INTRODUCTION

The primary movement associated with the ankle joint complex is dorsiflexion and plantarflexion at the tibio-talar joint. The axis of rotation for this movement is of considerable interest when selecting a method for describing three-dimensional motion at the ankle joint complex, when refining surgical techniques in order to reconstruct the joint in a physiological way as possible, and when calculating moments about the joint. This latter consideration is important in inverse dynamics and modelling purposes.

The focus of this paper is three-dimensional motion analysis. The three most common techniques are Euler angles, the Joint Coordinate System and the helical axis approach. When Euler angles are employed, the axes are commonly chosen to be aligned with the sagittal, frontal and transverse planes of the body. Where physiological motion occurs in all three planes, these may not be the most meaningful descriptive tool. The helical axis technique, pioneered and championed by Woltring, is a powerful technique in that motion is described as rotation about and translation along an axis fixed in space. The major limitation of the technique is that the axis calculated is ill-defined for rotations of a small amplitude – this precludes the accurate description of continuous motion. The Joint Coordinate System (Grood & Suntay, 1983) allows appropriate axes to be selected, and rotations about these axes to be calculated. This is desirable in terms of clinical relevance and significance, and ease of communication with clinicians. However, the authors suggest that the common practice of selecting axes based on anatomical landmarks may not be optimal in all circumstances.

A line connecting the tips of the lateral and medial malleoli (the intermalleolar line) is commonly used as an approximation to the axis of dorsiflexion and plantarflexion at the ankle joint complex (Zatsiorsky, 1998). This convention is recommended by Cappozzo et al (1995) and Wu et al (2002) when constructing a Joint Coordinate System for the ankle. As stated above, dorsiflexion and plantarflexion are assumed to take place primarily at the tibio-talar joint. The morphology of the talar and tibial surfaces that articulate with each other are such that the rotations at the joint may be expected to be of a complex, rather than uniaxial, nature. Furthermore, the loading conditions may be expected to modify the axis of rotation.

The work described here was undertaken as a preliminary investigation of the validity of the assumption that a subject’s axis of rotation for dorsiflexion/plantarflexion, determined using the helical axis approach, and their intermalleolar line are coincident for unloaded motion at the ankle joint complex. Rather than compare complete descriptions of the measured axes and the intermalleolar line, it was decided that the angle between the measured axis and the intermalleolar line would be calculated.

METHODS

Three subjects were selected from departmental colleagues. Subject 1 was female (28 years old), while Subjects 2 and 3 were male (56 and 38 years old, respectively). All subjects were mobile and free of injury, although their level of physical activity varied. The small and varied nature of the subject group was not considered important at this stage, as the objective was to establish generally whether or not the intermalleolar line and dorsiflexion/plantarflexion axis were parallel. However, the nature of the subject group does limit the conclusions that can be drawn from the results.

Subjects were seated on a treatment couch with their shanks hanging freely. Two rigid-body collections of three retro-reflective markers were used to track the movement. One set was attached to the shank over the tibial plateau, and the other was attached to the foot. The rigid body collections of markers are referred to as tools; the tools used for the foot and shank are shown in Figure 1.

Figure 1: Marker collections used for the shank (left) and foot (right)

The collections of markers were attached to the right limb using wide elasticated straps. A third set of markers was configured as a digitising pointer. The pointer, illustrated in Figure 2, was simply an aluminium rod, shaped to a point at one end, with the markers attached at the other end. The tips of the lateral and medial malleoli were palpated and digitised. Subjects were asked to alternately dorsiflex and plantarflex their foot to comfortable limits. They were instructed to minimise the movement of the toes. Five dorsiflexion/plantarflexion cycles were recorded, and the subject then relaxed. This was repeated three times. The foot and shank tools were then removed completely, before they were reattached and the entire procedure was repeated. Figure 3 shows the arrangement of the subject on the treatment couch.
with the markers attached to the shank and foot, with the Polaris position sensor on the left.

Figure 2: The digitising pointer

Although the subject depicted was part of a previous study, which is why the left rather than the right foot is being studied, the arrangement for recording the measurements described here was exactly the same.

The markers were tracked using a Polaris optoelectronic 3D measurement system from Northern Digital Incorporated. The Polaris system communicates with a PC via a serial RS232 link. Bespoke acquisition software was written in Agilent VeePro to record the ASCII data to disk via the serial port and then offline analysis of the data was performed using MATLAB, as described in the following section.

Figure 3: The subject testing arrangements

DATA ANALYSIS

Each rigid-body collection of markers, or tool, has an embedded local coordinate system (LCS). The LCS is defined when the tool is created, by specifying the locations of the individual markers using a cartesian coordinate system. The Polaris system utilises a global coordinate system (GCS) that is defined relative to the position sensor (shown supported on a stand in Figure 3). The three-dimensional transformations of the LCS’s for the tools relative to the GCS are reported. Polaris reports these transformations using quaternions to describe rotations and cartesian coordinates to describe translations. Due to the authors’ lack of familiarity with quaternions and in order to manipulate the transformations as required, it was decided that 4x4 transformation matrices would be used. Standard techniques exist for conversion from quaternions to relevant rotation matrix components. Manipulation of the transformation matrices was performed using MATLAB software from Mathworks.

In order to define the intermalleolar line, the transformation matrix describing the position and orientation of the pointer tool relative to the shank tool was calculated. The pointer tip offset coordinates were multiplied by this transformation matrix to give the coordinates of the malleoli in the shank LCS. The direction vector of the intermalleolar line could then be calculated from these three-dimensional coordinates.

For each sample point, the transformation matrix describing the position and orientation of the foot tool relative to the shank tool was calculated. From the resulting matrices, helical axis parameters were calculated between each sample point and the first. This allowed the identification of the peak plantarflexion and peak dorsiflexion positions; further calculations were then performed to derive the helical axis parameters describing movement between these points.

The helical axis parameters were calculated using Matlab code written by Christoph Reinschmidt and published on the ISB website. This code returns eight parameters. The first three are the components of the direction vector of the helical axis, the next three describe the point of intersection of the helical axis with a chosen plane (x, y or z=0). The seventh and eighth parameters are the rotation about and translation along the axis, respectively. As for the coordinates of the malleoli, these parameters were calculated in terms of the shank LCS. For this application, only the direction vector of the axis was required. The angle between the direction vectors of the measured axis and the intermalleolar line was calculated as the arcosine of their dot product.

RESULTS AND DISCUSSION

Sample results from the three subjects are presented in Table 1. Cycles 1 to 5 are the continuous dorsi/plantar flexion cycles for each of the separate series (Series 1 to 3). The first and most obvious point to note is that, in all cases, the angle between the direction vectors is non-zero. This indicates that under these measurement conditions, the dorsi/plantar flexion axis as measured here should not be assumed to be coincident with the intermalleolar line.

While there is considerable variation between subjects, for a given subject the results show a high degree of consistency. For Subjects 2 and 3 the agreement would be even better if the measurements from Cycle 1 were ignored; this could be justified as the range of motion (noted in brackets) is markedly smaller than for the other Cycles. This observation in itself may indicate that the axis changes over the range of movement.
It is interesting to note that for all three series for each subject, the first cycle is of smaller amplitude than the following ones. This may reflect the time that it takes a subject to acquire a repeatable movement pattern, so that in future studies the first cycle should be discarded.

There are two main points that need to be emphasised when considering the results that have been obtained so far. The first is that the helical axis calculated describes motion between two points – the maximally dorsiflexed position and the maximally plantarflexed position in any given cycle. Therefore, there is still a lack of information as to what is happening to the axis during the movement. This is important because although the evidence presented indicates that the helical axis measured and the intermalleolar line are not coincident, it is not possible to draw the conclusion that the helical axis measured is the better approximation to the true physiological situation. Secondly, only unloaded movements have been considered here; in fact the ankle joint is distracted by the weight of the foot. Compression of the joint when loaded may alter the results obtained significantly. Further investigations are underway to address these limitations.

**SUMMARY**

The results discussed here indicate that, for unloaded rotations, the axis of dorsiflexion/planterflexion deviates from the intermalleolar line, to a varying extent according to the individual. This should be taken into account whenever such motion is being analysed.

**REFERENCES**


**ACKNOWLEDGEMENTS**

The authors acknowledge the help of Graham Perley with analysis of the data and thank Christoph Reinschmidt for his Matlab routine used to calculate the helical axis parameters.

### Table 1: Sample results from three series of five dorsi-/planterflexion cycles for three subjects. The results presented are angles between direction vectors representing the helical axis and the intermalleolar line, with the amplitude of the rotation from which the axis was calculated in brackets; both are in degrees.

<table>
<thead>
<tr>
<th></th>
<th>Subject 1</th>
<th></th>
<th>Subject 2</th>
<th></th>
<th>Subject 3</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Series 1</td>
<td>Series 2</td>
<td>Series 3</td>
<td>Series 1</td>
<td>Series 2</td>
</tr>
<tr>
<td><strong>Cycle 1</strong></td>
<td>70.1 (54.4)</td>
<td>70.6 (52.7)</td>
<td>71.5 (54.6)</td>
<td>49.5 (44.0)</td>
<td>53.9 (43.1)</td>
</tr>
<tr>
<td><strong>Cycle 2</strong></td>
<td>71.8 (64.8)</td>
<td>71.3 (59.1)</td>
<td>71.3 (58.3)</td>
<td>56.5 (58.8)</td>
<td>55.6 (64.0)</td>
</tr>
<tr>
<td><strong>Cycle 3</strong></td>
<td>72.4 (62.1)</td>
<td>71.3 (55.4)</td>
<td>71.4 (59.2)</td>
<td>57.5 (61.6)</td>
<td>55.7 (61.8)</td>
</tr>
<tr>
<td><strong>Cycle 4</strong></td>
<td>70.8 (61.3)</td>
<td>71.6 (58.0)</td>
<td>71.8 (58.4)</td>
<td>58.2 (62.1)</td>
<td>59.6 (64.6)</td>
</tr>
<tr>
<td><strong>Cycle 5</strong></td>
<td>71.2 (60.0)</td>
<td>72.0 (62.9)</td>
<td>70.8 (58.6)</td>
<td>58.7 (62.4)</td>
<td>56.8 (61.6)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>71.3 (60.5)</td>
<td>71.4 (57.6)</td>
<td>71.4 (57.8)</td>
<td>56.1 (57.8)</td>
<td>56.3 (59.0)</td>
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