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 1998thatusesanX-raysourcethatmakesasinglecomplete360°turnaroundtheobjecttobeexamined, 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 timeslowerthanthatofconventionalCT.TheradiologicaldisciplinethathasmadetheConeBeamCT themostsuccessfulisthatrelatingtothedento-maxillofacialdistrict. Althoughthistechnologyiswidely 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 obtaindifferent3Dimagesathighresolutionandwithaverylowdoseinasinglescan,infactitensures an accurate diagnosis of the upper extremities in 3D and the lower extremities under load, optimizing bothperformanceandproductivity.Theworkfocusedontheorientationandrelativepositionofthefoot bonesinWeightBearingCT,highlightingtheeffectoftheloadandtheshoewiththeheel. Threescans 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 of the heeled shoe has been cut, as a closed-heeled shoe brings the forefoot to be crushed due to the narrow and deep toe and involves further modifications of the bones of the plant. The upper variable was therefore not added, but only the heel variable was managed, so as to allow the foot to be free and notsquashed.

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. Thesecondscan,CTonly,wasdonewiththe leftfootunderloadwiththeupperofthelefts hoewith the heelcut.
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 CTperformed.
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.

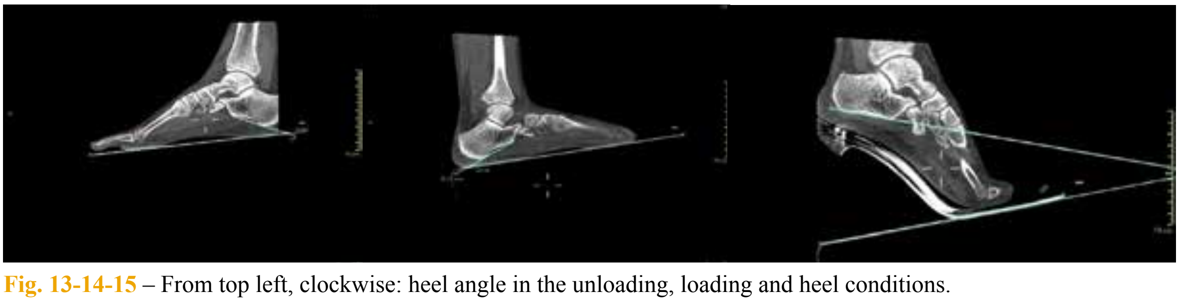

Fig. 13-14-15 – From top left, clockwise: heel angle in the unloading, loading and heel conditions.

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%
M1P1	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 Dor/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/Ev	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/Ev	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/Ev	Transverse	5,808	18,420	-12,612	12,612	-68,5%
MidFoot-Met Ab/Add	Coronal	2,910	-2,543	5,453	5,453	-214,4%
Calc-Met Flex/Ext	Sagittal	- 43,179	-41,298	-1,881	1,881	4,6%
Calc-Met Inv/Ev	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	91,89	-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	123,37 5	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.

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	36,14	36,14	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%
M1P1	Sagittal	71,16	12,14	59,02	59,02	486%
Tibio-talar angle	Sagittal	148,84	102,33	46,51	46,51	45%
P1D1	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%

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

ANGLES °	ANATOMICAL PLANE	HEEL	LOAD	RELATIVE DIFFERENCE	ABSOLUTE DIFFERENCE	DIFF. %
Ankle Dor/Pla	Sagittal	-36,441	1,369	-37,810	37,81	-2761,87 %
Ankle Inv/Ev	Transverse	-3,053	-0,706	-2,347	2,347	332,44%
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	1562,41 %
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.

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 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

SAGITTAL PLANE	TRANSVERSE PLANE	CORONAL PLANE
29±38°	8±5°	3±2°

Fig. 21 – Load-Gait-analysis effect

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
20±20°	2±2°

Fig. 22 – Heel Effect-CBCT

SAGITTAL PLANE	TRANSVERSE PLANE	CORONAL PLANE
26±15°	5±2°	4±3°

Fig. 23 – Heel Effect -Gait-Analysis.

From this it appears that the effect of the "load" has resulted in a significant alteration of the postureof 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 thejoints.
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 andprecise.
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 (129.949°) to the loading position (123.375°) .However, Gait has the advantage of being a non-invasive instrument, even if, with the following study, we used very low dose levels in CBCT, as the main objective was to accurately determine the orientation and relative position of the foot bones under realistic loading and also unloading conditions, and not that to make a diagnosis. Foot images were obtained at a radiation exposure level lower than traditional volumetric and "low" imaging technologies compared to other natural sources of radiationexposure.

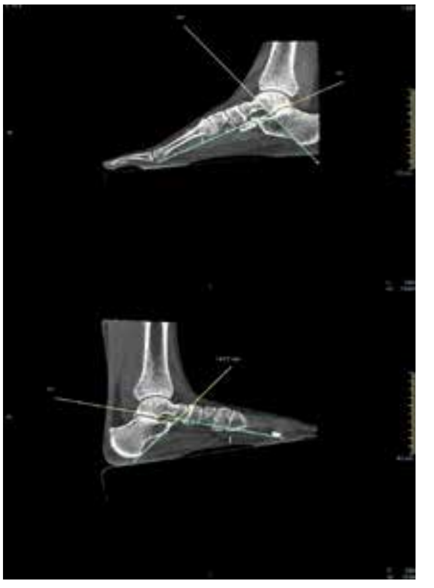

Fig. 24-25 – Costa Bertani CBCT angle in unloading (98.32°) and in loading (117.37°): it widens from the unloading position to the loading one. In Gait Analysis there is an opposite situation, in which the angle decreases from the unloading position (129.949°) to the loading position (123.375°)

As for the heeled shoe, it involves enormous deformations at the level of the metatarsophalangeal and ankle joints.
The Weight-Bearing acquisitions of the foot with high-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.
In conclusion, the results obtained are the fact that the effect of 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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