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 $\pm$ 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).

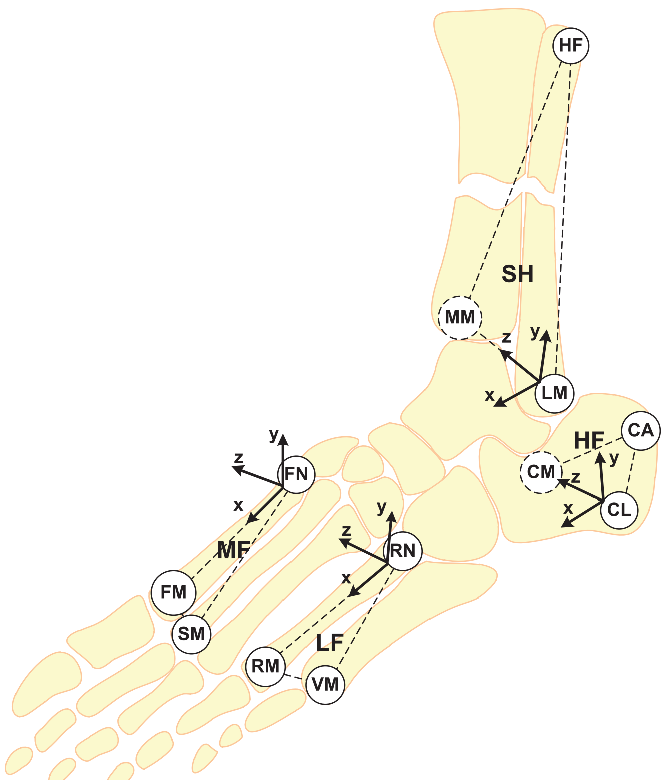

Fig. 1. Illustration of the anatomical landmarks (ALs) where the reflective markers were placed and illustration of the bone anatomical frames (BAFs). The dashed lines represent the anatomical planes upon from which the BAFs were built following the definitions in Table 1. ALs acronyms: head of fibula (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 $\times$ 8-trials $\times$ 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.

subject considering their eight trials. To compare the patterns, the Pearson's correlation coefficients (R) were calculated to investigate the linear relationship (as a measure of similarity) between the angles obtained through JCS and AV for each subject, joint, and rotation plane. Since only two curves were compared each time, multiple correlations analysis was not required. To compare the ROMs, a linear mixed-effects model (Pinheiro and Bates, 2000) was built using three factors which could potentially influence the ROM: the joints (SH–HF, HF–MF, and MF–LF), the rotation planes (sagittal, coronal, and transverse), and the descriptors (JCS and AV). After fitting the model to the mean ROM data points and estimating the unknown coefficients, the influence of the descriptor on the response (ROM) was assessed by testing the hypothesis of zero value for the coefficients representing this factor. In this study, linear mixed-effects models were used, because they are more general and flexible than repeated-measure statistics. Additionally, as another measure for similarity of ROMs, the correlation coefficient between the ROMs of each joint obtained through JCS and AV (for all subjects and in all rotation planes) was calculated.

To compare the sensitivity to experimental errors between descriptors, linear mixed-effects models, as previously described, were fitted to the simulation results (RMS). This analysis was done separately for each error type. A significance level of p-value < 0.05 was considered for all pair-wise comparisons.

3. Results

In general, the average angles over all trials of all subjects obtained using JCS and AV were similar and they even were almost identical for SH–HF and HF–MF (Fig. 2). This observation was maintained at the subject level since the median correlation coefficients (R) were higher than 0.9 for all joints and all rotation planes, except for the MF–LF transverse angle where it was 0.77 (Table 2).

No significant difference was observed between the ROMs obtained through JCS and AV when the ROMs of all subjects, joints and rotation planes were entered in the linear mixed-effects model ($p > 0.23$). When the differences between the ROMs obtained through JCS and AV were analyzed separately for each joint and rotation plane, the median and quartiles of the paired differences were below 3.2° and 3.8° (absolute values) for all joints and rotation planes except for the MF–LF sagittal and transverse angles where they were above 6.0° and 9.0°, respectively. The correlation coefficient between ROMs obtained through JCS and AV were 0.97, 0.92, and 0.45 for SH–HF, HF–MF, and MF–LF joints, respectively.

JCS showed significantly higher sensitivity to ALs misplacement errors than AV ($p < 0.001$), whereas no significant difference was observed between descriptors regarding the inaccuracy of the motion capture device ($p > 0.10$) (Table 3).

4. Discussion

Despite theoretical differences between JCS and AV, these descriptors may provide similar joints angles for the multi-segment foot during gait due to the joints small rotation. This would support researchers in the decision to compare results reported in different studies using these descriptors. Furthermore, the sensitivity to experimental errors is currently unknown for

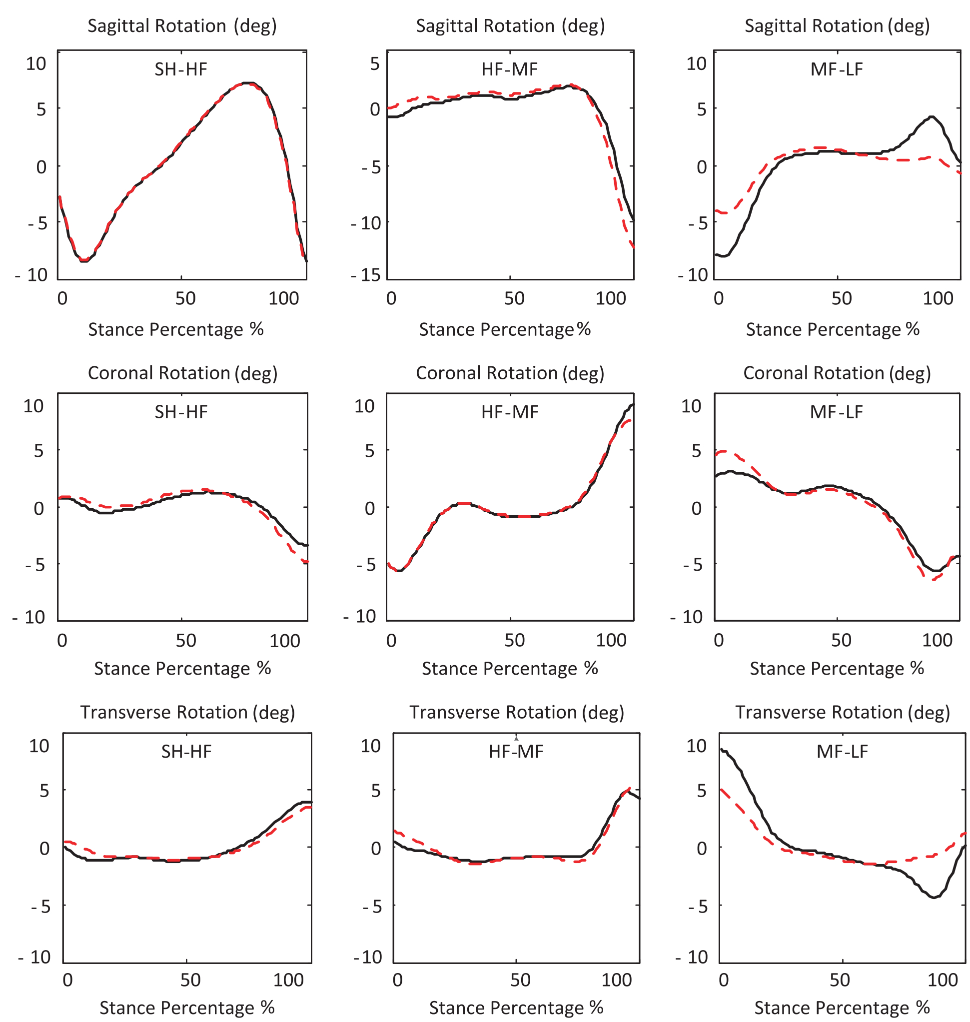

Fig. 2. Relative angle curves obtained through JCS (solid black) and AV (dashed red) for the SH–HF, HF–MF, and MF–LF joints in the sagittal, coronal, and transverse planes. The averaged curves over all trials of all subjects are presented. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
ROMs obtained through JCS and AV in the sagittal, coronal, and transverse planes for the SH–HF, HF–MF, and MF–LF joints. Median [1st quartile; 3rd quartile] values are presented over ROMs of six subjects. Differences between ROMs (ΔROM) obtained through JCS and AV for each subject are also presented. Correlation coefficients between angle patterns obtained through JCS and AV are similarly presented.

Joint	Rotation plane	ROM			Curve
		Amplitude		ΔROM	*R*
		JCS	AV	(JCS—AV)	JCS ~ AV
SH–HF	**Sagittal**	18.2[15.0;18.7]	17.9[16.0;18.7]	0.0[−0.2;0.1]	1.00[1.00;1.00]
	Coronal	5.5[4.0;7.3]	6.8[6.2;8.3]	−1.1[−2.2;−0.5]	0.97[0.93;0.99]
	Transverse	5.6[3.7;6.6]	4.3[3.8;5.4]	1.2[0.9; 1.3]	0.94[0.91;0.96]
HF–MF	**Sagittal**	12.0[10.0;15.8]	14.2[13.4;19.8]	−3.2[−3.8;−1.2]	0.97[0.96;0.98]
	Coronal	16.2[11.6;19.8]	13.4[10.3;20.2]	1.3[−0.2;2.2]	0.99[0.98;0.99]
	Transverse	6.6[3.6;11.5]	6.2[5.1;10.6]	−0.9[−2.3; 1.8]	0.91[0.85;0.97]
MF–LF	**Sagittal**	15.1[10.2;17.5]	7.5[6.4;8.3]	6.1[2.9; 9.2]	0.95[0.92;0.96]
	Coronal	9.4[7.4;16.4]	10.9[9.6;18.1]	−1.3[−1.7;−0.5]	0.97[0.91;0.99]
	Transverse	14.3[7.6;18.2]	8.0[6.0;9.5]	6.3[1.7; 8.7]	0.78[0.72;0.89]

Table 3
Sensitivity of the joint angles to ALs misplacement error and inaccuracy of the motion capture device expressed as RMS errors in degree. Statistical comparisons for sensitivity to ALs misplacement indicated the following significant differences: (1) JCS was more sensitive than AV ($p < 0.001$), (2) Coronal rotations were more sensitive than sagittal rotations ($p < 0.005$), (3) MF–LF joint angles was more sensitive than SH–HF and HF–MF joints angles (all $p < 0.001$). Statistical comparisons for sensitivity to inaccuracy of the motion capture device indicated the following significant difference: (1) Sagittal rotations were more sensitive than coronal and transverse rotations (all $p < 0.001$).

Error type	Rotation plane	Joint coordinate system (JCS)			Attitude vector (AV)		
		SH–HF	HF–MF	MF–LF	SH–HF	HF–MF	MF–LF
ALs misplacement	**Sagittal**	1.5	1.5	2.8	1.2	1.2	0.9
	Coronal	1.1	0.7	1.7	0.8	0.9	1.4
	Transverse	1.2	1.0	2.7	0.8	1.0	0.8
Inaccuracy of the motion capture device	**Sagittal**	0.5	0.4	0.4	0.5	0.4	0.2
	Coronal	0.2	0.3	0.3	0.2	0.3	0.4
	Transverse	0.2	0.3	0.4	0.2	0.3	0.2

multi-segment foot joints whose angle patterns during gait are different from knee and hip joints. This study aimed to experimentally determine whether the angles obtained through these descriptors are comparable and to analyze their sensitivity to experimental errors for multi-segment foot.

The 1st–3rd quartile interval of the difference between the ROMs obtained through JCS and AV for some joint angles did not include zero (Table 2). This confirmed that the angles obtained through these descriptors are not totally equivalent and thus are not systematically interchangeable. Nevertheless, the ROMs obtained through JCS and AV were not significantly different over all subject, joints, and rotation planes, and strong similarities were observed between JCS and AV in terms of angle patterns (median, 1st, and 3rd quartiles of *R*: 0.97, 0.90, and 0.99, over all joints and rotation planes). Besides, ROMs obtained through JCS and AV for SH–HF and HF–MF in all rotation planes showed high correlations ($R = 0.97$ and 0.92). Together, these results suggest that the angles of SH–HF and HF–MF obtained through JCS and AV can be compared. However, comparison between MF–LF angles obtained through JCS and AV should be treated cautiously due to the larger ROM differences (Table 2), the reduced pattern similarity particularly in the sagittal and transverse planes (Fig. 2), and smaller correlation between ROMs. Although these results of partial equivalence between JCS and AV agree with the theoretical definition of the descriptors and with previous comparative publications (Woltring, 1994; Chèze, 2000), only an experimental study could determine the actual level of similarity/dissimilarity between descriptors for multi-segment foot joints. Therefore, the results presented here are essential to determine which angles can be compared between studies that used different descriptors.

JCS reported a significantly higher sensitivity to ALs misplacement than AV, mainly for MF–LF. This agrees with previous observation of higher sensitivity to experimental errors for JCS at the knee (Woltring, 1994; Chèze, 2000). Although significant, the differences between descriptors were small, especially when related to their ROMs. Therefore, this higher sensitivity cannot categorically exclude the use of JCS in favor of AV for foot joints. This study also provided the first characterization of the sensitivity to experimental errors for a multi-segment foot model. This characterization is critical for any interpretation of kinematics data (Della Croce et al., 1999; Favre et al., 2010).

The number of subjects enrolled in this study was relatively small. However, this should have a limited effect on the analyses since the subjects were used as their own controls. Moreover, the ROMs and patterns reported here agree with literature (Carson et al., 2001; Jenkyn and Nicol, 2007; Leardini et al., 2007). Although similar conclusions are expected for pathological gait or other activities, these cases were not considered here.

5. Conclusion

Based on the results, it was concluded that qualitative comparisons can be done across descriptors for the shank–hindfoot and hindfoot–medial forefoot joints. However, the comparison should be interpreted carefully for the medial–lateral forefoot joint. Additionally, although JCS has higher sensitivity to experimental errors than AV, their differences were small compared to the ROMs and thus the use of both descriptors can be considered for multi-segment foot models.

Conflict of interest statement

None.

Acknowledgment

The work was supported by "Fonds National Suisse de la Recherche Scientifique", Grant No. 3200B0-120422/1. The authors also thank Dr. Mehdi Gholamrezaee for his advice in statistics.

References

Arndt, A., Wolf, P., Liu, A., Nester, C., Stacoff, A., Jones, R., Lundgren, P., Lundberg, A., 2007. Intrinsic foot kinematics measured in vivo during the stance phase of slow running. Journal of Biomechanics 40, 2672–2678.

Cappozzo, A., Catani, F., Della Croce, U., Leardini, A., 1995. Position and orientation in space of bones during movement: anatomical frame definition and determination. Clinical Biomechanics 10, 171–178.

Cappozzo, A., Della Croce, U., Leardini, A., Chiari, L., 2005. Human movement analysis using stereophotogrammetry: part 1: theoretical background 21, 186–196Gait and Posture 21, 186–196.

Carson, M.C., Harrington, M.E., Thompson, N., O'Connor, J.J., Theologis, T.N., 2001. Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis. Journal of Biomechanics 34, 1299–1307.

Chèze, L., 2000. Comparison of different calculations of three-dimensional joint kinematics from video-based system data. Journal of Biomechanics 33, 1695–1699.

Della Croce, U., Cappozzo, A., Kerrigan, D., 1999. Pelvis and lower limb anatomical landmark calibration precision and its propagation to bone geometry and joint angles. Medical and Biological Engineering and Computing 37, 155–161.

Ehara, Y., Fujimoto, H., Miyazaki, S., Mochimaru, M., Tanaka, S., Yamamoto, S., 1997. Comparison of the performance of 3D camera systems II. Gait and Posture 5, 251–255.

Favre, J., Crevoisier, X., Jolles, B.M., Aminian, K., 2010. Evaluation of a mixed approach combining stationary and wearable systems to monitor gait over long distance. Journal of Biomechanics 43, 2196–2202.

Grood, E.S., Suntay, W.J., 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. Journal of Biomechanical Engineering 105, 136–144.

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. Journal of Biomechanics 40, 3271–3278.

Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., Gainey, J., Gorton, G., Cochran, G.V.B., 1989. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. Journal of Orthopaedic Research 7, 849–860.

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 and Posture 25, 453–462.

Nester, C., Jones, R.K., Liu, A., Howard, D., Lundberg, A., Arndt, A., Lundgren, P., Stacoff, A., Wolf, P., 2007. Foot kinematics during walking measured using bone and surface mounted markers. Journal of Biomechanics 40, 3412–3423.

Pinheiro, J.C., Bates, D.M., 2000. Mixed-Effects Models in S and S-PLUS. Springer-Verlag, New York, pp. 3–52.

Rouhani, H., Favre, J., Crevoisier, X., Jolles, B.M., Aminian, K., 2011. Segmentation of foot and ankle complex based on kinematic criteria. Computer Methods in Biomechanics and Biomedical Engineering 14, 773–781.

Woltring, H.J., 1994. 3-D attitude representation of human joints: a standardization proposal. Journal of Biomechanics 27, 1399–1414.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D.D., Cristofolini, L., Witte, H., Schmid, O., Stokes, I., 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. Journal of Biomechanics 35, 543–548.