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The Clinical Biomechanics Award 2013 – presented by the International Society of Biomechanics: New observations on the morphology of the talar dome and its relationship to ankle kinematics

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ABSTRACT

Background: Ankle passive kinematics is determined primarily by articular surface morphology and ligament constraints. Previous morphological studies concluded that the talar dome can be approximated by a truncated cone, whose apex is directed medially and whose major axis is the axis of rotation of the ankle. This and other functional morphology concepts were evaluated in this study whose goal was to describe and quantify the 3D morphology of the talus using 3D image-based bone models and engineering software tools.

Methods: CT data from 26 healthy adults were processed to produce 3D renderings of the talus and were followed by morphological measurements including the radii of curvature of circles fitted to the medial and lateral borders of the trochlea and radii of curvature of coronal sections.

Findings: The surfaces containing the medial and lateral borders of the trochlea are not parallel and the radius of curvature of the medial border is larger than the lateral border. In the coronal plane the trochlear surface was mostly concave.

Interpretation: The trochlear surface can be modeled as a skewed truncated conic saddle shape with its apex oriented laterally rather than medially as postulated by Inman. Such shape is compatible, as opposed to Inman's cone postulate, with the observed pronation/supination and provides stable congruency in movements of inversion/eversion. The results challenge the fundamental theories of functional morphology of the ankle and suggest that these new findings should be considered in future biomechanical research and in clinical applications such as design of total ankle replacements.

1. Introduction

The passive kinematic properties of the ankle are the result of a complex interaction between bony articular morphology and ligament constraints. The basic patterns of motion however, are primarily determined by the geometric features of the articulating surfaces of the talus, and of the tibia and fibula, i.e. the trochlear surface and the tibial/fibular mortise.

Some of the first detailed studies of the functional morphology of the trochlea were conducted more than 60 years ago (Barnett and Napier, 1952; Close, 1956; Close and Inman, 1952; Hicks, 1953; Sewell, 1904) and included the seminal work by Inman and Close and their co-workers. At that time, most investigators regarded the talocrural joint as a one-degree of freedom joint with a fixed axis of rotation. Relying on the fixed axis of rotation assumption, Inman and his co-workers (Close, 1956; Close and Inman, 1952; Inman, 1976) then performed detailed morphological measurements on cadaver specimens and concluded that the trochlear surface of the talus can be represented as a frustum of a cone, whose apex is directed medially and whose major axis coincides (or actually forced to coincide) with the line connecting the tips of the medial and lateral malleolus (Close and Inman, 1952; Inman, 1976). Since Inman's original studies, despite the fact that the concept of a fixed axis of rotation for the ankle has been refuted by many studies (Barnett and Napier, 1952; Hicks, 1953; Lundberg et al., 1989; Sammarco, 1977; Siegler et al., 1988) and despite the apparent contradiction with experimental observations on ankle coupled behavior of pronation/supination (Close and Inman, 1952; de Asla et al., 2006; Siegler et al., 1988), the idea of a truncated cone with its apex directed medially, is still, to a large extent, accepted by experts in this field (Hintermann et al., 2004; Stiehl, 1991). In fact, this idea has been implemented in recent years in the geometry of surfaces of some modern total ankle replacements (Bonnin et al., 2004; Hintermann et al., 2004), clearly demonstrating the importance of this concept to the clinical management of ankle disorders. However, the validity of this concept becomes doubtful in light of the fact that it relies entirely on an assumed fixed axis of rotation for the ankle, shown, as indicated

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earlier, to be invalid. Therefore, the main goal of the present study was to provide a detailed description of the 3D morphology of the talus using 3D image-based bone models and engineering software tools unconstrained by the assumption of a fixed axis of rotation for the ankle. The results were then be used to evaluate Inman's truncated cone concept and other functional morphological concepts such as the curvature of the trochlea in the frontal plane.

2. Methods

The study was performed on CT data from 26 healthy ankles obtained from 26 individuals ranging in age between 18 and 35 years. The CT data was collected with a resolution of $0.5 \times 0.5 \times 1.5$ mm. All identifying data such as patient name and name of referring physician were removed from the DICOM files prior to being made available to the study from the Rothman Institute, Philadelphia, PA. The CT data from each ankle was imported into commercial image processing software (Analyze Direct™) to produce three dimensional numerical renderings of the bones articulating at the ankle joint consisting of the talus, the distal tibia and the distal fibula. The bone renderings were obtained by the process of segmentation, an edge detection algorithm for identifying the boundaries of each bone in each 2D slice, followed by 3D rendering algorithm in which the 2D segmented images were combined to produce surface representation of the talus, the distal tibia and the distal fibula. The 3D surface renderings were then exported from Analyze Direct™ for use in commercial, 3D CAD and reverse engineering software — Geomagic™ where they were slightly smoothed through a spatial filter to remove minor spikes introduced during the segmentation process (Fig. 1). All subsequent 2D and 3D processing and measurements were performed in both Geomagic™ and in AUTODESK INVENTOR™.

The general dimensions of length, height and width of each talus were recorded from the CAD environment as the dimensions of a "bounding box" which defined the extents of the talus across its major axes (Fig. 2).

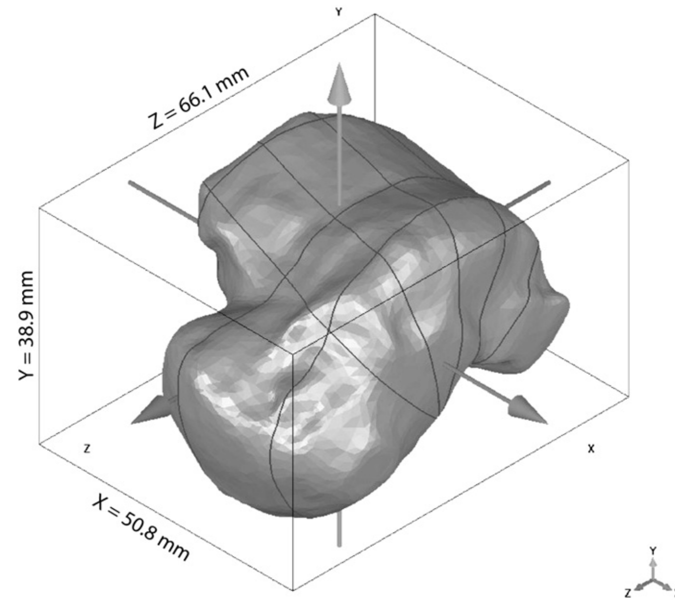

Fig. 2. An example of the general dimensions of the talus of width (X-dimension), height (Y-dimension) and length (Z-dimension) recorded as the boundary dimensions of a "bounding box".

Three near sagittal sections were created through the talus. A medial section was first selected manually so as to contain the medial shoulder of the trochlear surface of the talus representing the border between the medial side of the trochlear surface and the medial facet (MFP line in Fig. 1). A lateral section was then created by shifting a plane laterally, parallel to the medial section and then rotating this plane about a superior-to-inferior line so as to contain the lateral shoulder of the trochlear surface representing the border between the lateral side of the trochlea and the lateral facet (LFP line in Fig. 1). The angle between these two planes was measured. The width of the trochlea, W was defined and measured between the medial and lateral sections at the central coronal section (Fig. 1). The third sagittal section, the central section, was created by shifting a plane parallel to the medial section through a distance equal to half of the width W of the trochlea and

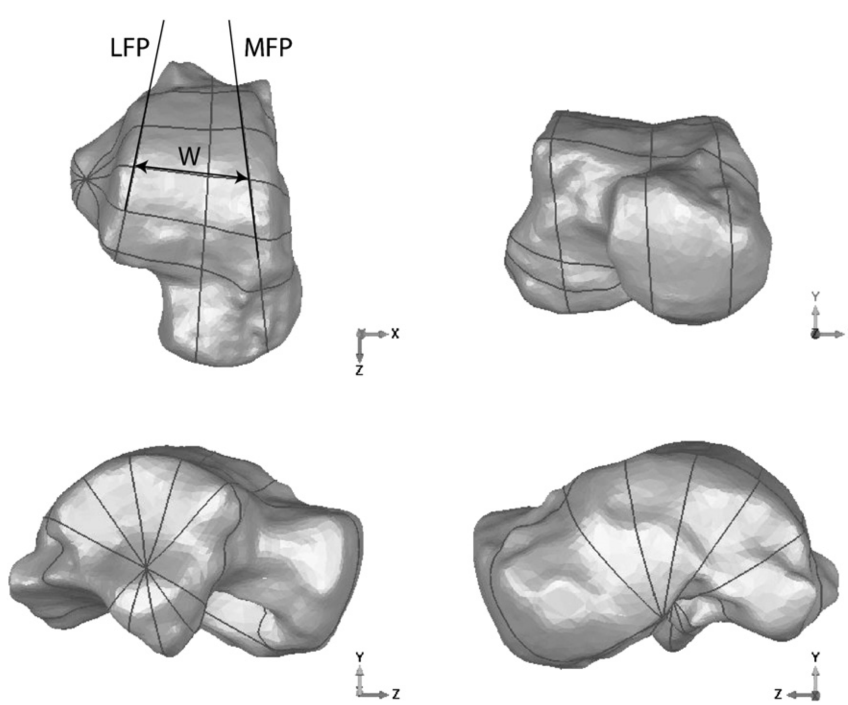

Fig. 1. Views (clockwise from top left: superior, frontal, medial and lateral) of the talus in the CAD environment (Geomagic™). Line LFP (lateral facet plane) and line MFP (medial facet plane) represent the medial and lateral facet sections through the trochlea. W represents the width of the trochlea measured at the central coronal section.