Moreover, despite different sensitivities to experimental errors, the effects of the experimental errors on the angles were small for both descriptors suggesting that both descriptors can be considered for multi-segment foot models.

1. Introduction

In order to analyze tridimensional (3D) rotation of a joint, a mathematical method must be chosen to express the relative orientation between the bone-embedded anatomical frames (BAFs) of the segments bounding the joint according to three angles (Cappozzo et al., 2005). Mainly, two mathematical methods (hereafter, referred as "descriptors") are used with multi-segment foot models (Arndt et al., 2007; Jenkyn and Nicol, 2007; Leardini et al., 2007; Rouhani et al., 2011), the joint coordinate system (JCS) (Grood and Suntay, 1983) and the attitude vector (AV) (Woltring, 1994). These two descriptors have been compared in terms of angle pattern, sensitivity to experimental errors, and clinical interpretability for the knee joint (Woltring, 1994; Chèze, 2000). However, there are functional differences between the multi-segment foot joints and the knee: (1) ranges of motion (ROM) are smaller for the foot joints; (2) segments considered in multi-segment foot models include several bones among which motion exists; (3) foot segments are smaller and the distances between markers are shorter; (4) foot soft tissue artifacts are different compared to soft tissue artifacts of the knee (Nester et al., 2007). These fundamental differences in kinematics and in experimental constraints for a multi-segment foot model compared to the knee challenge the validity of the conclusions obtained during previous comparison of JCS and AV, for the specific case of multi-segment foot joints. Similarly, it is not intuitive whether the results of previous analyses of sensitivity to experimental errors are applicable to multi-segment foot joints. These are key issues for the selection of a descriptor and for interpretation of multi-segment foot kinematics.

This study chose to compare the JCS and AV descriptors for multi-segment foot models using in vivo gait data. Specifically, this study evaluated whether the joint angles obtained through these descriptors are comparable (in terms of ROM and angle patterns) and assessed their sensitivity to experimental errors.

* Correspondence to: EPFL-STI-LMAM, ELH 137/Station 11, CH-1015 Lausanne, Switzerland. Tel.: +41 21 693 5675; fax: +41 21 693 6915.
E-mail addresses: hossein.rouhani@epfl.ch, horouhani@gmail.com (H. Rouhani).

0021-9290/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2012.05.018

2. Materials and methods

2.1. Experimental setup

Six healthy subjects without pathology of the lower limbs (five male; 27 ± 3 years (mean ± std); 174 ± 9 cm; 70 ± 10 kg) were enrolled in this study. Following Rouhani et al. (2011), four segments were considered in the foot and ankle complex: Shank (SH), Hindfoot (HF), Medial forefoot (MF), and Lateral forefoot (LF), and three joints were defined among them: SH–HF, HF–MF, and MF–LF. Twelve reflective markers were placed on anatomical landmarks (ALs) (Fig. 1). Subjects walked eight times at a self-selected speed on a walkway embedding a force-plate (Kistler, CH) and surrounded by six cameras (VICON, UK). Data were sampled at 200 Hz and normalized to 1–100% during stance time (derived from the force-plate). The local ethics committee approved the experimental protocol and informed consent was obtained from all subjects. The same experimental data was used in a previous study about foot modeling (Rouhani et al., 2011).

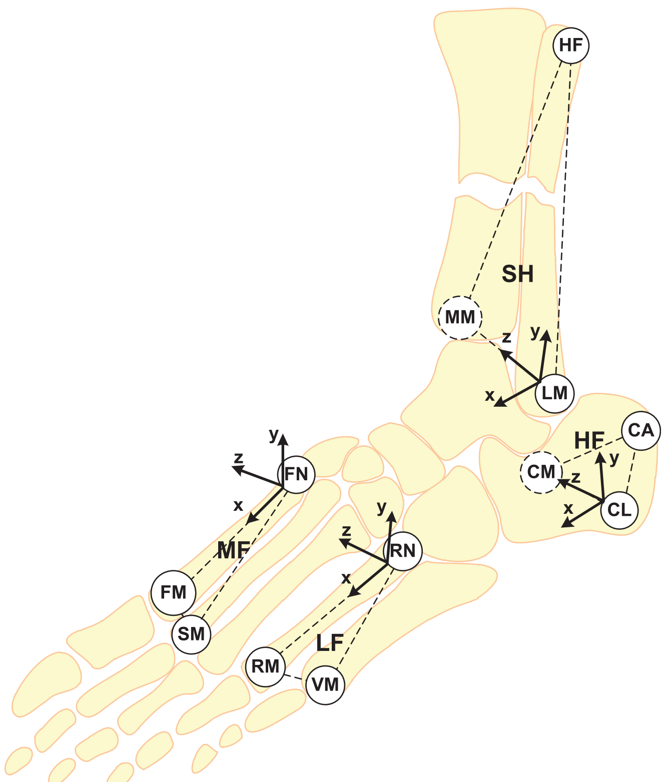

Fig. 1. Illustration of the anatomical landmarks (ALs) where the reflective markers were placed and illustration of the bone anatomical frames (BAFs). The dashed lines represent the anatomical planes upon from which the BAFs were built following the definitions in Table 1. ALs acronyms: head of fibula (HF), medial malleolus (MM), lateral malleolus (LM), great tuberosity of the calcaneus (CA), the most medial apex of the sustentaculum tali (CM), lateral apex of the peroneal tubercle (CL), most dorsal apex of the base of the 1st metatarsal (FN), most dorsal apex of the head of the 1st metatarsal (FM), most dorsal apex of the head of the 2nd metatarsal (SM), most dorsal apex of the base of the 4th metatarsal (RN), most dorsal apex of the head of the 4th metatarsal (RM), most dorsal apex of the head of the 5th metatarsal (VM).

2.2. Joint angles calculation

Like in other studies about multi-segment foot (Jenkyn and Nicol, 2007; Leardini et al., 2007), a BAF was assigned to each segment based on the ALs (Table 1 and Fig. 1). Then, for the three joints, the 3D rotation was calculated using both JCS and AV. In this study, JCS for all foot joints was implemented based on the ISB recommendation for the ankle joint (Wu et al., 2002) and corresponded to a dorsiflexion–plantarflexion around the medial–lateral axis (Z) of the proximal BAF, an internal–external rotation around the superior axis (Y) of the distal BAF, and an inversion–eversion around a floating axis ($Y \times Z$). For AV, the orientation of the distal BAF was calculated relative to the proximal BAF. Then, the calculation detailed in (Woltring, 1994) was applied to derive three angles from the relative orientation. To allow comparison between JCS and AV, the same proximal and distal BAFs were used with both descriptors.

2.3. Sensitivity to experimental errors

Simulations consisting of adding a noise representative of experimental errors to the original (measured) markers position and comparing the original and corrupted angles were done considering two types of errors: misplacement of markers on ALs and inaccuracy of the motion capture device. 3D errors with respect to the original BAF were used to model the ALs misplacement. This is because when the ALs are measured with a pointer (like in the CAST protocol (Cappozzo et al., 1995)), misplacement errors occur both parallel and perpendicular to the skin. These errors were defined relative to the corresponding segment's BAFs and were held constant with respect to the BAF throughout the entire stance phase. This is because once a marker's location is measured on a segment, it remains fixed with respect to the segment's BAF during the entire measurement trial. In accordance with Chèze (2000), the errors were assumed to be random and isotropic, with the same dispersion in three directions. Finally, following Favre et al. (2010) and based on our experiments, the ALs misplacement errors were defined as Gaussian errors with a dispersion of 6 mm in each direction. Inaccuracy of the motion capture device was modelled by Gaussian errors with a dispersion of 0.2 mm in each direction changing at each time sample. This dispersion corresponded to the precision of our experimental setup and agreed with the literature (Ehara et al., 1997). Twenty simulations were done for each trial of each subject. For each angle and trial, the difference between the original and corrupted curves was characterized by the RMS error over a trial. This resulted in 960 data points (6-subjects × 8-trials × 20-simulations) per angle. To avoid the differences due to the inter-subject variations in morphology, relative angles were considered for the RMS calculations by subtracting the mean value from each angle curve (Kadaba et al., 1989).

2.4. Statistical analyses

Joint angles were compared among descriptors in terms of pattern (curve) and ROM. To this end, first, the mean pattern and mean ROM were calculated for each

Table 1
Segments of the foot and ankle complex and their BAFs.

Segment	Included bones	Bone-embedded anatomical frame (BAF) definition
Shank	*tibia*	(a) YZ plane is formed by (HF), (LM) and (MM). (b) Z axis is from (LM) toward (MM) medially. (c) X axis is directed anteriorly and Y axis is directed proximally.
Hindfoot	*calcaneus, talus*	(a) XZ plane is formed by (CA), (CL) and (CM). (b) Z axis is from (CL) toward (CM) medially. (c) X axis is directed anteriorly and Y axis is directed proximally.
Medial forefoot	*navicular, cuneiforms, 1st to 3rd metatarsals*	(a) XZ plane is formed by (FN), (FM) and (SM). (b) X axis is from (FN) toward (FM) anteriorly. (c) Y axis is directed proximally and Z axis is directed medially.
Lateral forefoot	*cuboid, 4th and 5th metatarsals*	(a) XZ plane is formed by (RN), (RM) and (VM). (b) X axis is from (RN) toward (RM) anteriorly. (c) Y axis is directed proximally and Z axis is directed medially.