4DCT Evaluation of Rotational Instability and Subtalar Joint Motion in Ankle Osteoarthritis: A Stage-Based Comparative Study

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INTRODUCTION:

Rotational instability is a clinically important feature of ankle osteoarthritis (AOA), but it remains difficult to accurately assess using conventional imaging modalities such as static computed tomography (CT) or fluoroscopy, which are limited in their ability to capture dynamic or rotational joint motion. The subtalar joint compensates for deformities and instability of the tibiotalar joint and plays a significant biomechanical role in AOA. However, its complex structure and motion have made dynamic analysis challenging.

Four-dimensional computed tomography (4DCT) is a novel modality that captures real-time joint motion and enables dynamic three-dimensional assessment. This study aimed to evaluate tibiotalar and subtalar joint kinematics, focusing on rotation and instability, in both healthy individuals and AOA patients across disease stages.

METHODS:

Between February 2021 and April 2025, patients scheduled for surgery for ankle AOA at our institution who provided informed consent underwent preoperative 4DCT imaging. In addition, healthy volunteers without radiographic evidence of AOA or a history of ankle fractures were also recruited after providing informed consent. Participants underwent 4DCT imaging of one or both ankles. Each scan included 8-second sequences of three movement patterns: active dorsiflexion and plantarflexion, passive inversion and eversion, and passive internal and external rotation. Image data were reconstructed and analyzed using Synapse VINCENT software.

We measured:

Axial Tibiotalar Angle (ATTA): angle between the distal tibia and talus in axial view (reflecting subtalar rotation) (Figure 1A).

Axial Talocalcaneal Angle (ATCA): angle between talus and calcaneus in axial view (reflecting subtalar rotation) (Figure 1B).

Coronal Talocalcaneal Angle (CTCA): angle between the talar dome and calcaneal articular surface in coronal view (reflecting subtalar inversion/eversion) (Figure 1C).

Each angle was assessed at neutral and maximum motion positions. AOA staging was done using the Takakura-Tanaka classification (Figure 2). Group comparisons and progression trends were analyzed using Kruskal-Wallis and Dunn's post hoc tests ($p<0.05$).

RESULTS:

A total of 43 ankles (10 healthy, 33 AOA: 11 stage 3a, 11 stage 3b, 11 stage 4) were analyzed.

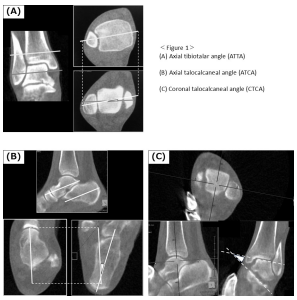
Tibiotalar Rotation (ATTA) (Figure 3): Neutral position showed mild internal rotation across groups. The ATTA range (plantarflexion to dorsiflexion) increased from 0.6° (controls) to 6.4° (3a) and 15.3° (3b), then declined to 4.8° (stage 4). Significant differences were found between control-3a, 3a-3b, and 3b-4 ($H=21.64$, $p<0.05$). With axial rotation, the ATTA range was 18.8° (3a), 17.4° (3b), 11.7° (control), and 9.8° (4), with significant differences between 3a-4 and 3b-4 ($H=10.29$).

Subtalar Rotation (ATCA) (Figure 4A): Neutral ATCA increased from 17.3° (controls) to 26.9° (3b), then dropped to 16.6° (4). Motion range was reduced in stage 4 (3.9°), with significant differences for 3a-4 and 3b-4 ($H=16.07$).

Subtalar Inversion/Eversion (CTCA) (Figure 4B): Motion range was 30.8° (controls), 26.8° (3a), 14.6° (3b), and 12.3° (4). Significant reductions were seen for control-3b, control-4, 3a-3b, and 3a-4 ($H=23.48$).

DISCUSSION AND CONCLUSION:

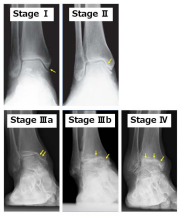
The rotational range of motion in the tibiotalar joint was significantly reduced in stage 4 compared to stages 3a and 3b. In addition, rotation associated with dorsiflexion and plantarflexion increased significantly from the healthy group to stage 3a, and from stage 3a to stage 3b, but then decreased significantly from stage 3b to stage 4. These findings suggest that rotational instability becomes more prominent in stages 3a and 3b, which are often accompanied by marked varus deformity, whereas in stage 4—where overall malalignment is less severe—rotational instability may actually be reduced. As for the subtalar joint, a reduction in range of motion was observed in inversion/eversion from stage 3b onward, and in rotation specifically at stage 4. Previous reports have noted that the subtalar joint can compensate for varus malalignment of the tibiotalar joint through valgus movement. However, it has also been reported that this compensatory mechanism is diminished in more advanced stages such as 3b and beyond. Our results are consistent with these findings in terms of decreased inversion/eversion mobility in advanced stages, reflecting a loss of compensatory function. However, regarding rotational compensation, a significant decline was evident only at stage 4. These results support the utility of 4DCT in dynamically assessing joint instability and compensatory function in AOA and may inform personalized treatment strategies.



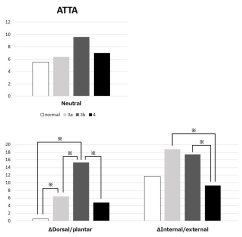
< Figure 1 >
(A) Axial tibiotalar angle (ATTA)

(B) Axial talocalcaneal angle (ATCA)

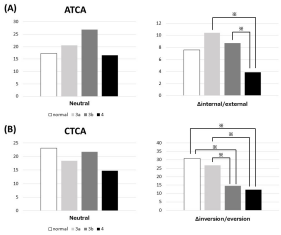
(C) Coronal talocalcaneal angle (CTCA)



< Figure 2 >
Takakura-Tanaka classification :
Stage 1) no narrowing of the joint-space, but early sclerosis and formation of osteophytes;
Stage 2) narrowing of the medial joint space
Stage 3) obliteration of this space with subchondral bone contact
3a) obliteration of the joint space is limited to the medial malleolus
3b) the obliteration extends to the roof of the dome of the talus.
Stage 4) obliteration of the whole joint space with complete bone contact



< Figure 3 >
ATTA (Axial tibiotalar angle) in neutral position, and changes in angle during dorsiflexion/plantarflexion and internal/external rotation across different groups.
Statistically significant differences (p < 0.05) are indicated by asterisks.



< Figure 4 >
(A) ATCA (Axial talocalcaneal angle) in neutral position, and changes in angle during internal/external rotation across different groups.
(B) CTCA (Coronal talocalcaneal angle) in neutral position, and changes in angle during inversion/eversion across different groups.
Statistically significant differences (p < 0.05) are indicated by asterisks.