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Short communication

Passive motion characteristics of the talocrural and the subtalar joint by dual Euler angles

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Abstract

The objective of this study is to validate previous descriptions of hindfoot kinematics using dual Euler angle methods in a passive cadaveric model. The dual Euler angle method was chosen so as to facilitate description of the translational and rotational movement occurring at both the ankle and subtalar joints. A non-metal experimental set-up was fabricated to generate motion in foot cadaver specimens. Three-dimensional kinematic data of the ankle joint complex was collected from ten knee-below foot cadaver specimens using a 'Flock of Birds' electromagnetic tracking device. The data correlates well with previously published kinematic descriptions of the ankle subtalar joint complex. Both the ankle and subtalar joint show 6 degree of freedom motion and multiaxial characteristics.

The motions of the talocrural joint, the talocalcaneal joint, and the gross motion between the foot and the shank were analyzed. During dorsiflexion–plantarflexion the motion of the calcaneus with respect to the tibia occurs mainly at the ankle joint, with little motion at the subtalar joint. The subtalar joint contributes more than the ankle joint during inversion–eversion.

Keywords: Ankle joint complex; Kinematics; Dual Euler angles; Flock of Birds

1. Introduction

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 analyze the kinematic characteristics of the ankle joint complex in vitro (Engsberg, 1987; Siegler et al., 1988; Stähelin et al., 1997; Leardini et al., 1999) or in vivo (Lundberg, 1989; Buczek and Cavanagh, 1990; Keppel et al., 1990; Kitaoka et al., 1997). In previous studies, the Euler angles and screw axis methods were widely used methods to represent ankle joint complex motions (Chao, 1980; Tupling and Pierrynowski, 1987; Ramakrishnan and Kadaba, 1991). The screw axis method is not comparable with clinical motion description and does not facilitate clinical interpretation, 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. As a variation of the Euler angles method, Grood and Suntay (1983) proposed a non-orthogonal joint coordinate system (JCS) to avoid some of the

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difficulties inherent in the use of Euler angles. Though JCS combines rotation and translation, it is not orthogonal, and presents a serious problem when joint forces and moments need to be determined (Zatsiorsky, 1998).

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 and Kim (2002) recently. 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 also an advantage over JCS because of its orthogonality.

In this study, kinematic data collected from ten foot cadaver specimens were analyzed using dual Euler angle parameters and the motions at the ankle and the subtalar joint were described.

2. Methods

Motion at the ankle joint complex was measured using the 'Flock of Birds' (FOB) electromagnetic tracking system (Ascension Technology Inc., Burlington, Vermont, USA).

Because measurements were made using an electromagnetic motion tracking system, all elements of the testing system were built from non-ferromagnetic materials. A custom rig was designed and built using acrylic plastic. The footplate was designed to rotate freely around a horizontal axis. It could also be rotated around a vertical axis and locked into one of two positions at 90° to one another. This would allow simulated flexion–extension and inversion–eversion of the foot. A shank rod, designed to be inserted into the medullary canal of the tibia, was threaded through an aperture in the upper part of the rig. The aperture was about 1 cm larger than the diameter of the rod, allowing it to move freely. The position of the aperture could be adjusted to center the leg directly above the footplate.

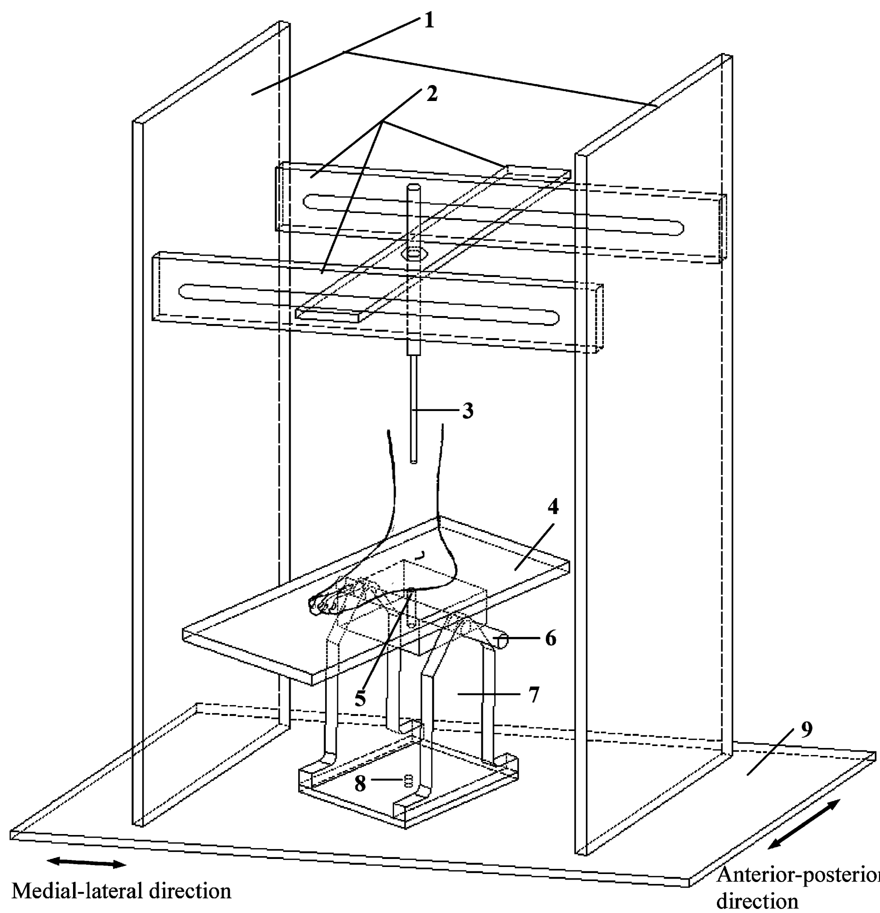

Fig. 1. Experimental set-up for in vitro experiments on foot/shank specimens: (1) Vertical stands, (2) Beams supporting shank rod, (3) Shank rod, (4) Foot plate, (5) Screw securing footplate on supporting bracket, (6) Horizontal axis of the foot plate, (7) Supporting bracket, (8) Screw securing supporting bracket on ground plate, (9) Ground plate.

Ten fresh frozen cadaveric specimens were obtained of the leg and foot, including the entire tibia. Each specimen was defrosted to ambient temperature prior to the experiment. The skin around the ankle and hindfoot was removed, preserving all the ligaments, tendons and other soft tissues. A 9-mm diameter drill hole was made into the tibial plateau, allowing the intramedullary shank rod to be threaded through it. Three of the motion-tracking receivers were attached to the tibia, talus and calcaneum using plastic screws. The motion of the construct was tested to ensure that the screws or receivers moved freely without obstructing the normal motion of the hindfoot on the platform (Fig. 1).

Four points (tibial tuberosity, head of fibula, medial and lateral malleoli) were identified and the most prominent point on each was marked. After placing the cadaveric specimen on the rig, these four points were digitised using a fourth motion-tracking receivers attached to a stylus. Together, these four points formed the anatomical system on which movements of the hindfoot would take reference from (Fig. 2).

The specimen was then passively cycled through first from maximum dorsiflexion to plantarflexion, and then from maximum inversion to maximum eversion, while the position and rotation of the three segments were simultaneously and continuously measured using the FOB system. This process was repeated 10 times for each motion and the dual Euler angle parameters for each specimen were averaged from these 10 trials.

3. Results

The dual Euler angles of the 10 specimens were averaged at the maximum ranges of flexion–extension and inversion–eversion. The details can be found in Table 1, Figs. 3 and 4. All descriptions are with respect to the tibia.

The sequence of screw motions was selected as first 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 system

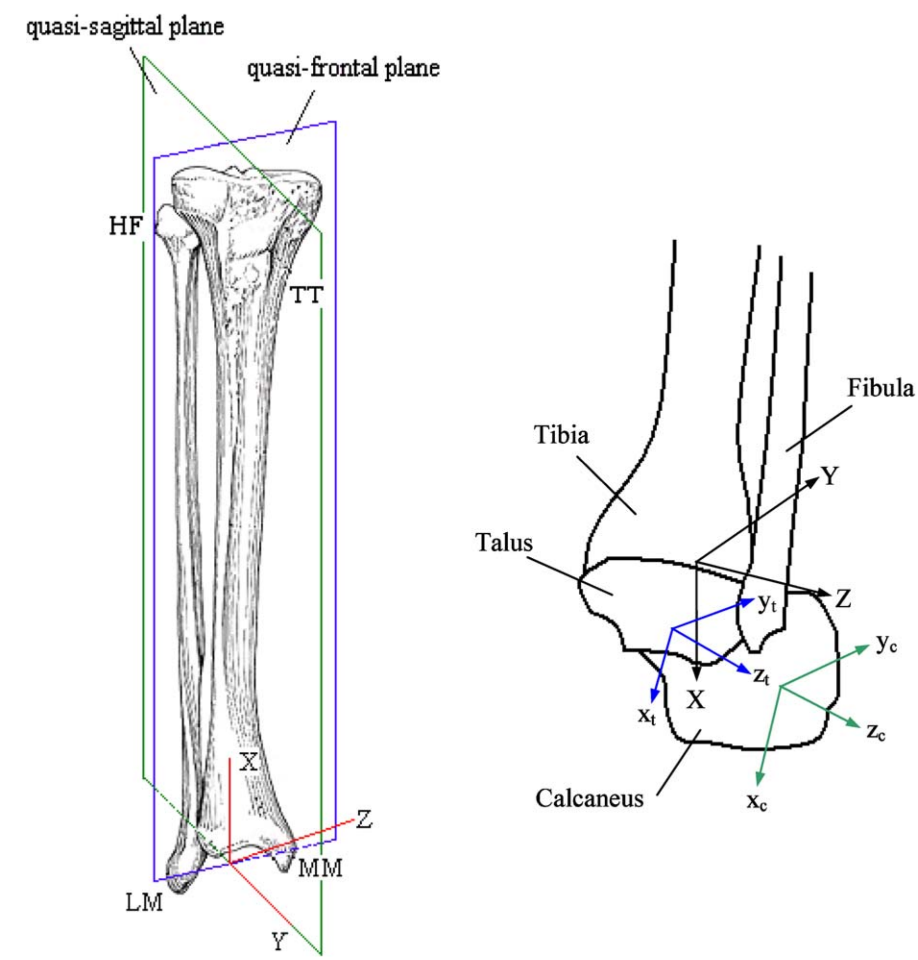

Fig. 2. Anatomical coordinate system of the shank and coordinate systems for analyzing passive motions of ankle joint complex (X-Y-Z: coordinate system of the tibia; x_t-y_t-z_t: coordinate system of the talus; x_c-y_c-z_c: coordinate system of the calcaneus).

Table 1
Summary of the average motions (±standard deviation) at the ankle joint complex

	Rotation (deg)			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±1.25	3.69±0.67	5.77±1.07	0.74±0.2	7.45±1.4	4.41±0.67
Motion at the ankle joint	27.01±0.78	1.86±0.67	3.23±0.72	0.30±0.46	6.22±1.23	5.25±0.72
Motion at the subtalar joint	2.09±0.56	1.92±0.82	2.48±0.92	0.86±0.41	1.38±0.77	1.03±0.51
Dorsiflexion						
Gross motion of the foot	18.6±0.97	2.45±0.87	4.54±0.6	0.71±0.33	4.94±1.	1.16±0.47
Motion at the ankle joint	19.12±0.39	1.96±0.56	4.33±0.41	0.62±0.46	5.78±0.77	1.60±0.31
Motion at the subtalar joint	0.64±0.41	0.06±0.31	0.25±0.31	0.12±0.21	0.69±0.31	0.50±0.22
Inversion						
Gross motion of the foot	2.72±1.	10.0±1.09	8.11±0.73	2.74±0.8	3.88±0.8	1.61±0.33
Motion at the ankle joint	4.40±1.13	2.16±0.56	0.28±0.62	1.79±0.74	0.66±0.59	1.78±0.53
Motion at the subtalar joint	7.11±1.03	7.88±0.63	7.55±0.79	0.79±0.60	3.01±0.63	0.64±0.52
Eversion						
Gross motion of the foot	1.80±1.2	4.50±1.22	2.12±0.47	2.93±0.47	1.10±0.73	0.83±1.
Motion at the ankle joint	0.66±0.79	0.66±0.31	1.32±0.33	0.82±0.34	0.48±0.36	0.70±0.31
Motion at the subtalar joint	2.52±0.99	3.81±0.25	1.50±0.87	2.15±0.40	0.67±0.63	1.57±0.61

along with the sequence of screw motions adopted in this study, the screw motion through the z-axis can be considered as flexion–extension and lateral-medial shift. Similarly the screw motion through the y'-axis reflects inversion–eversion and anteroposterior translation. Finally, the screw motion through the x''-axis can be interpreted as the abduction–adduction and distraction-shortening.

To analyze 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 the dorsiflexion–plantarflexion and eversion–inversion were obtained.

Table 1 provides contingent or coupled movements of the ankle. The plantarflexion (z-axis) correlated with both the inversion (y-axis) and adduction (x-axis) of the calcaneus with respect to the tibia. There was also an associated lateral translation (z-axis), anterior translation (y-axis), and shortening (x-axis). The dorsiflexion was coupled with both the eversion (y-axis) and abduction (x-axis) of the calcaneus with respect to the tibia. There was also an associated medial translation, posterior translation, and distal translation.

The inversion was coupled with the plantarflexion, adduction, lateral shift, anterior translation, and distal translation of the calcaneum with respect to the tibia. The eversion was coupled with the dorsiflexion, abduction, medial translation, posterior translation, and distal translation of the calcaneum with respect to the tibia.

Translational and angular motion parameters were also plotted graphically for each specimen to compare the relationships between these parameters. Two obvious trends emerged. Firstly, the graphs plotted were non-linear, confirming the multi-axial nature of the two joints. Secondly, although overall trends were similar, there were significant differences in the slope and shape of the curves between specimens.

4. Discussion

The data correlates well with the previously published kinematic descriptions of the ankle subtalar joint complex. The results obtained by researchers such as Sammarco et al. (1973), Engsberg (1987), Siegler et al. (1988), and Lundberg et al. (1993) have questioned the view that the ankle and subtalar joints were uniaxial, ideal hinge joints, held by Hicks (1953), Isman and Inman (1969), Inman (1976). Both the ankle and subtalar joint show 6 degree of freedom motion and multiaxial characteristics. In addition, motion characteristics varied considerably between individual specimens.

The majority of plantarflexion–dorsiflexion occurred at the ankle joint. This was coupled with adduction–inversion during plantarflexion and abduction–eversion during dorsiflexion, occurring in almost equal amounts at both the ankle and subtalar joints (Fig. 3a). This is similar to data described by Siegler et al. (1988) and Leardini et al. (1999). The overall trend suggests both the ankle joint and subtalar joint axes as passing from medial, proximal and anterior to lateral, distal and posterior, with respect to the coordinate axes.

Translational movement during plantarflexion–dorsiflexion was quite significant. Antero-posterior

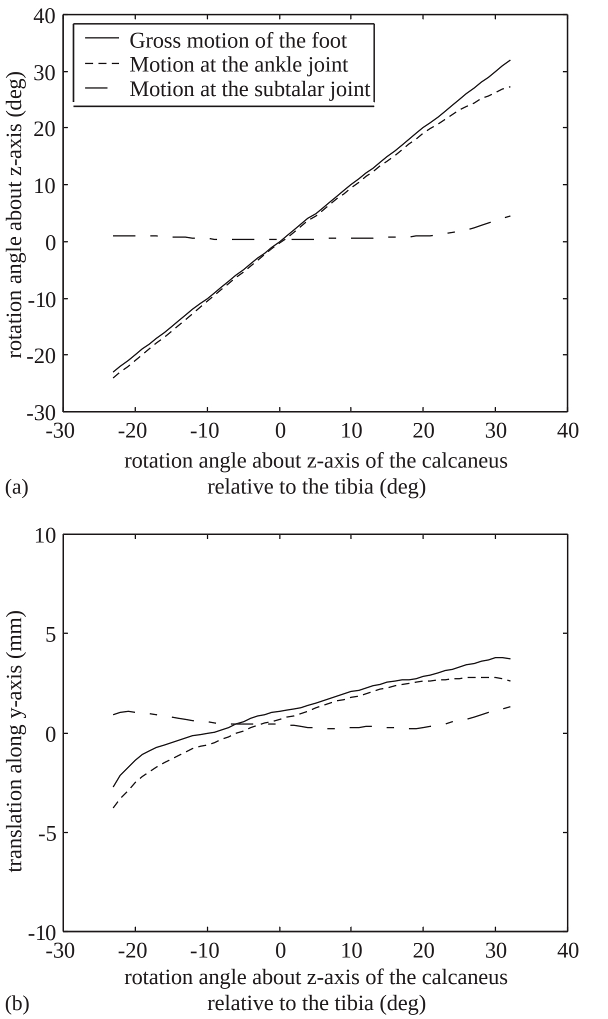

Fig. 3. (a) Three relative rotations about z-axes during the dorsiflexion–plantarflexion; (b) three relative translations along y'-axes during the dorsiflexion–plantarflexion.

translation of the talus during flexion–extension averaged 12 mm, and axial translation 6.9 mm (Fig. 3b). Leardini has previously described the antero-posterior translation as a four-bar linkage based on the calcaneofibular ligament and the tibiocalcaneal ligament.

Inversion of the foot was associated with a significant amount of internal rotation (Fig. 4a) and plantarflexion at the subtalar joint. This correlates well with the mitred hinge concept (torque converter) as described by Mann (1978) (Fig. 4b). In addition, a significant degree of anterior translation occurred at the subtalar joint, supporting the concept of a screw type mechanism in the subtalar joint. Manter (1941) modeled the subtalar joint as a spiral of Archimedes. The results from this study show that the pitch of the screw motion through the y'-axis—the ratio of the motion of draw to the motion of inversion–eversion fits a certain constant value, approximately 0.2 mm/deg, based on the linear relationship during the movements (Fig. 4c).

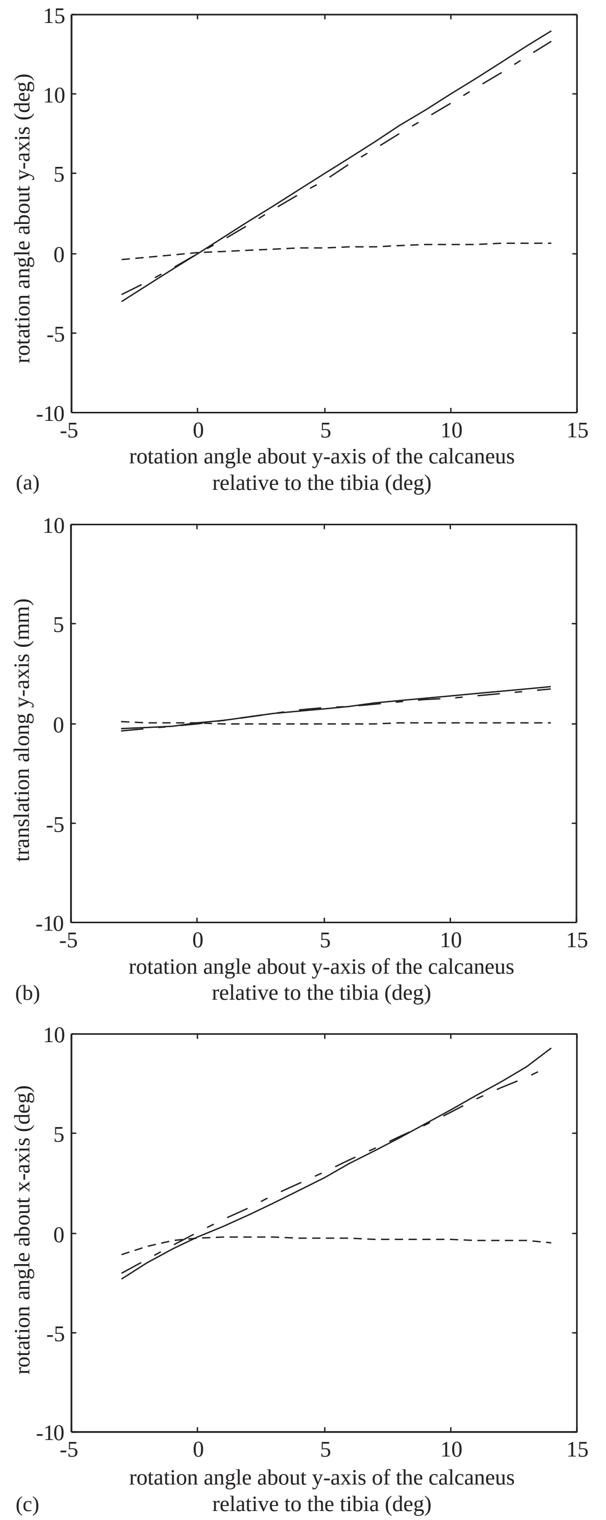

Fig. 4. (a) Three relative rotations about y'-axes during the inversion–eversion, (b) Three relative translations along y'-axes during the inversion–eversion, (c) Three relative translations along x''-axes during the inversion–eversion.

In summary, the data supports previous descriptions of the ankle–subtalar complex. The dual Euler angle method allows the data to be accurately captured, at the same time presenting it in a way that is clinically useful and relevant.

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