WEIGHT BEARING CT AND RELATIVE ORIENTATION OF FOOT BONES: EFFECT OF LOADING AND HEELED SHOES

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ABSTRACT

The purpose of this article is to determine the orientation and relative position of the foot bones in Weight Bearing CT, highlighting the effect of the load and the shoe with the heel. Thanks to a Cone Beam CT (OnSight 3D Extremity System, Carestream) equipment, three scans of the foot of a healthy young subject were carried out in three conditions: “unloading”, “loading”, and wearing a shoe with “heel”. In order to assess the accuracy of the articular angles of the foot through non-invasive measurements, a measurement was performed by Gait-Analysis with passive markers in the same conditions. The effect of the “load” resulted in a significant alteration of the foot posture especially in the sagittal plane, with crushing of the longitudinal medial arch. The heeled shoe involves enormous deformations at the level of the metatarsophalangeal joints and the ankle.

INTRODUCTION

Cone Beam Computed Tomography (CBCT) is a radiological imaging technology introduced since 1998 that uses an X-ray source that makes a single complete 360° turn around the object to be examined, emitting a conical or pyramidal beam rather than reproducing sections or body layers of the patient as in CT. This technique has greatly reduced exposure to radiation, allowing moreover a better three-dimensional resolution of the images. In fact, the Cone Beam CT has an average X-ray exposure 23 times lower than that of conventional CT. The radiological discipline that has made Cone Beam CT the most successful is that relating to the dento-maxillofacial district. Although this technology is widely used in dento-maxillofacial diagnostics, it also finds applications in interventional radiology, in guided imaging radiotherapy, in mammography, in the study of the lower and upper joints. The present study was carried out using a Cone Beam CT (OnSight 3D Extremity System, Carestream) which allows to obtain different 3D images at high resolution and with a very low dose and ensures an accurate diagnosis of the upper extremities in 3D and the lower extremities under load, optimizing both performance and productivity. The work focused on the orientation and relative position of the foot bones in Weight Bearing CT, highlighting the effect of the load and the shoe with the heel. Three scans of the foot of a healthy young subject were carried out in the three conditions: “unloading”, “loading”, and wearing a shoe with “heel”. The upper variable was therefore not added, but only the heel variable was managed, so as to allow the foot to be free and not squashed.

MATERIALS AND METHODS

The project was carried out at the Rizzoli Orthopedic Institute in Bologna, starting primarily from the scans of the foot thanks to the use of the CARESTREAM OnSight 3D Extremity System:

1. The first scan, scout and CBCT, was done with the left foot under load without a shoe.

Fig. 1-2-3 - From left: CBCT scan in loading without shoe; top view of the left foot under load; seen from behind of the left foot under load.
2. These second scan, CT only, was done with the left foot under load with the upper of the left foot heel with the heel cut.

3. The third CT scan was performed in unloading on the left foot without a shoe.

The scans were carried out with a very low dose since the goal was to study the modification of the bones of the foot in different positions, and not to make a diagnosis.

In order to evaluate the accuracy of the articular angles of the foot by means of non-invasive measurements, a measurement was performed by Gait Analysis with passive markers in the same conditions of “unloading”, “loading” and “heel”, in the GAIT laboratory ANALYSIS (or computerized analysis of walking) of the Rizzoli Orthopedic Institute, which allows you to monitor movement and quantitatively measure aspects of walking. The laboratory is equipped with an infrared camera system capable of recording the luminous signal of the markers that are positioned on the patient and transducing it into a digital signal. The first step was to perform anthropometric measurements: only height and body weight in this case.

Then the markers were placed on the left foot and leg, i.e. passive markers of reflective material. After positioning the body markers, a first static acquisition was performed with the left foot under load and the right leg raised. The standing position was maintained for about 2-5 seconds during which positions were acquired. These measures, integrated with the anthropometric ones, allow to calculate the reference systems associated with the bone segments and the position of the articular centers of the lower limbs. A second trial was then performed with the shoe under heel under load. The third test was carried out in the supine position. The work through Gait Analysis aimed to provide more detailed information on the structure of the foot, comparing the data already obtained through the Cone Beam CT performed.

After performing the scans and obtaining further data thanks to Gait Analysis, the next step was to identify the main radiographic angles of the foot on the CBCT scans performed. The measurements relating to the Gait Analysis of the joint angles were calculated using the “Rizzoli Foot Model”, thanks to the group of the “Movement Analysis Laboratory”.

Fig 4-5 - CBCT scan under load with high-heeled shoe.

Fig.6-7-8 – From left: CBCT sitting unloading; left foot inside the equipment without shoe; left foot without shoe with closed door.

Fig 9-10-11-12 – From top left, clockwise : Gait Analysis acquisition with left foot under load; with shoe with heel (front view); with heeled shoe (side view); unloading.

Fig. 13-14-15 – From top left, clockwise: heel angle in the unloading, loading and heel conditions.
RESULTS AND DISCUSSION

Once the main radiographic angles were calculated, the measurements were put into four tables, two referring to the loading and unloading position in CBCT and Gait Analysis. Two referred to the loading and heel position in CBCT and Gait Analysis. In each table, the differences between the “unloaded” vs “loaded” and “heel” vs “loaded” positions were calculated both in real value and as absolute value. Furthermore, the percentage differences, the mean absolute difference and the standard deviation were obtained.

| ANGLES ° | ANATOMICAL PLANE | LOAD | UNLOADING | RELATIVE DIFFERENCE | ABSOLUTE DIFFERENCE | DIFF. % |
|----------|----------------|------|-----------|---------------------|---------------------|--------|
| Calcaneal Inclination Angle | Sagittal | 24,34 | 26,58 | -2,24 | 2,24 | -8,4% |
| Talar declination angle | Sagittal | 24,32 | 26,77 | -2,45 | 2,45 | -9,2% |
| First metatarsal declination angle | Sagittal | 126,9 | 126,73 | 0,17 | 0,17 | 0,1% |
| Fifth metatarsal declination angle | Sagittal | 106,56 | 144,48 | -37,92 | 37,92 | -26,2% |
| Maery’s angle | Sagittal | 11,8 | 16,04 | -4,24 | 4,24 | -26,4% |
| Lateral talo-calcaneal angle | Sagittal | 56,5 | 42,31 | 14,19 | 14,19 | 33,5% |
| MIP1 | Sagittal | 12,14 | 25,12 | -12,98 | 12,98 | -51,7% |
| Tibio-talar angle | Sagittal | 102,33 | 115,56 | -13,23 | 13,23 | -11,4% |
| P1D1 | Sagittal | 10,86 | 6,64 | 4,22 | 4,22 | 63,6% |
| Talo-navicular angle | Sagittal | 12,71 | 12,79 | -0,08 | 0,08 | -0,6% |
| Moreau Costa-Bertani angle | Sagittal | 117,37 | 98,32 | 19,05 | 19,05 | 19,4% |
| Hallux abductus angle | Transverse | 11 | 7,06 | 3,94 | 3,94 | 55,8% |
| 1-2 Intermetatarsal angle | Transverse | 8,8 | 0,81 | 7,99 | 7,99 | 986,4% |
| Tibial-calcaneal angle | Coronal | 15,35 | 26,5 | -11,15 | 11,15 | -42,1% |

Fig. 16 – CBCT foot angles: loading and unloading with difference expressed in real and absolute value.

| ANGLES ° | ANATOMICAL PLANE | LOAD | UNLOADING | RELATIVE DIFFERENCE | ABSOLUTE DIFFERENCE | DIFF. % |
|----------|----------------|------|-----------|---------------------|---------------------|--------|
| Ankle Dors/Pla | Sagittal | 1,369 | -5,453 | 6,822 | 6,822 | -125,1% |
| Ankle Inv/Ev | Transverse | -0,706 | 11,332 | -12,038 | 12,038 | -106,2% |
| Ankle Ab/Add | Coronal | 8,631 | 11,708 | -3,077 | 3,077 | -26,3% |
| Shank-Calc Flex/Ext | Sagittal | 6,182 | -1,717 | 7,899 | 7,899 | -460% |
| Shank-Calc Inv/Ext | Transverse | 13,365 | -2,094 | -11,271 | 11,271 | 538,3% |
| Shank-Calc Ab/Add | Coronal | 12,308 | 15,417 | -3,109 | 3,109 | -20,2% |
| Calc-MidFoot Flex/Ext | Sagittal | 24,867 | 34,519 | -9,652 | 9,652 | -28% |
| Calc-MidFoot Inv/Ext | Transverse | -2,908 | 2,142 | -5,050 | 5,05 | -235,8% |
| Calc-MidFoot Ab/Add | Coronal | -3,839 | -0,613 | -3,226 | 3,226 | 526,3% |
| MidFoot-Met Flex/Ext | Sagittal | -68,673 | -75,146 | 6,473 | 6,473 | -8,6% |
| MidFoot-Met Inv/Ext | Transverse | 5,808 | 18,420 | -12,612 | 12,612 | -68,5% |
| Calc-Met Flex/Ext | Sagittal | 43,179 | -41,298 | 1,881 | 1,881 | 4,6% |
| Calc-Met Inv/Ext | Transverse | 8,281 | 19,550 | -11,269 | 11,269 | -57,6% |
| Calc-Met Ab/Add | Coronal | -1,210 | -0,513 | -0,697 | 0,697 | 135,9% |
| I Met vs Hallux | Transverse | 27,344 | 31,049 | -3,705 | 3,705 | -11,9% |
| II vs I Met | Transverse | 11,572 | 12,482 | -0,910 | 0,91 | -7,3% |
| II vs V Met | Transverse | 3,382 | -0,619 | 4,001 | 4,001 | -646,4% |
| I Met vs Hallux | Sagittal | 18,786 | 19,617 | -0,831 | 0,831 | -4,2% |
| I Met vs Ground | Sagittal | 24,559 | -67,331 | 91,890 | 91,890 | -136,5% |
| II Met vs Ground | Sagittal | 26,573 | -57,792 | 84,365 | 84,365 | -146% |
| V Met vs Ground | Sagittal | 2,692 | -72,095 | 74,787 | 74,787 | -103,7% |
| MLA | Sagittal | 123,375 | 129,949 | -6,574 | 6,574 | -5,1% |

Fig. 17 – Foot angles in Gait Analysis: loading and unloading with difference expressed in real and absolute value.
Foot angles in Gait Analysis: loading and unloading with difference expressed in real and absolute value.

**Fig. 18** – CBCT foot angles: heel and load with difference expressed in real and absolute value.

| ANGLES ° | ANATOMICAL PLANE | HEEL | LOAD | RELATIVE DIFF. | ABSOLUTE DIFF. | DIFF. % |
|----------|------------------|------|------|----------------|----------------|--------|
| Calcaneal Inclination Angle | Sagittal | 20.67 | 24.34 | -3.67 | 3.67 | -15% |
| Talar declination angle | Sagittal | 60.46 | 24.32 | -26.14 | 26.14 | 149% |
| First metatarsal declination angle | Sagittal | 125.52 | 126.9 | -1.38 | 1.38 | -1% |
| Fifth metatarsal declination angle | Sagittal | 134.48 | 106.56 | 27.92 | 27.92 | 26% |
| Maery's angle | Sagittal | 1.67 | 11.8 | -10.13 | 10.13 | -86% |
| Lateral talo-calcaneal angle | Sagittal | 41.56 | 56.5 | -14.94 | 14.94 | -26% |
| M1P | Sagittal | 71.16 | 12.14 | -59.02 | 59.02 | 486% |
| Tibio-talar angle | Sagittal | 148.84 | 102.33 | 46.51 | 46.51 | 45% |
| PIDI | Sagittal | 6.27 | 10.86 | -4.59 | 4.59 | -42% |
| Talo-navicular angle | Sagittal | 5.02 | 12.71 | -7.69 | 7.69 | -61% |
| Moreau Costa-Bertani angle | Sagittal | 114.58 | 117.37 | -2.79 | 2.79 | -2% |
| Hallux abductus angle | Transverse | 11.89 | 11 | 0.89 | 0.89 | 8% |
| 1-2 Intermetatarsal angle | Transverse | 5.73 | 8.8 | -3.07 | 3.07 | -35% |
| Tibial-calcaneal angle | Coronal | 4.11 | 15.35 | -11.24 | 11.24 | -73% |

By dividing the angles according to the sagittal, axial and coronal reference anatomical planes, it was found that in the CBCT and in the Gait Analysis, the effect of the “loading and unloading” conditions is most noticeable in the sagittal plane. In fact, it is noted that the average of the absolute differences in the sagittal plane as regards the “loading” and “unloading” conditions in the CBCT is 10.07 ° with respect to the average in the axial plane which is 5.97 °. In the Gait Analysis we have the same result: the effect of the “loading and” unloading “conditions is most noticeable in the sagittal plane. In fact, the averages...

| ANGLES ° | ANATOMICAL PLANE | HEEL | LOAD | RELATIVE DIFFERENCE | ABSOLUTE DIFFERENCE | DIFF. % |
|----------|------------------|------|------|---------------------|---------------------|--------|
| Ankle Dors/Pla | Sagittal | -36,441 | 1,369 | -37,810 | 37,81 | 2761,87% |
| Ankle Inv/Ev | Transverse | -3,053 | -0,706 | -2,347 | 2,347 | 323,44% |
| Ankle Ab/Add | Coronal | 16,046 | 8,631 | 7,415 | 7,415 | 85,91% |
| Shank-Calc Flex/Ext | Sagittal | -24,586 | 6,182 | -30,768 | 30,768 | 497,70% |
| Shank-Calc Inv/Ev | Transverse | -19,140 | -13,365 | -5,775 | 5,775 | 43,21% |
| Shank-Calc Ab/Add | Coronal | 17,602 | 12,308 | 5,294 | 5,294 | 43,01% |
| Calc-MidFoot Flex/Ext | Sagittal | 23,093 | 24,867 | -1,774 | 1,774 | -7,13% |
| Calc-MidFoot Inv/Ev | Transverse | 1,401 | -2,908 | 4,309 | 4,309 | 148,18% |
| Calc-MidFoot Ab/Add | Coronal | -2,047 | -3,839 | 1,792 | 1,792 | -46,68% |
| MidFoot-Met Flex/Ext | Sagittal | -84,594 | -68,673 | -15,921 | 15,921 | 23,18% |
| MidFoot-Met Inv/Ev | Transverse | 9,223 | 5,808 | 3,415 | 3,415 | 58,80% |
| MidFoot-Met Ab/Add | Coronal | 4,008 | 2,910 | 1,098 | 1,098 | 37,73% |
| Calc-Met Flex/Ext | Sagittal | -61,754 | -43,179 | -18,575 | 18,575 | 43,02% |
| Calc-Met Inv/Ev | Transverse | 11,396 | 8,281 | 3,115 | 3,115 | 37,62% |
| Calc-Met Ab/Add | Coronal | 5,224 | -1,210 | 6,434 | 6,434 | 531,74% |
| I Met vs Hallux | Transverse | 20,290 | 27,344 | -7,054 | 7,054 | -25,80% |
| II vs I Met | Transverse | 7,018 | 11,572 | -4,554 | 4,554 | -39,35% |
| II vs V Met | Transverse | -3,217 | 3,382 | -6,599 | 6,599 | 195,12% |
| I Met vs Hallux | Sagittal | 56,431 | 18,786 | 37,645 | 37,645 | 200,39% |
| I Met vs Ground | Sagittal | 60,843 | 24,559 | 36,284 | 36,284 | 147,74% |
| II Met vs Ground | Sagittal | 66,364 | 26,573 | 39,791 | 39,791 | 149,74% |
| V Met vs Ground | Sagittal | 44,752 | 2,692 | 42,060 | 42,06 | 156,41% |
| MLA | Sagittal | 127,348 | 123,375 | 3,973 | 3,973 | 3,22% |

**Fig. 19** – Foot angles in Gait analysis: heel and load with difference expressed in real and absolute value.
of the absolute differences in the three sagittal, axial and coronal anatomical planes are respectively 29.12° -7.61° and 3.11°.

| SAGITTAL PLANE | TRANSVERSE PLANE |
|----------------|------------------|
| 10±11°         | 6±3°             |

**Fig. 20 – Load-CBCT**

Also with regard to the two conditions of “heel” and “load” there is a greater effect in the sagittal plane, both in the CBCT and in the Gait Analysis. The average value relative to the sagittal reference plane between the two conditions of “heel” and “load” in the CBCT is 19.53°; in the axial plane instead it is 1.98°.

In Gait Analysis the averages of the absolute differences between the “heel” and “load” conditions in the sagittal, axial and coronal anatomical planes are respectively 26.46° -4.65° and 4.41°.

| SAGITTAL PLANE | TRANSVERSE PLANE |
|----------------|------------------|
| 26±3°          | 6±3°             |

**Fig. 21 – Load-Gait-analysis effect**

From this it appears that the effect of the “load” has resulted in a significant alteration of the posture of the foot especially in the sagittal plane, with flattening of the medial longitudinal arch. The effect of the load is more visible in the sagittal plane for two reasons: for an anatomical reason as the joints have a greater degree of freedom in the sagittal plane and for the weight force, since the vertical load belongs to the sagittal plane, in fact the Ground forces produce moments of the joints.

The Gait Analysis also shows important data on the structure of the foot, in fact the effect of the load is confirmed, but not all the data obtained are consistent: this can be seen, for example, from the longitudinal medial arch (Costa Bertani angle in CBCT) which does not widens from the unloading position to the loading position in the Gait; there is thus a situation opposite to that of the CBCT which is more reliable and accurate.

In fact, the Costa Bertani CBCT angle in unloading is 98.32° and 117.37° in loading: it widens from the unloading position to the loading position. In Gait Analysis there is an opposite situation, in which the angle decreases from the unloading position (129.94°) to the loading position (123.37°).

In conclusion, the results obtained are the fact that the effect of the loading and unloading conditions are more visible in the sagittal plane; the same principle applies to the two conditions of heel and load. CBCT is also more precise and reliable than Gait Analysis, despite being a non-invasive method.

Finally, the heeled shoe revealed the truth about the enormous stress exerted on the structure of the foot which is subjected to joint rotations very close to the maximum excursion.

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