

The Use of the Dual Euler Angles for Describing Passive Motion Characteristics of the Ankle-Subtalar Joint

Ying Ning *MS, PhD*, Kim Wangdo *MS, PhD*, Wong Yueshuen *FRCGS (Edin), MSc*,¹ Kam Boon Horng *BSc, MEng*²

School of Mechanical and Production Engineering, Nanyang Technological University, Singapore

¹Department of Orthopaedic Surgery, Alexandra Hospital, Singapore

²Department of Experimental Surgery, SGH

ABSTRACT

Background. The objective of this study was to apply the dual Euler angles method to investigate the passive motion characteristics of the human ankle joint complex. Besides the Euler angles and screw axis methods, the dual Euler angles method has been proposed as an alternative approach to quantify general spatial human joint motion. The dual Euler angles method provides a way to combine rotational and translational joint motions and to interpret motions in Cartesian coordinate systems, which can avoid the problems caused by the use of the joint coordinate system due to non-orthogonality.

Methods. Three-dimensional kinematic data of the ankle joint complex was collected from 10 knee-below foot cadaver specimens. A non-metal experimental setup was fabricated to generate motion in foot cadaver specimens. The kinematic data during passive dorsiflexion-plantarflexion was measured using a “Flock of Birds” electromagnetic tracking device.

Results. The kinematic coupling characteristics and the respective contribution of the ankle joint and the subtalar joint to the gross motion of the foot with respect to the shank were analysed based on dual Euler angle parameters. The results obtained in this study were generally in agreement with the observations reported previously.

Conclusion. The dual Euler angles method was suitable for analysing the motion characteristics of the ankle joint complex. The motion at the ankle joint complex involves rotations about and translations along three axes. Our study showed that the dual Euler angle methods allows precise identification of the respective contributions of the subtalar joint and the ankle joint during the motion of the ankle joint complex as a whole.

Keywords: ankle joint complex, dual Euler angles, Flock of Birds, kinematics

INTRODUCTION

The ankle joint complex consists of the ankle (talocrural) joint and the subtalar (talocalcaneal) joint. The gross motion between the foot and the shank is the result of the motions at the ankle joint complex. Because the ankle joint complex is crucial to human locomotion, accurate knowledge on the kinematics of these joints is essential for the proper diagnosis and treatment of injuries and diseases in this region, and for the design of effective and reliable prosthetic devices.

Numerous investigations have been carried out to analyse the kinematic characteristics of the ankle joint complex *in vitro* or *in vivo*.¹⁻⁸ In previous studies, the Euler angles and screw axis methods were two widely used methods to represent ankle joint complex motions quantitatively.⁹⁻¹¹ Each method has its advantages and disadvantages. The screw axis method is not comparable with clinical motion description and does not facilitate communication between engineers and clinicians, though it can describe full six-degree-of-freedom joint motions. Euler angles can only describe the rotation of a segment and an additional three-dimensional position vector is required to describe the

translation. The position vector is referred with respect to the coordinate system of the fixed segment while the Euler angles are usually referred with respect to the coordinate system of the moving segment. The difference of the reference systems for rotation and translation does not facilitate the interpretation of the parameters. As a variation of the Euler angles method, Grood *et al* proposed a non-orthogonal joint coordinate system (JCS) to avoid some of the difficulties inherent in the use of Euler angles.¹² Though JCS combines rotation and translation, it is not orthogonal. Non-orthogonality presents a serious problem when joint forces and moments need to be determined.¹³

As an alternative method for quantifying general spatial human joint motions, the dual Euler angles method has been proposed and applied to study the gross motion between the foot and the shank *in vivo* by Ying *et al*.¹⁴ In this method, the gross motion of the foot relative to the shank is represented by three screw motions through the coordinate axes of the Cartesian coordinate system fixed in the foot. In this way, the rotation and translation of the foot are combined and interpreted with respect to the same Cartesian coordinate system. Moreover, the dual Euler angles method has an advantage over JCS because of its orthogonality.

Because tracking the motion of the talus using non-invasive *in vivo* techniques is not possible, the respective contributions of the ankle joint and the subtalar joint to the gross motion between the foot and the shank cannot be determined. Studies by Siegler *et al* have indicated that the gross motion between the foot and the shank is the result of motion at both the ankle joint and the subtalar joint.² In this study, based on the kinematic data collected from a total of ten foot cadaver specimens, the respective motions at the ankle joint and the subtalar joint and their contribution to the gross motion produced between the foot and the shank were analysed using dual Euler angle parameters.

METHODS

Measurement Device and Experimental Setup

The passive motion at the ankle joint complex was measured using the “Flock of Birds” (FOB) electromagnetic tracking system (Ascension Technology Inc, Burlington, Vermont, USA). The tracking system, consisting of four receivers and one standard range transmitter, was set at its default configuration (103Hz, AC wide filter on, DC low pass filter on) during the measurements. Three of the four receivers were used to measure the position and

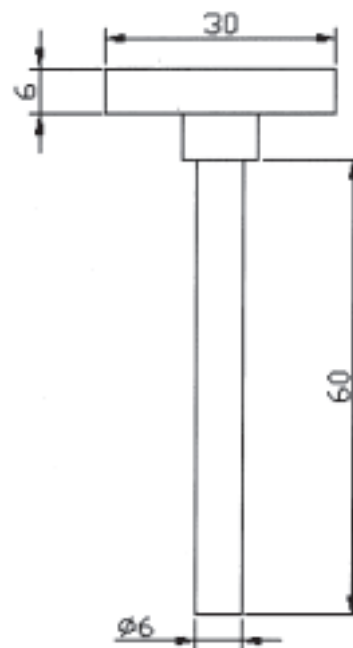


Fig. 1. Fixture for installing a receiver into a bone (unit: mm).

orientation of the bones while one was fixed on a stylus to digitise the position of points of interest. The accuracy of the measurement system has previously been reported by various authors.¹⁵⁻¹⁷ In the authors' previous work, the accuracy of dual angles obtained from the FOB system was also evaluated to be less than 1° and 1mm for rotations and translations, respectively.¹⁴

To install the receivers into the bones rigidly, receiver fixtures were fabricated (Fig. 1). Each receiver fixture consists of an acrylic square plate, which was used for attachment of a receiver, and a plastic screw, which was used for insertion into a bone. The square plate and the screw were glued together tightly.

An experimental setup made of non-metal materials was used to generate passive motion to the shank/foot cadaver specimens (Fig. 2). This is similar to the design of Stähelin *et al*.³ The foot plate, which was secured on the supporting bracket via a vertical screw in the bracket, was able to rotate around a horizontal axis in the supporting bracket. The supporting bracket could be secured on the ground plate in any direction by a vertical screw in the ground plate. By changing the direction of the foot plate with respect to its supporting bracket and the direction of the supporting bracket with respect to the ground plate, the foot plate could be placed at any orientation with respect to the ground plate to introduce different angular movements to the foot. The shank rod passed through a hole in the

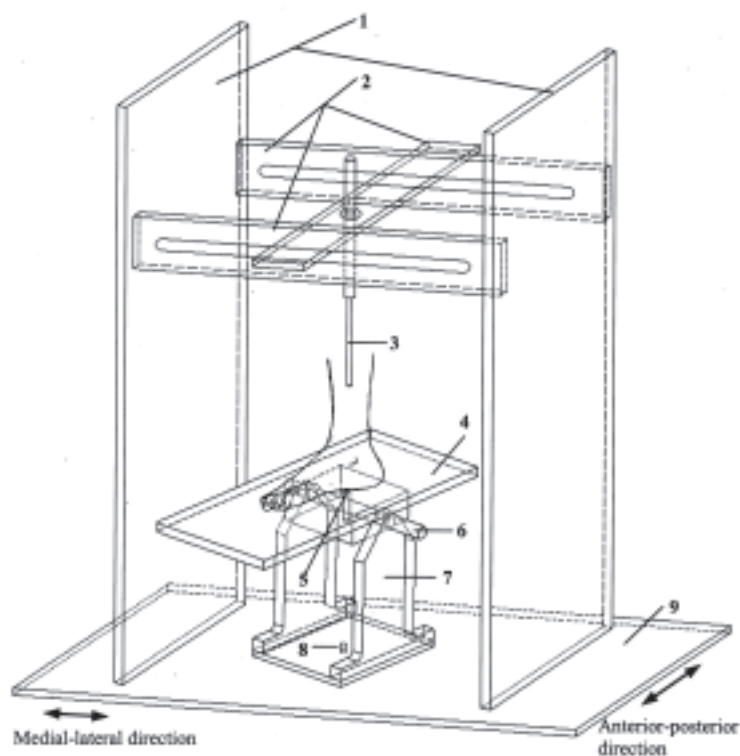


Fig. 2. Experimental set-up for *in vitro* experiments on foot/shank specimens.

Legends

- 1: Vertical stands
- 2: Beams supporting shank rod
- 3: Shank rod
- 4: Foot plate
- 5: Screw securing foot plate on supporting bracket
- 6: Horizontal axis of the foot plate
- 7: Supporting bracket
- 8: Screw securing supporting bracket on ground plate
- 9: Ground plate

horizontal beam, which was in the anterior-posterior direction. The diameter of the hole was larger than that of the shank rod so that the shank rod could move and rotate in the hole. The position of the shank rod in the horizontal plane can be adjusted by moving the anterior-posterior beam in the horizontal plane. Vertically, the distance of the horizontal beams to the ground plate could also be adjusted to adapt to the heights of cadaver specimens.

Experiment Procedure

The passive dorsiflexion-plantarflexion was measured without considering weight and muscle forces. Ten below-knee amputation cadaver specimens were tested.

Prior to the experiment, specimens were thawed for 24 hours at room temperature. At the time of the testing, specimens were prepared as described below. A hole of 9mm diameter, a little smaller than the diameter of the lower part of the shank rod, was drilled along the medullary channel to allow insertion of the shank rod. Specimens were dissected carefully to remove soft tissue around the ankle joint complex while the ligamentous system remained intact. The soft tissue at the head of the fibula and the tibia tuberosity was also removed. Four landmarks for definition of the tibia-fibula anatomical coordinate system were identified and marked for digitisation — the distal apex

of the medial and lateral malleolus (MM, LM), the apex head of the fibula (HF), and the prominence of the tibia tuberosity (TT). The screws of the receiver fixtures were inserted into the tibia, talus, and calcaneus respectively: the screw in the distal part of the tibia was inserted anteriorly and medially; the one into the talus at the anteromedial aspect of the neck, and that in the calcaneus at the lateral side of the heel.

The experimental setup was adjusted as follows. The bracket supporting the foot plate was aligned and secured on the ground plate with the horizontal axis in the medial-lateral direction. The foot plate was then secured on the supporting bracket with its longitudinal axis in the anterior-posterior direction. After the setup had been adjusted to the appropriate position, the specimen with three receivers attached was mounted to the setup. The foot was fixed on the foot plate in the anterior-posterior direction and the ankle axis was approximately parallel to the horizontal axis. The shank rod was then inserted into the medullary channel. The position of the anterior-posterior beam in the horizontal plane was adjusted to align the shank rod along with the longitudinal axis of the tibia in a vertical position, that is, perpendicular to the foot. This position was considered as the neutral position, with respect to which the motion of the joints would be described. The foot plate was placed horizontally, so as to have the foot in a plantigrade and neutral position.

The foot was not rigidly locked in place. The foot was placed on the foot plate and the forefoot strapped down with a low-tension elastic strap. The foot was allowed to deform freely on the foot plate. The shank rod was threaded through a small hole in the jig about 1 meter above the foot plate. The hole was roughly half a centimeter greater in size than the diameter of the rod, allowing it to rotate freely, and also allowing more than sufficient degree of angular deflection.

At the neutral position, each of the four landmarks was digitised. At this joint configuration, the position and orientation of the receivers attached to the bones were also recorded. After collecting the required data at the neutral position, the position and orientation of the receivers were recorded continuously while the foot plate was rotated manually and slowly from maximum dorsiflexion of the specimen to maximum plantarflexion.

Data Analysis

To describe the passive motions at the ankle joint complex, the anatomical coordinate system of the tibia proposed by Cappozzo *et al* is used.¹⁸ This system is based on the four landmarks on the shank — MM, LM, HF, and TT. The coordinate system of the tibia is defined as:

1. Origin is at the midpoint of the line joining MM and LM
2. Y-axis is orthogonal to the quasi-frontal plane defined by MM, LM, and HF
3. Z-axis is orthogonal to the quasi-sagittal plane defined by the Y-axis and TT
4. X-axis is the cross product of the Y- and Z-axis

At the neutral position, the coordinate systems of the talus and the calcaneus coincide with that of the tibia in both origin and the direction of axes. Figure 3 schematically shows the coordinate systems used for analysing passive motions of the ankle joint complex.

The relative motion of the calcaneus with respect to the tibia, that is, the gross motion of the foot with respect to the shank; the relative motion of the talus with respect to the tibia, that is, the motion at the ankle joint; and the relative motion of the calcaneus with respect to the talus, that is, the motion at the subtalar joint, were obtained by using the dual Euler angles method. The sequence of screw motions selected began through the z-axis, then through the y'-axis, and finally through the x''-axis of the moving coordinate systems. According to the definition of the coordinate

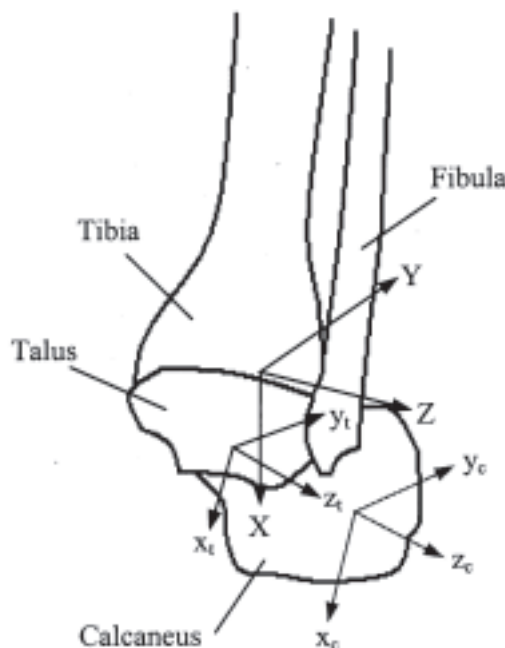


Fig. 3. Coordinate systems for analysing passive motions of ankle joint complex (X-Y-Z: coordinate system of the tibia; x_t-y_t-z_t: coordinate system of the talus; x_c-y_c-z_c: coordinate system of the calcaneus).

systems along with the sequence of screw motions adopted in this study, the screw motion through the z-axis could be considered as the flexion-extension and lateral-medial shift of the bones. Similarly, the screw motion through the y'-axis reflected the inversion-eversion and anteroposterior drawer of the bones. Finally, the screw motion through the x''-axis could be interpreted as the abduction-adduction rotation and distraction-compression of the bones.

Though dual Euler angles can be obtained based on point coordinates,¹⁴ the method suitable for using raw data collected from the FOB is provided as follows. First, using the data measured by the FOB system, at any joint configuration, the position vector **d_b** and rotation matrix **[R_b]** of a bone relative to the global coordinate system fixed in the transmitter are computed as

$$[R_b] = [r_{c'}^N]^T [r_{c'}^T] [R_{c'}] \tag{1}$$

$$d_b = d_{c'} - [R_b] [r_{c'}^T]^T (d_{c'}^N - d_{c'}^T)$$

where

[R_b^N] and **d_b^N** are the rotation matrix and position vector of the bone with respect to the global coordinate system when the joint complex is at the neutral position.

[R_{s-b}^N] and **d_{s-b}^N** are the rotation matrix and position vector of the receiver on the bone with respect to the

global coordinate system when the joint complex is at the neutral position.

$[R_{s,b}]$ and $\mathbf{d}_{s,b}$ are the rotation matrix and position vector of the receiver on the bone with respect to the global coordinate system when the joint complex is at any joint position.

Let $[R_T]$ and \mathbf{d}_T denote the rotation matrix and position vector of the tibia with respect to the global coordinate system. $[R_{Ta}]$ and \mathbf{d}_{Ta} represent the rotation matrix and position vector of the talus, respectively, with respect to the global coordinate system respectively. At any joint position, the dual-number transformation matrix of the talus with respect to the tibia ${}^T\hat{R}_{Ta}$ is given as:

$${}^T\hat{R}_{Ta} = [{}^T R_{Ta}] + \varepsilon [{}^T S_{Ta}] \quad (2)$$

$$= ([R_T]^{-1} [R_{Ta}]) + \varepsilon ([D_{Ta}] [R_T]^{-1} [\mathbf{d}_{Ta}])$$

where

${}^T R_{Ta}$ and ${}^T S_{Ta}$ are the primary and dual parts, respectively, of the dual-number transformation matrix of the talus relative to the tibia.

$[R_T]$ and $[R_{Ta}]$ are the rotation matrix of the tibia and the talus, respectively, with respect to the global coordinate system.

$$[D_{Ta}] = \begin{bmatrix} 0 & -d_3 & d_2 \\ d_3 & 0 & -d_1 \\ -d_2 & d_1 & 0 \end{bmatrix}$$

is a skew symmetric matrix given by

$$\{d_1 \quad d_2 \quad d_3\}^T = [R_T]^{-1} (\mathbf{d}_{Ta} - \mathbf{d}_T)$$

At the same joint position, the dual-number transformation matrix of the calcaneus with respect to the tibia ${}^T\hat{R}_{Ca}$ can be similarly calculated. Subsequently, at any joint configuration, the dual-number transformation matrix of the calcaneus with respect to the talus ${}^{Ta}\hat{R}_{Ca}$ was computed according to the following equation:

$${}^{Ta}\hat{R}_{Ca} = [{}^{Ta}\hat{R}_{Ta}]^{-1} [{}^T\hat{R}_{Ca}] \quad (3)$$

Once the dual-number transformation matrices were obtained, the dual Euler angles were computed according to the relationship between the dual-number transformation matrix and dual Euler angles.¹⁴ Before computing dual-number transformation matrices, the raw data obtained from the FOB were smoothed using the dynamic programming and generalised cross-validation method to reduce the noise as originally proposed by Dohrmann *et al.*¹⁹

RESULTS

Figures 4 and 5 show the relative motion of the calcaneus and the talus with respect to the tibia during dorsiflexion-plantarflexion. The relative motion of the calcaneus with respect to the talus is shown in Figure 6. The dual Euler angle parameters are plotted against the primary motion, that is, the flexion-extension angle of the foot relative to the shank, which is the rotation angle about the z-axis of the calcaneus with respect to the tibia.

To analyse the kinematic coupling characteristics and the respective contributions of the ankle and subtalar joints to the gross motion of the foot, the average dual Euler angles of the ten specimens at the maximum range of dorsiflexion-plantarflexion were obtained. The results showed that during dorsiflexion-plantarflexion, at maximum plantarflexion of the foot, 29.2° of plantarflexion of the calcaneus with respect to the tibia was associated with 27° of plantarflexion at the ankle joint and with 2.1° of plantarflexion at the subtalar joint. At maximum of dorsiflexion of the foot, 18.6° of dorsiflexion of the calcaneus relative to the tibia was associated with 19.1° of dorsiflexion at the ankle joint and with 0.6° plantarflexion at the subtalar joint.

When the foot was moved from the neutral position to maximum plantarflexion, plantarflexion of the foot was coupled with about 3.7° of inversion and 5.8° of adduction. Besides rotations, the foot also moved about 0.7mm in a lateral direction, about 7.5mm in an anterior direction, and about 4.4mm in a proximal direction. At the ankle joint, besides plantarflexion of about 27°, there was about 1.9° of inversion, 3.2° of adduction, 0.3mm of lateral shift, 6.2mm of anterior drawer, and 5.3mm of compression simultaneously. At the subtalar joint, besides 2.1° of plantarflexion, the calcaneus also underwent about 1.9° of inversion, 2.5° of adduction, 0.9mm of lateral shift, 1.4mm of anterior drawer, and 1mm of distal translation.

When the foot was moved from the neutral position to maximum dorsiflexion, the dorsiflexion of the foot was coupled with about 2.5° of eversion and about 4.5° of abduction (Table 1). Meanwhile, the foot also moved about 0.7mm in a medial direction, about 4.9mm in a posterior direction, and about 1.2mm in a distal direction. At the ankle joint, with respect to the tibia, besides the dorsiflexion of about 19.1°, the talus also everted about 2°, abducted about 4.3°, and translated in the medial, posterior, and distal direction about 0.6mm, 5.8mm, and 1.6mm, respectively. At the subtalar joint, though both rotation and translation occurred as well, the values were relatively small.

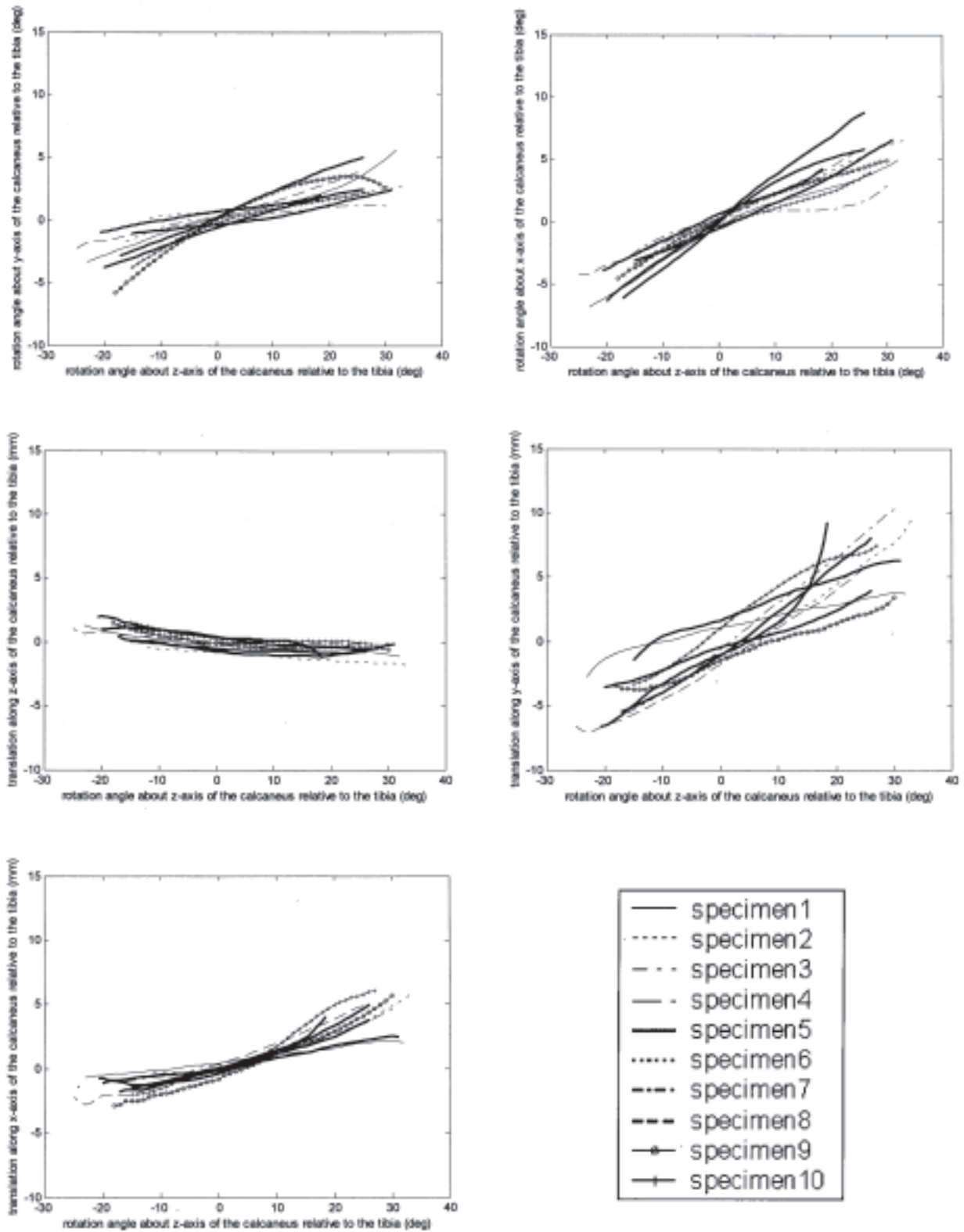


Fig. 4. Relative motion of the calcaneus with respect to the tibia during the dorsiflexion-plantarflexion.

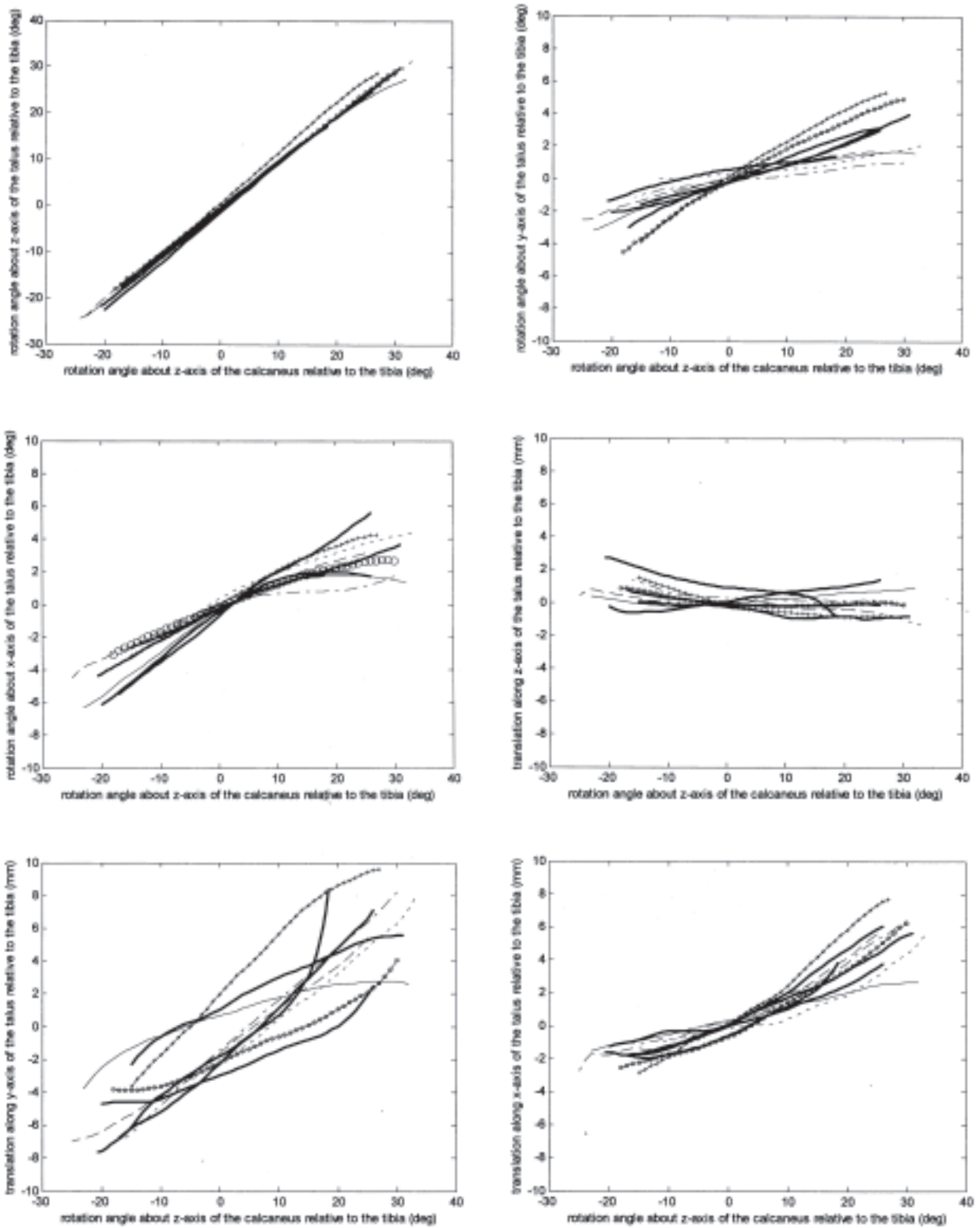


Fig. 5. Relative motion of the talus with respect to the tibia during the dorsiflexion-plantarflexion.

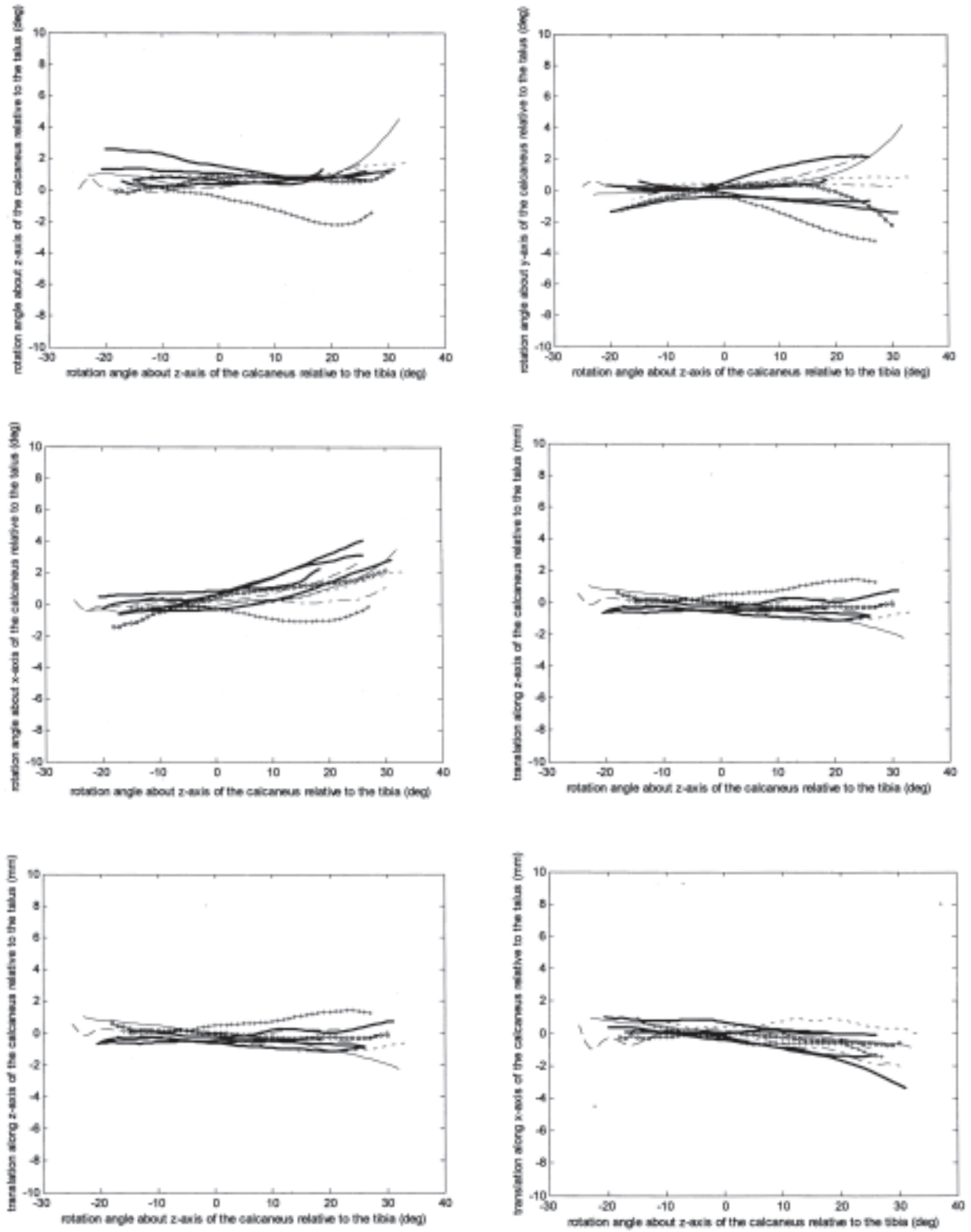


Fig. 6. Relative motion of the calcaneus with respect to the talus during the dorsiflexion-plantarflexion.

Table 1. Average motions at the ankle joint complex.

		Rotation (°)*			Translation (mm)**		
		About z-axis	About y-axis	About x-axis	Along z-axis	Along y-axis	Along x-axis
Plantarflexion	Gross motion of the foot	29.2	3.69	5.77	-0.74	7.45	4.41
	Motion at the ankle joint	27.01	1.86	3.23	-0.30	6.22	5.25
	Motion at the subtalar joint	2.09	1.92	2.48	-0.86	1.38	-1.03
Dorsiflexion	Gross motion of the foot	-18.6	-2.45	-4.54	0.71	-4.94	-1.16
	Motion at the ankle joint	-19.12	-1.96	-4.33	0.62	-5.78	-1.60
	Motion at the subtalar joint	0.64	0.06	-0.25	0.12	0.69	0.50
Inversion	Gross motion of the foot	2.72	10.0	8.11	-2.74	3.88	-1.61
	Motion at the ankle joint	-4.40	2.16	0.28	-1.79	0.66	-1.78
	Motion at the subtalar joint	7.11	7.88	7.55	-0.79	3.01	-0.64
Eversion	Gross motion of the foot	-1.80	-4.5	-2.12	2.93	-1.10	-0.83
	Motion at the ankle joint	0.66	-0.66	-1.32	0.82	-0.48	0.70
	Motion at the subtalar joint	-2.52	-3.81	-1.5	2.15	-0.67	-1.57

* Rotations: plantarflexion, inversion, and internal rotation are positive

** Translations: anterior drawer, medial shift, and compress are positive

DISCUSSION

In the past, a lot of effort had been devoted to analysing the motion characteristics of the ankle joint and the subtalar joint and their contribution to the gross motion between the foot and the shank. Researchers such as Sammarco *et al*, Engsborg, Siegler *et al* and Lundberg *et al* had questioned the view held by Hicks, Isman and Inman that the ankle and subtalar joints are uniaxial, ideal hinge joints.^{1,2,20-24} During dorsiflexion-plantarflexion, both the ankle joint and the subtalar joint rotate about and translate along the three axes simultaneously (Figs. 4 to 6). The kinematic results from this *in vitro* study indicate that both the ankle joint and the subtalar joint have six-degree-of-freedom and their motions demonstrate multiaxial motion characteristics, which is in agreement with what has been reported by Engsborg *et al*.¹

Manter modelled the subtalar joint as a spiral of Archimedes in 1941.²⁵ The results from this study showed that the pitches of the screw motions through the three axes varied during the movements and could not be fitted linearly, which meant that it might not be accurate enough to model the subtalar joint as a screw with a fixed pitch and rotation axis when detailed motion characteristics of the joint was required.

The results also indicated that movements of dorsiflexion-plantarflexion of the foot resulted from a combination of both the motions at the ankle joint and the subtalar joint. However, during dorsiflexion-plantarflexion, the motion of the calcaneus with respect to the tibia occurred mainly at the ankle joint with little motion at the subtalar joint, which was similar

to those observed by Siegler *et al* and Leardini *et al*.^{2,4} There was also a significant antero-posterior translation of the talus during this movement, indicating a significant rolling motion, and also a lesser amount of vertical motion. In summary, the results support previous descriptions of the ankle-subtalar complex. The ankle joint is primarily a hinge joint, but also has a significant amount of translational motion. It is easy to understand in this context why the early constrained prostheses failed. For example, plantarflexion is associated with contingent anterior translation in the normal ankle. With the use of a rigid hinged prosthesis, plantarflexion would be associated with an anteriorly directed force due to the surrounding ligaments, predicting an early failure.

During plantar flexion, there was significant anterior and proximal translation at the ankle joint. An opposite translation was associated with dorsiflexion. This motion may relate to the four bar linkage concept in ankle motion as described by Leardini *et al*.²⁶ They have reported that the calcaneofibular ligament and tibiocalcaneal ligament remained approximately isometric during flexion-extension. These ligaments, together with the articular surfaces, direct the pathway of the instantaneous centre of rotation and account for the sagittal plane motion as described. Based on the sequence, the axes chosen demonstrated flexion-extension, followed by inversion-eversion, and finally internal-external rotation. This sequence of screw motions was chosen to make the data more clinically meaningful, by approximating ankle, followed by subtalar motion, and then finally describing the coupled internal and external rotations.

In this study, the *in vitro* measurements on foot cadaver specimens were performed under conditions where weight and muscle forces were not applied. The motions of the foot with respect to the shank were also produced by applying moments without forces. Further investigation on the motions of the ankle joint complex responding to other loading conditions, such as applying forces in the axial, anterior-posterior, and medial-lateral direction, is still needed.

CONCLUSION

The results based on the dual Euler angle parameters indicate kinematic characteristics of the ankle joint complex consistent with the literature. Compared with the Euler angles and screw axis methods, this method provides an alternative approach for describing general spatial human joint motions by decomposing the motions into the axes of orthogonal Cartesian coordinate systems, which will benefit kinetic studies. The similarity and relationship of dual-number transformation matrices and rotation matrices provide a convenient way of obtaining dual angles when the FOB is used as a measurement system.

ACKNOWLEDGEMENTS

The authors would like to thank Robert Ng Teck Hin of Department of Experimental Surgery, Singapore General Hospital for his assistance during the cadaveric experiments.

REFERENCES

- Engsberg JR. A biomechanics analysis of the talocalcaneal joint-in vitro. *J Biomech* 1987; 20: 429-42.
- Siegler S, Chen J, Schneck CD. The three-dimensional kinematics and flexibility characteristics of the human ankle and subtalar joints - Part I: kinematics. *J Biomech Eng* 1988; 110:364-73.
- Stähelin T, Nigg BM, Stefanyshyn DJ, van den Bogert AJ, Kim SJ. A method to determine bone movement in the ankle joint complex in vitro. *J Biomech* 1997; 30:513-6.
- Leardini A, O'Connor JJ, Catani F, Giannini S. Kinematics of the human ankle complex in passive flexion; a single degree of freedom system. *J Biomech* 1999; 32:111-18.
- Lundberg A. Kinematics of the ankle and foot: in vivo roentgen stereophotogrammetry. *Acta Orthop Scand* 1989; 233:1-24.
- Buczek FL, Cavanagh PR. Stance phase knee and ankle kinematics and kinetics during level and downhill running. *Med Sci Sports Exerc* 1990; 22:669-77.
- Kepple TM, Stanhope SJ, Lohmann KN, Roman NL. A video-based technique for measuring ankle-subtalar motion during stance. *J Biomech* 1990; 12:273-80.
- Kitaoka HB, Luo Z, An KN. Three dimensional analysis of normal ankle and foot mobility. *Am J Sports Med* 1997; 25:238-42.
- Chao EY. Justification of the triaxial goniometer in the measurement of joint rotation. *J Biomech* 1980; 13:989-1006.
- Tupling SJ, Pierrynowski MR. Use of cardan angles to locate rigid bodies in three-dimensional space. *Med Biol Eng Comput* 1987; 25:527-32.
- Ramakrishnan HK, Kadaba MP. On the estimation of joint kinematics during gait. *J Biomech* 1991; 24:969-77.
- Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng* 1983; 105:136-44.
- Zatsiorsky VM. *Kinematics of Human Motion*. Champaign, IL: Human Kinetics, 1988;100-1.
- Ying N, Kim W. Use of dual Euler angles to quantify the three-dimensional joint motion and its application to the ankle joint complex. *J Biomech* 2002; 35:1647-57.
- Bottlang M, Marsh JL, Brown TD. Factors influencing accuracy of screw displacement axis detection with a D.C.-based electromagnetic tracking system. *J Biomech Eng* 1998; 120:431-35.
- Bull AMJ, Berkshire FH, Amis AA. Accuracy of an electromagnetic measurement device and application to the measurement and description of knee joint motion. *Proceedings of the Institute of Mechanical Engineers Part H* 1998; 212:347-55.
- Meskers CG, Fraterman H, van der Helm FC, Vermeulen HM, Rosing PM. Calibration of the "Flock of Birds" electromagnetic tracking device and its application in shoulder motion studies. *J Biomech* 1999; 32:629-33.
- Cappozzo A, Catani F, Della C, Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin Biomech* 1995; 10:171-78.
- Dohrmann CR, Busby HR, Trujillo DM. Smoothing noisy data using dynamic programming and generalized cross-validation. *J Biomech Eng* 1988; 110:37-41.
- Sammarco GJ, Burstein AH, Frankel VH. Biomechanics of the ankle: a kinematic study. *Orthop Clin North Am* 1973; 4:75-96.
- Lundberg A, Svensson O K, Nemeth G, Selvik G. The axes of rotation of the talocalcaneal and talonavicular joints. *The Foot* 1993; 3:65-70.
- Hicks JH. The mechanics of the foot 1: the joints. *J Anat* 1953; 87:345-57.
- Isman R, Inman V. Anthropometric studies of the human foot and ankle. *Bull Prosthet Res* 1969; 10-11:97-129.
- Inman VT. *The Joints of the Ankle*. Baltimore: The Williams & Wilkins Company, 1976.
- Manter JT. Movement of the subtalar and transverse tarsal joints. *Anat Rec* 1941; 80:397-410.
- Leardini A, O'Connor JJ, Catani F, Giannini S. A geometric model of the human ankle joint. *J Biomech* 1999; 32:585-91.