Chapter 6

Determination of consistent patterns of range of motion in the ankle joint with a computed tomography stress-test

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Abstract

Background
Measuring the range of motion of the ankle joint can assist in accurate diagnosis of ankle laxity. A computed tomography-based stress-test (3D CT stress-test) was used that determines the three-dimensional position and orientation of tibial, calcaneal and talar bones. The goal was to establish a quantitative database of the normal ranges of motion of the talocrural and subtalar joints. A clinical case on suspected subtalar instability demonstrated the relevance the proposed method.

Methods
The range of motion was measured for the ankle joints in vivo for 20 subjects using the 3D CT stress-test. Motion of the tibia and calcaneus relative to the talus for eight extreme foot positions were described by helical parameters.

Findings
High consistency for finite helical axis orientation (n) and rotation (θ) was shown for: talocrural extreme dorsiflexion to extreme plantarflexion (root mean square direction deviation (η) 5.3° and θ: SD 11.0°), talocrural and subtalar extreme combined eversion–dorsiflexion to combined inversion–plantar flexion (η: 6.7°, θ: SD 9.0° and η: 6.3°, θ: SD 5.1°), and subtalar extreme inversion to extreme eversion (η: 6.4°, θ: SD 5.9°). Nearly all dorsi– and plantar flexion occurs in the talocrural joint (θ: mean 63.3° (SD 11°)). The inversion and internal rotation components for extreme eversion to inversion were approximately three times larger for the subtalar joint (θ: mean 22.9° and 29.1°) than for the talocrural joint (θ: mean 8.8° and 10.7°). Comparison of the ranges of motion of the pathologic ankle joint with the healthy subjects showed an increased inversion and axial rotation in the talocrural joint instead of in the suspected subtalar joint.

Interpretation
The proposed diagnostic technique and the acquired database of helical parameters of ankle joint ranges of motion are suitable to apply in clinical cases.
1. Introduction

Lateral ankle ligament injuries involving the anterior talofibular ligament and the calcaneofibular ligament are among the most frequent injuries presented at emergency departments [5, 15]. Six-and-a-half years after lateral ankle ligament injury 40% of patients sustain chronic ankle instability [34]. These patients have residual complaints like pain, giving way, actual functional instability and swelling [34]. In severe cases, these symptoms interfere with activities of daily living and sports. The high incidence of chronic lateral ankle instability after ankle ligament injury necessitates accurate diagnostic methods that are required for adequate decision making in therapy.

In clinical practice, manual and radiographic stress tests are used for testing the stability of the talocrural joint. The subjective nature of the manual ankle stress tests causes poorly reproducible and only qualitative results, which are unreliable when deciding on treatment [7]. With suspected lateral ankle joint instability, the anterior drawer and talar tilt radiographic stress tests can be performed [9, 21, 24]. In the anterior drawer stress radiograph, the anterior translation of the talus in relation to the tibia is measured [2, 11, 13, 19, 32]. In the talar tilt stress radiograph, the inversion rotation of the ankle joint is measured [2, 11, 17, 19, 22]. Frost and Amendola described that talar tilt testing and anterior drawer testing yield a high positive predictive value for diagnosis of ankle instability (88 to 100% and 78 to 100%), but a low negative predictive value (4 to 74% and 0 to 65%), respectively [6]. Stress radiography for the ankle joint proved to be accurate in predicting lateral ligamentous injury when the range of ankle inversion or talar tilt is 10° or more. However, this was the case in less than 40% of the symptomatic patients [27]. Kerkhoffs et al. [16] proposed two mechanical testing devices to evaluate the anterior drawer motion, i.e. a dynamic anterior ankle tester and a quasi-static anterior ankle tester. A disadvantage of these stress tests is the inability to discriminate between ankle instability, subtalar instability or combinations thereof. It is thought that subtalar instability occurs in 10 to 25% of patients having lateral ankle instability [14]. The most important subtalar stabilizers include the calcaneofibular, the talocalcaneal interosseous and the cervical ligament. Numerous reports are available on the effects of sectioning these ligaments that stabilize the subtalar joint [17, 18, 35]. However, there is no consensus regarding the clinical definition of subtalar joint instability and no reliable test is available for testing combined or isolated subtalar instability. In this study, only motion between the calcaneus and talus was considered as subtalar joint motion.

A clinical test that provides sufficient accuracy should be developed for assessment of ankle and subtalar joint laxity. When a ligament is seriously and permanently damaged, it loses the ability to stabilize the joint and protect it from excessive motion. A test that can stress the bones of the ankle and subtalar joints beyond the normal range of motion is able to indicate ligamentous damage or joint laxity. We developed a highly accurate diagnostic tool that measures the in vivo range of motion of the ankle and subtalar joints in a loaded state with three-dimensional computed tomography images (3D CT stress-test) [4]. From these CT-data sets, the bony contours...
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of the talus, calcaneus and distal tibia can be segmented and their relative positions accurately measured in every stressed position. The purpose of this study was to determine the range of motion of the talocrural and subtalar joints for healthy individuals with the 3D CT stress-test. More specifically, to qualify the 3D CT stress-test for clinical implementation, a set of particular motions should be highly consistent in a healthy population. To illustrate the clinical application of the proposed method, a clinical case on suspected subtalar instability is presented.

2. Methods
2.1 Subjects

CT-data sets of 20 healthy volunteers were used, involving ten males and ten females (mean 26.3 years (SD 3.6)). None of the subjects had any ankle or foot complaints, underwent prior surgery of the lower extremities, or sustained substantial ankle or foot trauma. Only right ankles were tested. The study was approved by the Medical Ethical Committee (AMC, Amsterdam, The Netherlands). The subjects signed an informed consent form indicating their willingness to participate in the study.

2.2 Measurement protocol

A Philips MX8000 spiral CT-scanner was used to acquire the CT-scans (Philips Medical Systems, Eindhoven, The Netherlands). The scan protocol was described in detail in a previous in vivo study [4]: gantry tilt was 0, field of view was 154 mm, slice thickness was 0.6 mm, increment was 0.3 mm, image matrix was 512 × 512, pitch was 0.875, rotation time was 0.75 sec., resolution was ultra high and reconstruction filter was C.

Each subject was situated supine on the CT-table. The lower leg was secured to a holding platform and the right foot was secured on a custom made radiolucent footplate (Fig. 1). The unloaded foot was positioned neutral relative to the lower leg as defined by the International Society for Biomechanics (ISB) [39]. A CT-scan in neutral position was acquired using a regular-dose technique (150 mA). The subsequent eight CT-scans were made with a foot loaded cranially to the footplate and a low-dose scan technique (26 mA) to reduce the ionizing load. The total effective dose for a subject undergoing a complete testing sequence was estimated to be 0.3 mSv. Loading was started from extreme dorsiflexion (DF) and continued in a clockwise order: extreme combined eversion–dorsiflexion (EVDF), extreme eversion (EV), extreme combined eversion–plantar flexion (EVPF), extreme plantar flexion (PF), extreme combined inversion–plantar flexion (INPF), extreme inversion (IN) and extreme combined inversion–dorsiflexion (INDF) (Fig. 1). The external load that was applied in the extreme foot positions was the maximum load that was tolerated by the subject (mean 60.9 N (SD 8.0)).
The purpose of this study was to determine the range of motion of the talocrural and subtalar joints for healthy individuals with the 3D CT stress-test. More specifically, to qualify the 3D CT stress-test for clinical implementation, a set of particular motions should be highly consistent in a healthy population. To illustrate the clinical application of the proposed method, a clinical case on suspected subtalar instability is presented.

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Consistent patterns of ROM

2.3 Image processing
The same segmentation and matching protocol was used as described by Beimers et al. [4]. In the first step, bone segmentation was performed of the tibia, talus and calcaneus by a region growing algorithm using the regular-dose CT-scan. In the second step, matching software found an optimal set of displacement parameters for the tibia, talus and calcaneus in the low-dose CT-registrations of the extreme positions.

2.4 Description of kinematics
The range of motion in a joint was defined as movement around one axis between two extreme positions. For each subject, ranges of motion were calculated of the tibia and calcaneus relative to the fixed talus from DF to PF, from IN to EV, from EVDF to INPF, and from INDF to EVPF. For quantitative analysis, the ranges of motion were expressed in a finite helical axis (FHA) with direction (n), a rotation about this helical axis (θ), and a translation along this axis (t) [36, 37]. The FHAs were represented in a right hand rule XYZ-coordinate system that coincided with the geometric principal axes of the talus (Fig. 2) [31]. The origin of the talus-based coordinate system
was placed in the geometric centroid of the talus; the X-, Y- and Z-axes coincided with the principal axes of the talus. For every subject a unique XYZ-coordinate system was calculated, which were all aligned to form one reference coordinate system. The translation \( t \) and position of all FHAs of 20 subjects were scaled using a scaling factor calculated from the mean length of the major principal axis of the 20 calcaneal bones. The mean direction of the FHAs was calculated by averaging the \( xyz \) components of \( n \) (Fig 2). The variation of the FHAs directions was calculated as the root mean square direction deviation of the individual deviation angles with the mean FHA \((\eta)\). This is comparable to calculating a standard deviation. The pitch indicating the relation between \( \theta \) and \( t \) was calculated by their quotient.

Each FHA was decomposed into three rotation components relative to the coordinate axes of the talus (Fig. 2) [36]. These three components are PF–DF, IN–EV, and internal–external rotation and facilitate clinical interpretation. Simultaneous motion in more than one anatomical direction within a joint is named coupled motion, whereas combined motion is composed of similar motion components that occur simultaneously in more than one joint. To determine these latter motion patterns for the ankle joint, quantitative description of subtalar joint motion was additionally determined.

<table>
<thead>
<tr>
<th>Motion Description</th>
<th>Joint</th>
<th>Direction vector ( \vec{n} )</th>
<th>( \theta )</th>
<th>( \eta )</th>
<th>( t )</th>
<th>SD ( \theta )</th>
<th>SD ( \eta )</th>
<th>SD ( t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme PF to extreme DF</td>
<td>Talocrural</td>
<td>0.377, 0.880, -0.288</td>
<td>6.7, 49.4</td>
<td>9.0, 1.2</td>
<td>0.6, 1.2</td>
<td>0.025, 0.015</td>
<td>0.015, 0.011</td>
<td>0.01, 0.01</td>
</tr>
<tr>
<td>Extreme DF to extreme PF</td>
<td>Talocrural</td>
<td>0.369, 0.907, -0.204</td>
<td>5.3, 63.3</td>
<td>11.0, 1.0</td>
<td>0.8, 1.0</td>
<td>0.018, 0.01</td>
<td>0.011, 0.01</td>
<td>0.011, 0.01</td>
</tr>
<tr>
<td>Extreme EVPF to extreme INDF</td>
<td>Talocrural</td>
<td>-0.454, -0.843, -0.287</td>
<td>29.6, 21.7</td>
<td>13.6, -0.3</td>
<td>1.0, -1.0</td>
<td>-0.026, 1.0</td>
<td>0.052, 0.052</td>
<td>0.052, 0.052</td>
</tr>
<tr>
<td>Mean</td>
<td>Talocrural</td>
<td>0.365, 0.897, -0.214</td>
<td>5.2, 61.4</td>
<td>10.7, 0.8</td>
<td>0.8, 1.0</td>
<td>0.018, 0.01</td>
<td>0.011, 0.01</td>
<td>0.011, 0.01</td>
</tr>
<tr>
<td>Mean</td>
<td>Subtalar</td>
<td>-0.614, -0.128, 0.779</td>
<td>6.3, 29.7</td>
<td>5.1, 2.1</td>
<td>1.1, 1.1</td>
<td>0.061, 0.025</td>
<td>0.027, 0.027</td>
<td>0.025, 0.025</td>
</tr>
</tbody>
</table>

**Figure 2** The talus-based XYZ-coordinate system and the attitude vector \((\vec{t} \cdot \vec{n})\). To define the orientation of the FHAs in the XYZ-coordinate system, their directions are given by a unity direction vector \( \vec{n} \). As is indicated, \( \vec{n} \) is multiplied by \( \vec{t} \), and decomposed into rotational components along the XYZ-axes (Fig. 4).
2.5. Clinical case
A female patient aged 27 years was seen at the orthopaedic outpatient clinic of our hospital with left ankle problems. She had sustained repetitive inversion traumas of the left ankle and underwent two ligamentous reconstruction procedures earlier. Her complaints were ankle pain and a feeling of ‘giving way’ when the left foot was stressed into inversion. Physical examination showed normal ranges of motion of both talocrural and subtalar joints with a slightly increased anterior drawer and talar tilt. Routine stress radiographs with the Telos device (load 150 N) demonstrated normal ankle stability. Based on these findings, the initial diagnosis was suspected subtalar instability. The patient signed informed consent and her ankles were evaluated bilaterally with the 3D CT stress-test.

3. Results
3.1. Finite helical axes orientation
The orientation of the talocrural axes for DF–PF and EVDF–INPF motion show good consistency with a relative small $\eta$ of 5.3° and 6.7°, respectively (Table 1). For the EV–IN motion three outliers were present that affect the consistency (Fig. 3C). For the talocrural EVPF–INDF motion, a wider range of possible axes directions is found resulting in an $\eta$ of 29.6° (Fig. 3D). For the subtalar joint, EV–IN, EVDF–INPF and EVPF–INDF motions show consistent orientation of the axes with $\eta$ being 6.4°, 6.3° and 7.3°, respectively (Table 1). The orientation of the subtalar FHAs for DF–PF motion varies considerably ($\eta$ 37.8°) (Table 1).

### Table 1
Mean (SD) of the direction vector $n$, rotation ($\theta$), translation ($t$) and pitch of the FHAs in the talocrural and subtalar joints for 20 subjects as calculated for the motion between extreme foot positions (for nomenclature see Fig. 1). $n_x$, $n_y$, and $n_z$ are components of direction unity vector $n$. $\eta$ is root mean square direction deviation.

<table>
<thead>
<tr>
<th>Direction of movement</th>
<th>Joint</th>
<th>Mean $n_x$</th>
<th>Mean $n_y$</th>
<th>Mean $n_z$</th>
<th>Mean $\eta$ (°)</th>
<th>SD $\theta$ (°)</th>
<th>Mean $t$ (mm)</th>
<th>SD $\theta$ (mm²)</th>
<th>SD $t$ (mm²)</th>
<th>Mean pitch (mm)</th>
<th>SD $\eta$ (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme DF to extreme PF</td>
<td>Talocrural</td>
<td>0.369</td>
<td>0.907</td>
<td>-0.204</td>
<td>5.3</td>
<td>63.3</td>
<td>11.0</td>
<td>1.0</td>
<td>0.8</td>
<td>0.01</td>
<td>0.011</td>
</tr>
<tr>
<td>Subtalar</td>
<td>0.684</td>
<td>0.122</td>
<td>-0.720</td>
<td>37.8</td>
<td>4.1</td>
<td>8.7</td>
<td>2.1</td>
<td>1.9</td>
<td>0.292</td>
<td>0.488</td>
<td></td>
</tr>
<tr>
<td>Extreme EVDF to extreme INPF</td>
<td>Talocrural</td>
<td>0.377</td>
<td>0.880</td>
<td>-0.288</td>
<td>6.7</td>
<td>49.4</td>
<td>9.0</td>
<td>1.2</td>
<td>0.6</td>
<td>0.025</td>
<td>0.015</td>
</tr>
<tr>
<td>Subtalar</td>
<td>-0.614</td>
<td>-0.128</td>
<td>0.779</td>
<td>6.3</td>
<td>29.7</td>
<td>5.1</td>
<td>1.1</td>
<td>0.6</td>
<td>0.039</td>
<td>0.022</td>
<td></td>
</tr>
<tr>
<td>Extreme EV to extreme IN</td>
<td>Talocrural</td>
<td>0.414</td>
<td>0.746</td>
<td>-0.521</td>
<td>22.5</td>
<td>23.7</td>
<td>11.5</td>
<td>0.5</td>
<td>0.7</td>
<td>0.006</td>
<td>0.053</td>
</tr>
<tr>
<td>Subtalar</td>
<td>-0.617</td>
<td>-0.057</td>
<td>0.785</td>
<td>6.4</td>
<td>37.3</td>
<td>5.9</td>
<td>2.3</td>
<td>1.1</td>
<td>0.061</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>Extreme EVPF to extreme INDF</td>
<td>Talocrural</td>
<td>-0.454</td>
<td>-0.843</td>
<td>-0.287</td>
<td>29.6</td>
<td>21.7</td>
<td>13.6</td>
<td>-0.3</td>
<td>1.0</td>
<td>-0.026</td>
<td>0.052</td>
</tr>
<tr>
<td>Subtalar</td>
<td>-0.625</td>
<td>-0.026</td>
<td>0.780</td>
<td>7.3</td>
<td>35.5</td>
<td>5.7</td>
<td>2.9</td>
<td>1.1</td>
<td>0.080</td>
<td>0.027</td>
<td></td>
</tr>
</tbody>
</table>

Consistent patterns of ROM
3.2. Rotations
The maximum talocrural rotation occurs for the DF–PF foot motion with a mean $\theta$ 63.3° (SD 11°). The amount of rotation decreases as the EV–IN rotation component becomes more dominant (Table 1). The variation in rotation of the subtalar joint is relatively small for EV–IN, EVPF–INDF and EVDF–INPF movements (Table 1).

3.3. Translations
Overall, subtalar translations were larger than talocrural translations (Table 1). The mean translations were the largest in the subtalar joint for EVPF–INDF movement: 2.9 mm (SD 1.1). For this range of motion, the smallest talocrural translation occurred: 0.3 mm (SD 1.0). The standard deviations were large compared to the mean translations (Table 1).

Figure 3 Three-dimensional representation of the FHAs of 20 subjects for talocrural motion from (A) DF–PF, (B) EVDF–INPF, (C) EV–IN and (D) EVPF–INDF. One talus is shown with the coordinate system as defined in Fig. 2. The FHAs are all 75 mm long.
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![Figure 4](image_url) Rotation components of both joints for all four extreme foot motions of 20 subjects. Total rotation is decomposed into three rotation components: PF–DF, IN–EV and internal–external rotation (as defined in Fig. 2). Additionally, the data of both patient’s ankles are given by the dashed lines. Where the indication ‘L’ or ‘R’ is given the range of motion is outside the 95% confidence interval of the normal group. ‘L’ indicates the left symptomatic ankle joint and ‘R’ indicates the right normal ankle joint.

3.4. Coupled and combined motions

The most prominent combined motion is movement from EVDF to INPF where considerable inversion and internal rotation take place in both joints, in equal amounts (Fig. 4). A clear difference can be seen between the relative positions of the talus and calcaneus. For EV–IN and EVPF–INDF motions, the inversion and internal rotation components are strongly coupled and also combined, where approximately three times more rotation takes place in the subtalar joint (mean \( \theta \) 22.9° and 29.1°) than in the talocrural joint (mean \( \theta \) 8.8° and 10.7°) (Fig. 4). Contrarily, DF–PF range of motion is restricted to the talocrural joint with minimal combined motion.

For all ranges of motion and for both joints, inversion is coupled to internal rotation and eversion to external rotation (Fig. 4), except for the EVPF–INDF movement in the talocrural joint. To a lesser extent, coupling is present for plantarflexion, inversion and internal rotation in the talocrural joint,
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also referred to as supination. The same holds for the opposite direction, where coupling is found of external rotation, eversion and to some extent dorsiflexion. Notice, the internal rotation component of the talocrural joint drops around 5° from the EVDF–INPF movement (mean $\theta_1 14.3^\circ$ (SD 5.5°)), to the EV–IN movement (mean $\theta_1 10.7^\circ$ (SD 5.1°)) and ends with the EVPF–INDF movement (mean $\theta 5.4^\circ$ (SD 5.6°)).

3.5. Clinical case

The female patient had normal ranges of subtalar motion in both ankles compared to the healthy subject population, but had increased ranges of motion in the bilateral talocrural joints regarding in- and external rotation (Table 2 and Fig. 4). Most importantly, her symptomatic left talocrural joint also showed increased inversion range of motion (Fig. 4). Based on these findings, the diagnosis was reconsidered and changed into talocrural instability of the left ankle.

### Table 2

The direction vector $\mathbf{n}$, rotation ($\theta$), translation ($t$) and pitch of the FHAs in the talocrural and subtalar joint for the symptomatic left ankle of the patient as calculated for the motion between extreme foot positions (for nomenclature see Fig. 1).

<table>
<thead>
<tr>
<th>Direction of movement</th>
<th>Joint</th>
<th>Direction vector $\mathbf{n}$</th>
<th>$n_x$</th>
<th>$n_y$</th>
<th>$n_z$</th>
<th>$\theta$ ($^\circ$)</th>
<th>$t$ (mm)</th>
<th>pitch (mm/$^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme DF to extreme PF</td>
<td>Talocrural</td>
<td>0.482</td>
<td>0.747</td>
<td>-0.458</td>
<td></td>
<td>67.5</td>
<td>1.3</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>Subtalar</td>
<td>0.737</td>
<td>0.191</td>
<td>-0.648</td>
<td></td>
<td>16.6</td>
<td>5.7</td>
<td>0.344</td>
</tr>
<tr>
<td>Extreme EVDF to extreme INPF</td>
<td>Talocrural</td>
<td>0.562</td>
<td>0.663</td>
<td>-0.495</td>
<td></td>
<td>55.3</td>
<td>1.2</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>Subtalar</td>
<td>-0.585</td>
<td>0.0449</td>
<td>0.810</td>
<td></td>
<td>27.5</td>
<td>3.9</td>
<td>0.141</td>
</tr>
<tr>
<td>Extreme EV to extreme IN</td>
<td>Talocrural</td>
<td>0.615</td>
<td>0.547</td>
<td>-0.568</td>
<td></td>
<td>40.9</td>
<td>2.6</td>
<td>0.063</td>
</tr>
<tr>
<td></td>
<td>Subtalar</td>
<td>-0.585</td>
<td>0.076</td>
<td>0.808</td>
<td></td>
<td>33.4</td>
<td>5.4</td>
<td>0.161</td>
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<tr>
<td>Extreme EVPF to extreme INDF</td>
<td>Talocrural</td>
<td>-0.450</td>
<td>-0.408</td>
<td>-0.794</td>
<td></td>
<td>13.8</td>
<td>0.3</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>Subtalar</td>
<td>-0.590</td>
<td>0.093</td>
<td>0.802</td>
<td></td>
<td>33.7</td>
<td>5.0</td>
<td>0.149</td>
</tr>
</tbody>
</table>

4. Discussion

With the 3D CT stress-test technique, normal ranges of motions of the ankle joints in a relatively young and healthy population were obtained. The coupled and combined ranges of motion of the tibia and calcaneus relative to the talus were documented. The results confirm the expected increase in accuracy and consistency of the application of the new 3D CT stress-test technique. Additionally, the inter-subject variability of FHA parameters was minimized by using the local coordinate system of the talus as defined by its geometric principal axes as reference system instead of anatomical axes. Scaling of all bones to a mean size only concerned the translation values.
4.1. Finite helical axes orientation

The high consistency in the orientation of the talocrural FHAs during DF–PF and EVDF–INPF movement can be attributed to joint geometry. During both movements, the talus at the talocrural joint is guided by stiff bony structures over a considerable motion range, facilitating a large and consistent rotation. Additionally, the talus has a preferred anatomical endpoint in these four enforced foot positions, which apparently is similar for all subjects. The other two ranges in motion, EV–IN and EVPF–INDF, are unnatural to the talocrural joint. Variations in the externally applied load location due to variation of subjects’ foot sizes in combination with variation in ankle mortise flexibility, ligament laxity, and congruency of the talar surface in the ankle mortise can significantly influence the extreme end position, for EV–IN and EVPF–INDF. This results in lower consistency of talocrural FHA orientations.

In the subtalar joint, FHA orientations show high consistency, except for DF–PF motion. The latter is an unnatural and limited motion in the subtalar joint. Conclusively, the EVDF–INPF movement gives the most consistent FHA orientation for both the subtalar and ankle joint.

4.2. Rotation

The talocrural joint has a large DF–PF rotation component in the sagittal plane [23]. As the talocrural joint has relatively limited bony containment, multidirectional motion becomes possible. Inversion–eversion and internal–external rotation result from the limited bony containment, the ankle mortise flexibility and ligament laxity. Subtalar motion predominantly exists of coupled inversion–internal rotation or eversion–external rotation, as a result of the specific anatomy of the subtalar joint [30]. Its two or three articular facets have a vertical aspect in the coronal plane [3, 26]. Consequently, subtalar FHAs run more in anterior–posterior direction than talocrural FHAs, leading to marginal PF–DF rotation. From the direction of the FHAs of both joints and their rotational components (Fig. 4), it becomes clear that rotation around either of the three anatomical axes requires combined motions [20]. Concluding, absence of or enhanced combined inversion and internal rotation during EVDF–INPF and EV–IN movement can be considered abnormal [25]. On the other hand, the presence of combined motion for DF–PF movement in a healthy population is marginal.

4.3. Translations

Our loading protocol focused on rotational range of motion. Thereto, no true absolute maximum translations were determined. The translations can be considered as motions that are coupled to the forced rotations. The result was that subtalar translations exceeded talocrural translations. For clinical diagnosis, non-scaled translations would have to be more than 5 mm in all range of motion directions to be indicative for an abnormality as based on their standard deviations found in our normal population.
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4.4. Other 3D stress techniques

Other 3D stress techniques have been described [23, 25, 28, 29, 33]. The various study designs differ from our technique and set up in the following aspects: the use of MRI instead of CT [10, 29, 33], investigation of a limited number of foot positions (Metz-Schimmerl et al. [23]: neutral, 12° dorsi-flexion and 23° planter flexion, Udupa et al. [33]: neutral, extreme pronation to extreme supination in 10° intervals), in vitro measurements instead of in vivo measurements of ankles [25], and linking CT-data sets to dynamic measurements instead of focusing on clinical diagnosis [28]. In addition to these differences, quantitative comparison is even more complicated, because in our study, the rotation components were established by decomposition of motion along the talar geometrical principal axes. These do not run parallel to the global anatomical directions, but were selected to make inter-individual comparisons less prone to errors in aligning the coordinate axes.

For instance, in this study the talocrural FHA for DF–PF movement is orientated obliquely relative to the standard anatomical sagittal axis which results in a coupled motion (Fig. 4). Generally, our results on FHA directions and rotations are of the same order of magnitude as other studies [12, 38]. All these studies reveal important information on the kinematics of the ankle joint, but their results are sometimes hard to interpret for clinical purposes [10, 25, 33].

4.5. Clinical application

The proposed 3D stress technique is intended to be a diagnostic tool that aims at describing the complete range of motion of the ankle in clinically relevant terms. A large advantage of this new technique is the quantitative detailed information. Grood and Suntay [8] introduced clinically relevant terms to describe motion by defining a specific rotation sequence, which mimicked a cardan system. However, we preferred representation in FHA parameters and their rotation components in anatomical directions for easy interpretation of the results by clinicians (Fig. 4) [33]. The reason is that the finite helical axis method is free of interobserver errors regarding coordinate systems and the rotation components always represent the true spatial rotation, as opposed to the three sequence-dependent Euler angles in a cardinal representation [1].

We propose to use the combination of \( n \) and \( \theta \) as a new set of diagnostic parameters, as it is expected that in a pathologic ankle both \( n \) and \( \theta \) are altered compared to a healthy subject population. If required, a bilateral 3D CT stress-test could be performed to compare the orientations of the FHAs and the rotations of the pathologic ankle with the contralateral (healthy) ankle. As intra-subject variability in joint laxity can be assumed to be lower than variability in joint laxity within a normal population, a smaller deviation from normal can be detected.

Based on the results, PF–DF and EVDF–INPF movements showed the most consistent orientations of FHAs and rotation values (all SD < 11.5°). Measuring bone positions and orientation in the four foot positions belonging to these ranges of motion has the highest potential to optimize detection of an abnormal range of motion of the ankle or subtalar joint. Notice that the EVDF–INPF movement is comparable to the talar tilt test. There was a mean \( \theta \) 18.5° (SD 4.6°) of talocrural inversion and a mean \( \theta \) 18.2° (SD 3.9°) of subtalar inversion [25]. When talocrural inversion exceeds...
subtalar inversion by more than 5°, talocrural laxity can be suspected. This suggestion is supported by our clinical case (Fig. 4).

In addition to quantitative parameters, the visualization of the bones in 3D should facilitate the insight in the complex functional pathologic anatomy and the restraining function of the articulations and soft tissues (Fig. 3) [31, 33].

The minimally required dose to produce CT-scans suitable for segmentation was determined a priori. For clinical assessment of ankle joint pathology, a reduced number of scanned foot positions is necessary (DF, PF, EVDF, INPF). This will account for 0.13 mSv, as opposed to 0.3 mSv for nine positions and opposed to 0.06 mSv for a set of stress radiographs (two neutral, two talar tilt, and two anterior drawer).

At this stage both the footplate and the segmentation need improvement for actual clinical introduction. A new footplate that is smaller and more ergonomic is required. Segmentation – even though performed semi-automatically – still takes a considerable amount of time. In the future, this process needs to be further automated to speed up data processing and analysis. A next step will involve studying ankle or subtalar joint pathology and the resulting changes in FHA parameters using the 3D CT stress-test.

5. Conclusions

The 3D CT stress-test enables one-stage measurement of subtalar and talocrural joint range of motion simultaneously by CT-scanning of the bones in various loaded conditions. In healthy subjects, EVDF–INPF movement showed the most consistent orientation of FHAs and smallest variation in rotation for both ankle and subtalar joint. DF–PF motion is restricted to the talocrural joint and shows high consistency in FHAs orientation. Subtalar FHAs shows good consistency for EV–IN, EVDF–INPF and EVPF–INDF movement. EV–IN always occurs as a combined motion in both joints, where twice as much eversion occurs in the subtalar joint as in the talocrural joint. The general orientation of the FHAs leads to coupling of inversion to internal rotation and eversion to external rotation in both joints [20, 30], and absence of this coupling may indicate pathology. The clinical case on suspected subtalar instability clearly indicates the relevance and potential of the 3D CT stress-test. Optimization of the footplate and segmentation, and further documentation of patients are the next steps towards implementation in clinical practice.

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