

# The value of axial loading three dimensional (3D) CT as a substitute for full weightbearing (standing) 3D CT: Comparison of reproducibility according to degree of load



Dong Hun Kang, Chan Kang\*, Deuk Soo Hwang, Jae Hwang Song, Seok Hwan Song

Department of Orthopedic Surgery, Chungnam National University School of Medicine, Daejeon, Republic of Korea

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## ABSTRACT

**Background:** Full weightbearing (WB) three dimensional computed tomography (3D CT) is an excellent imaging tool. However, due to its high cost, it is only used in a few hospitals. We evaluated the usefulness and cost-effectiveness of axial loading (AL) 3D CT by comparing bony alignments with standing radiographs, and assessed reproducibility according to the degree of AL.

**Methods:** Eighty patients (156 feet), who underwent standing radiographs and 3D CT with an AL device from January 2016 to May 2017, were investigated. According to the degree of AL (AL force  $\times$  100/body weight), the patients were randomly assigned to three groups: Group A (30–50%; n = 21, 40 feet), Group B (50–70%; n = 32, 63 feet), and Group C (70–100%; n = 27, 53 feet). The following angles were measured three times by two orthopedists: hallux valgus (HVA), 1st–2nd intermetatarsal (IMA1–2), and talonavicular coverage (TNCA), calcaneal pitch (CPA), talo–1st metatarsal (T1MA), and talo–calcaneal angle (TCA). Agreements between the two imaging methods were analyzed and compared according to the degree of axial loading in each group.

**Results:** Intra- and interobserver reliability was excellent ( $>0.75$ ). In Group A (30–50% AL), all of the angles except HVA and IMA1–2 differed ( $p < .05$ ). In Group B (50–70%), TNCA ( $p = .023$ ), T1MA ( $p = .017$ ), and TCA ( $p = .035$ ) differed. In Group C (70–100%), none of the angles differed between the two imaging methods ( $p > .05$ ). Higher agreement between the two imaging methods was realized when 70% or more ( $>70%$ ) AL was applied.

**Conclusions:** AL 3D CT with  $>70%$  axial load has full WB effects and can be substituted for expensive full WB 3D CT.

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## 1. Introduction

Weightbearing (WB) plain radiographs are a basic imaging tool to assess alignment and joint space for foot and ankle diseases [1] such as flat foot, hallux valgus, impingement of the tibiotalar joint or subtalar joint, and osteoarthritis. However, bony pathologies are often difficult to visualize due to superimposition of multiple adjacent bones that form the complex skeletal structure [2]. Three dimensional (3D) imaging with conventional computed tomography (CT) allows for the exact analysis of 3D data that are not influenced by projection and/or foot orientation but lack WB [3–5]. For this reason, full WB 3D CTs such as Planmed Verity (Planmed Oy, Helsinki, Finland), PedCAT (CurveBeam LLC, Warrington, IN,

USA) and so on, which are not affected by projection and/or foot orientation, were developed. However, these CT devices are not offered in most hospitals because of their high cost (a device for radiography is around \$100,000 United States Dollar (USD), whereas PedCAT and Planmed Verity are about \$350,000 USD and a CT is about \$400,000 USD). Furthermore, these devices are cost-ineffective because they are mostly used for the foot and ankle region. Actually, only four hospitals in South Korea have WB CT by May 2017, and only a few hospitals worldwide have them.

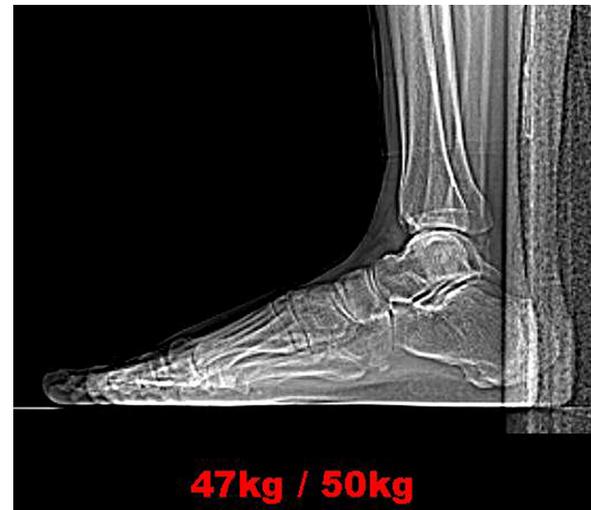
Thus, we specially devised an axial loading device for taking 3D CT scans in the supine position and called it “axial loading 3D CT”. We evaluate the cost-effectiveness and usefulness of axial loading 3D CT by comparing specific bony alignments (angles) with those on standing radiographs, assuming that angle measurements on standard radiographs were similar to angle measurements on WB CT, as both methods were performed while patients were standing. Another aim of this study was to assess reproducibility according to the degree of axial loading.

\* Corresponding author at: Department of Orthopedic Surgery, Chungnam National University School of Medicine, 266 Munwha-ro, Jung-gu, Daejeon 301-721, Republic of Korea.

E-mail address: [coolriver@cnuh.co.kr](mailto:coolriver@cnuh.co.kr) (C. Kang).

## 2. Materials and methods

The Institutional Review Board approved this study, and informed consent was obtained from all of the patients. Eighty patients (156 of 160 feet), who had undergone foot radiographs in full WB and in a standing position as well as axial loading 3D CT on the same day from January 2016 to May 2017, were investigated. Because both feet could be acquired by axial loading CT, involved and non-involved feet were all included except for four feet that were severely destroyed by charcot, rheumatoid arthritis (diagnosed before twenty years), or other factors. The study group included patients aged  $\geq 18$  years, who fulfilled the indications for radiographs and axial loading 3D CT. The indication for radiographs and axial loading 3D CT was defined by the following local standards. Exclusion criteria were as follows: age  $< 18$  years, no indication for radiographs and/or axial loading 3D CT, and participation in another orthopedic study [5]. For the axial loading 3D CT, we devised a long wooden board, fitted at its caudal end with a fixed vertical foot piece and at its cephalic end with an adjustable and locking shoulder device. Patients were placed supine on the wooden board. The feet rested over a platform made of strong spongiform radiolucent material, beneath which lay a weighing scale for measuring how much pressure the patient applies through the feet. The shoulders were positioned distal to the pads of the shoulder rail. The patients were instructed to push both feet towards the board by extending the knee as far as possible (Fig. 1 a, b). If a patient felt discomfort, the shoulder bar level was adjusted. Then axial loading forces were recorded as shown in the scale and saved with the CT image (Fig. 2). The degree of axial load (%) was defined as: axial loading force (kg)  $\times$  100/body weight (kg). The patients were randomly assigned to one of three

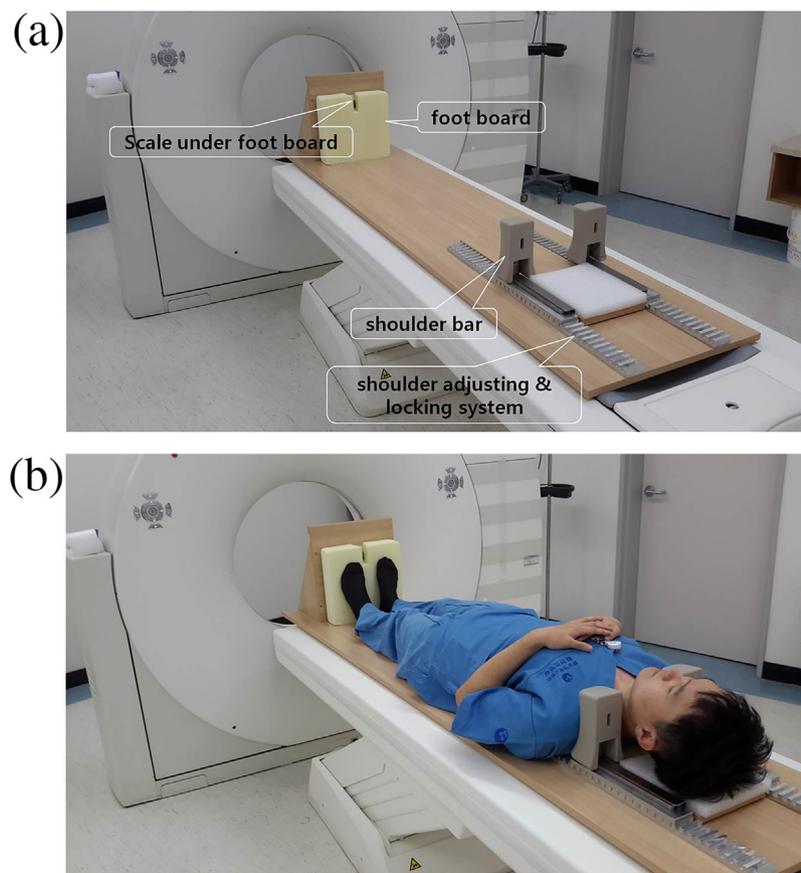


**Fig. 2.** The axial loading force is recorded as shown in the scale and saved with a computed tomography (CT) image. The front number indicates the axial loading force, and the back number indicates body weight.

groups according to the degree of axial load: Group A (30–50%; n = 21, 40 feet), Group B (50–70%; n = 32, 63 feet), and Group C (70–100%; n = 27, 53 feet).

### 2.1. Radiologic evaluation

Radiographic image acquisition followed a standardized protocol with a fully digital device. The patient was positioned



**Fig. 1.** Axial loading device. (a) Composition of the axial loading device. (b) The patients were instructed to push both feet towards the board by extending the knee as far as possible.

on a special step used to hold the apparatus for digital film. The X-ray emitter was adjusted and the images were taken (feet bilateral, dorsoplantar, and lateral views) [5,6]. After positioning the patient as described above for axial loading 3D CT (Siemens Somatom Emotion, Siemens Medical Solutions USA, Malvern, PA), both feet and ankles were scanned from 10 cm proximal to the ankle. Slice thickness was adjusted to 1 mm and pure scanning time was 60 s. Axial loading 3D CT was composed of coronal, axial, and sagittal views with 3D reformations (Fig. 3). The angles were digitally measured on PACS (Marosis M-view V5.4.10.40). The following angles were measured three times on both the foot and ankle by two different orthopedists: hallux valgus angle (HVA), first to second intermetatarsal angle (IMA1–2) and the talo-navicular coverage angle (TNCA) on the dorsoplantar projection for both feet and the calcaneal pitch angle (CPA), talo-first metatarsal angle (T1MA), and talo-calcaneal angle (TCA) on the lateral projection for both ankles. The angles were digitally measured, and agreements between the two imaging methods (standing radiographs and axial loading CT) were analyzed and compared statistically according to the degree of axial loading in the three groups. The HVA was defined as the angle between the axis of the dorsal protrusions of the hallux and the first metatarsal in the dorsoplantar view (radiograph) or the axial/horizontal 3D reformation (axial loading 3D CT). The IMA1–2 was defined as the angle between the axis of the first and second metatarsal in the dorsoplantar view (radiograph) or the axial/horizontal 3D reformation (axial loading 3D CT). The TNCA was defined as the angle between the axis of the articular surface of the talus and the navicular bone in the dorsoplantar view (radiograph) or the axial/horizontal 3D reformation (axial loading 3D CT) (Fig. 4a, b). The CPA was defined as the angle between the line from the lowest part of the posterior calcaneal process to the lowest part of the anterior calcaneal process and a horizontal line in the lateral view (radiograph) or a parasagittal 3D reformation (axial loading 3D CT). The T1MA was defined as the angle between the axis of the first metatarsal and the talus in the lateral view (radiograph) and a parasagittal 3D reformation (axial loading 3D CT). The TCA was defined as the angle between the lines drawn down the axis of the talus and calcaneus in the lateral view (radiograph) or a parasagittal 3D

reformation (axial loading 3D CT) (Fig. 5a, b). The plane for the measurement was virtually rotated within the 3D dataset to achieve exact congruency to the bone axes for axial loading 3D CT. The axes of the bones were defined as a straight vertical line between the centers of the bones drawn proximally to distally. These bone centers were defined by linear measurements [5].

## 2.2. Statistical analysis

Significant differences between standing radiographs and axial loading 3D CT in the three groups were assessed using the paired *t*-test. Intraobserver and interobserver reliability were quantified for all of the measurements using the intraclass correlation coefficient (ICC). An ICC value  $>0.75$  was considered excellent,  $0.4$ – $0.75$  was fair to good, and  $<0.4$  was poor [7]. A *P* value  $<0.05$  was considered statistically significant. SPSS for Windows (ver. 20.0; SPSS Inc., Chicago, IL, USA) was used for all of the statistical analyses.

## 3. Results

The patient profiles such as sex, mean age, axial loading force, body weight, and degree of axial load in the three groups are shown in Table 1. Intraobserver and interobserver reliabilities of the alignments for both imaging methods were excellent ( $>0.75$ ) (Table 2). In Group A (30–50% axial load), the parameters between the two imaging methods (radiographs vs. axial loading CT) were as follows (Table 3): HVA ( $16.3 \pm 7.56$  vs.  $16.3 \pm 7.49$ ), IMA1–2 ( $9.1 \pm 2.11$  vs.  $8.9 \pm 2.11$ ), TNCA ( $21.8 \pm 7.15$  vs.  $17.7 \pm 7.34$ ), CPA ( $17.6 \pm 4.74$  vs.  $20.0 \pm 4.67$ ), T1MA ( $8.7 \pm 5.23$  vs.  $6.4 \pm 4.64$ ), and TCA ( $44.6 \pm 5.97$  vs.  $43.2 \pm 5.83$ ). In Group B (50–70% axial load), the parameters were as follows (Table 4): HVA ( $16.3 \pm 11.4$ ), IMA1–2 ( $9.8 \pm 3.53$  vs.  $9.7 \pm 3.58$ ), TNCA ( $22.1 \pm 6.58$  vs.  $19.8 \pm 6.62$ ), CPA ( $18.3 \pm 4.87$  vs.  $19.2 \pm 4.78$ ), T1MA ( $7.8 \pm 4.97$  vs.  $6.2 \pm 4.89$ ), and TCA ( $45.5 \pm 5.23$  vs.  $45.2 \pm 7.59$ ). In Group C (70–100% axial load), the parameters were as follows (Table 5): HVA ( $20.0 \pm 11.0$  vs.  $19.9 \pm 11.0$ ), IMA1–2 ( $11.0 \pm 3.57$  vs.  $10.9 \pm 3.61$ ), TNCA ( $20.0 \pm 7.62$  vs.  $19.6 \pm 7.52$ ), CPA ( $19.0 \pm 4.31$  vs.  $19.3 \pm 4.16$ ), T1MA ( $7.2 \pm 4.56$  vs.  $6.9 \pm 4.49$ ), and TCA ( $45.7 \pm 5.52$  vs.  $46.0 \pm 5.64$ ). In Group A, all of the angles

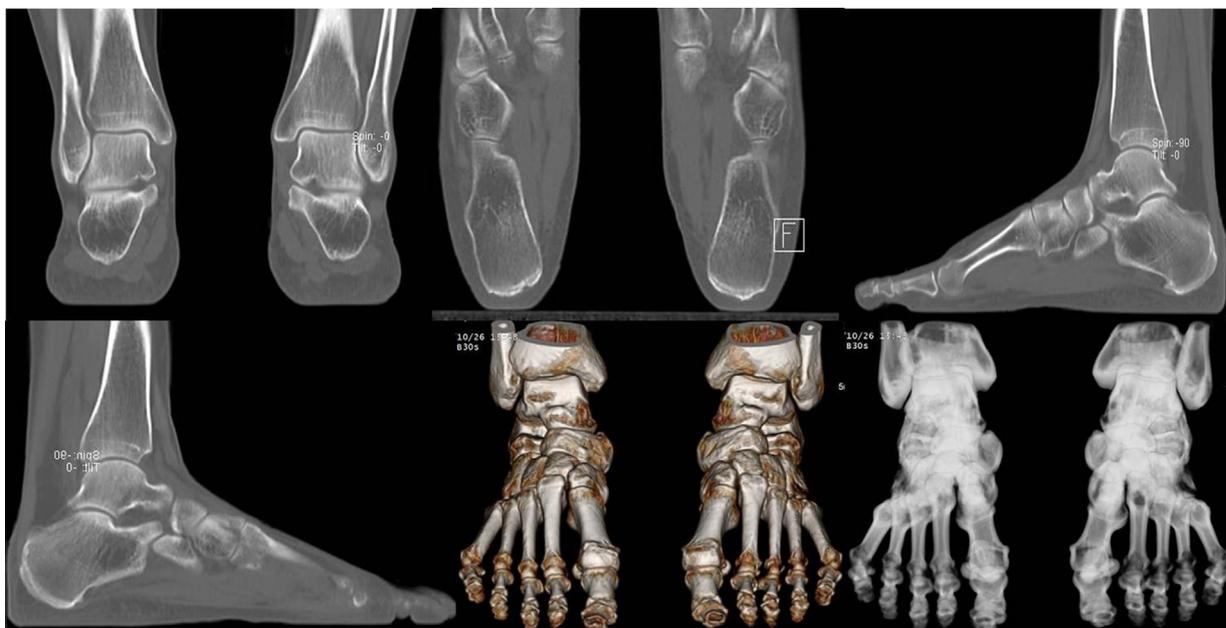
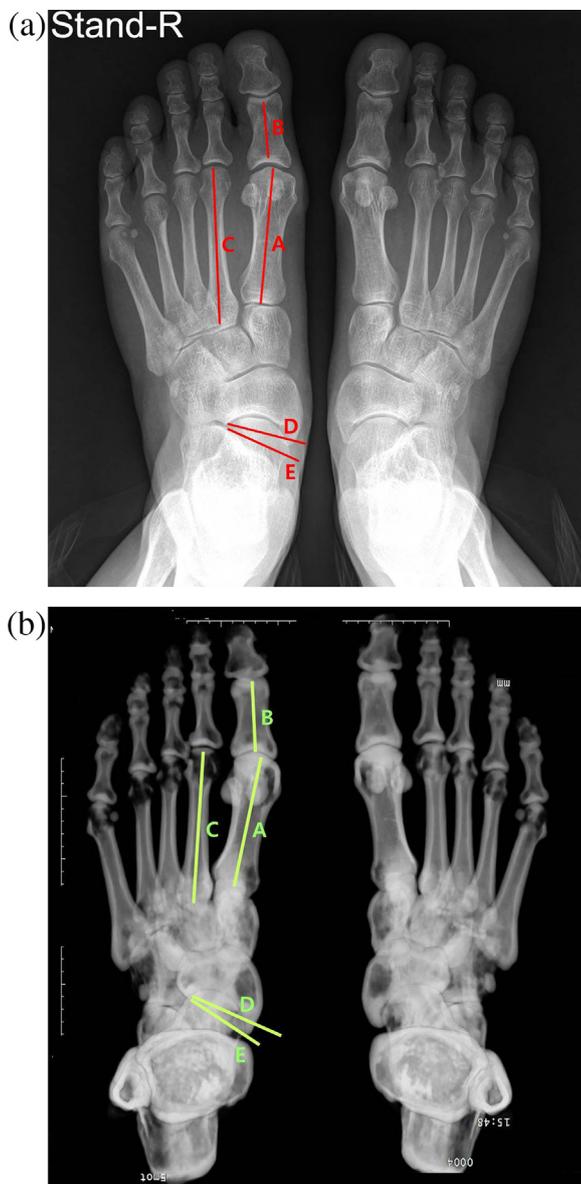
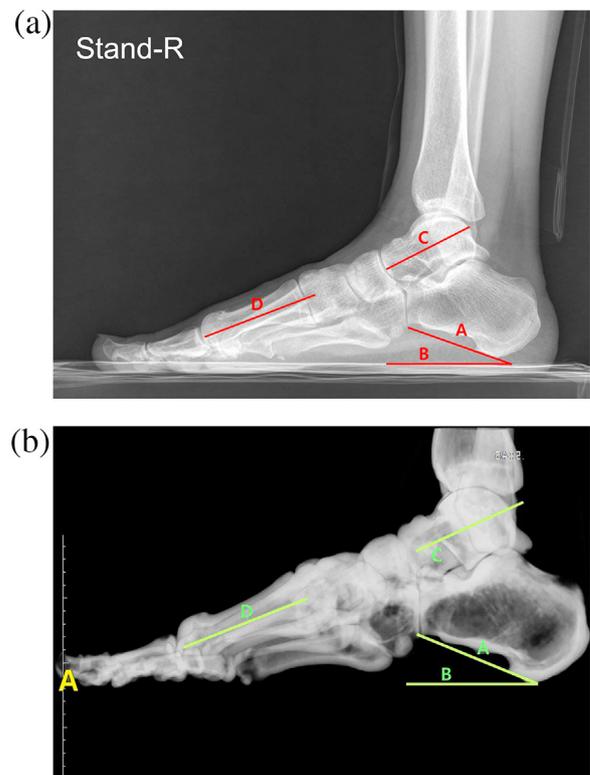


Fig. 3. Axial loading three dimensional computed tomography (3D CT) is composed of coronal, axial, and sagittal views, as well as 3D reformations. Both right and left images can be acquired with one shot, enabling abnormal lesions to be compared to normal anatomy.



**Fig. 4.** Measurements of HVA, IMA1–2, and TNCA using the two imaging methods. HVA is the angle between lines A and B. IMA1–2 is the angle between lines A and C. TNCA is the angle between lines D and E. (a) Measurements of HVA, IMA1–2, and TNCA on a dorsoplantar view of a standing radiograph. (b) Measurements of HVA, IMA1–2, and TNCA on axial loading three-dimensional computed tomography (3D CT).

except HVA ( $p=0.927$ ) and IMA1–2 ( $p=0.124$ ) differed between the two imaging methods ( $p < 0.05$ ). In Group B, TNCA ( $p=0.002$ ), T1MA ( $p=0.001$ ), and TCA ( $p=0.035$ ) differed between the two imaging methods but HVA ( $p=0.846$ ), IMA1–2 ( $p=0.952$ ), and CPA ( $p=0.252$ ) did not. In Group C, none of the angles were different significantly between the two imaging methods ( $p > 0.05$ ). In other



**Fig. 5.** Measurements of CPA, T1MA, and TCA using the two imaging methods. CPA is the angle between lines A and B. T1MA is the angle between lines C and D. TCA is the angle between lines A and C. (a) Measurements of CPA, T1MA, and TCA on dorsoplantar view of standing radiograph. (b) Measurements of CPA, T1MA, and TCA on axial loading three-dimensional computed tomography (3D CT).

words, there was higher agreement between the two imaging methods when 70% or more (>70%) axial load was applied.

#### 4. Discussion

WB radiographs of the foot and ankle are essential for the accurate diagnosis of osteoarthritis and ankle impingement, as well as for the preparation of operative procedure plans. Furthermore, CTs also improve the accuracy of hindfoot alignment, as well as the location and degree of ankle osteoarthritis by eliminating the problems of superimposition of the bones on routine radiographs.

Several groups have developed various devices that produce WB during CT scan examinations. Malicky et al. [8] and Greisberg et al. [9] devised a custom loading frame (75 N axial compression) for adult flatfoot studies. Ananthakrishnan et al. [10] and Ledoux et al. [11] applied either a 10% or 20% body weight load to the foot in the supine position for flatfoot studies, and Ferri et al. [3] applied a 50% body weight load to the foot with a specialized apparatus in the sitting position for dynamic CT studies of pes planus. Kido et al. [4,12,13] developed a foot loading device, which was applied

**Table 1**  
Patient profiles in the three groups.

	Group A (30–50%)	Group B (50–70%)	Group C (70–100%)
Number	21 (40 feet)	32 (63 feet)	27 (53 feet)
Sex	M 7/F 14	M 12/F 21	M 11/F 17
Age	51.6 (19.0–79.0)	50.7 (20.0–67.0)	49.5 (20.0–74.0)
Axial loading force (kg)	29.3 (20.0–40.0)	38.6 (29.0–55.0)	48.6 (32.0–62.0)
Body weight (kg)	64.9 (45.0–81.0)	65.2 (49.0–90.0)	59.6 (43.0–84.0)
Degree of Axial load (%)	45.2 (35.1–50.0)	59.2 (50.8–68.8)	81.8 (70.6–100.0)

**Table 2**  
Reliability assessed by the intraclass correlation coefficient (ICC).

Parameters		Intra-observer (ICC 95% CI)	Inter-observer (ICC 95% CI)
HVA	Radiographs	0.93 (0.87–0.96)	0.86 (0.81–0.90)
	Axial loading CT	0.86 (0.82–0.90)	0.84 (0.81–0.88)
IMA1–2	Radiographs	0.91 (0.83–0.94)	0.85 (0.79–0.88)
	Axial loading CT	0.85 (0.82–0.89)	0.81 (0.76–0.85)
TNCA	Radiographs	0.87 (0.81–0.91)	0.85 (0.79–0.88)
	Axial loading CT	0.90 (0.85–0.94)	0.80 (0.76–0.85)
CPA	Radiographs	0.89 (0.84–0.95)	0.90 (0.87–0.92)
	Axial loading CT	0.81 (0.77–0.86)	0.87 (0.82–0.94)
T1MA	Radiographs	0.85 (0.82–0.89)	0.76 (0.72–0.81)
	Axial loading CT	0.92 (0.89–0.96)	0.78 (0.75–0.82)
TCA	Radiographs	0.79 (0.75–0.83)	0.77 (0.70–0.82)
	Axial loading CT	0.82 (0.77–0.86)	0.76 (0.71–0.79)

HVA: hallux valgus angle, IMA1–2: first to second intermetatarsal angle, TNCA: talonavicular coverage angle, CPA: calcaneal pitch angle, T1MA: talo-first metatarsal angle, TCA: talo-calcaneal angle, CI: confidence interval.

**Table 3**  
Comparisons between the two imaging methods in Group A.

Group A (30–50% axial load)					
Parameter	Radiographs		Axial loading CT		P value
	Mean	STD	Mean	STD	
HVA	16.3	7.56	16.3	7.49	>0.05 (0.927)
IMA1–2	9.1	2.11	8.9	2.11	>0.05 (0.124)
TNCA	21.8	7.15	17.7	7.34	<0.05 (0.001)
CPA	17.6	4.74	20.0	4.67	<0.05 (0.002)
T1MA	8.7	5.23	6.4	4.64	<0.05 (0.006)
TCA	44.6	5.97	43.2	5.83	<0.05 (0.010)

**Table 4**  
Comparisons between the two imaging methods in Group B.

Group B (50–70% axial load)					
Parameter	Radiographs		Axial loading CT		P value
	Mean	STD	Mean	STD	
HVA	16.3	11.4	16.1	11.4	>0.05 (0.846)
IMA1–2	9.8	3.53	9.7	3.58	>0.05 (0.952)
TNCA	22.1	6.58	19.8	6.62	<0.05 (0.002)
CPA	18.3	4.87	19.2	4.78	>0.05 (0.252)
T1MA	7.8	4.97	6.2	4.89	<0.05 (0.001)
TCA	45.5	5.23	45.2	7.59	<0.05 (0.035)

**Table 5**  
Comparisons between the two imaging methods in Group C.

Group C (70–100% axial load)					
Parameter	Radiographs		Axial loading CT		P value
	Mean	STD	Mean	STD	
HVA	20.0	11.0	19.9	11.0	>0.05 (0.219)
IMA1–2	11.0	3.57	10.9	3.61	>0.05 (0.176)
TNCA	20.0	7.62	19.6	7.52	>0.05 (0.135)
CPA	19.0	4.31	19.3	4.16	>0.05 (0.206)
T1MA	7.2	4.56	6.9	4.49	>0.05 (0.613)
TCA	45.7	5.52	46.0	5.64	>0.05 (0.345)

between the foot and knee with the hip and knee flexed in the supine position, to simulate a full body weight load. Zhang et al. [14] designed a foot loading device that simulates full body WB with weight plates linked to a footplate. Kimura et al. [15,16] manufactured a novel device that was applied to the sole in the supine position. The authors linked a weight plate, which was axial

load equivalent, to the body weight to a footplate and compared foot scans while the patients were in standing and WB positions, and found no significant differences.

A novel fluoroscopy system provides accurate 3D reconstructions of the foot in the upright position [17–20]. Furthermore, full WB standing 3D CT devices, such as Planmed Verity Extremity or PedCAT and so on have been developed in recent years, allowing for the more functional and accurate diagnosis of foot and ankle problems. Correspondingly, studies about Planmed Verity Extremity [1,17,21–25] and PedCAT [2,5,26–29] are actively in process. However, full WB standing CTs are expensive, and are only available in a few hospitals and countries. Moreover, it is not easy to use WB CT for issues other than orthopedic problems, particularly in foot and ankle specialized hospitals, which cause cost-ineffectiveness. Here, we designed a new axial loading device as a substitute for full WB 3D CT.

In previous studies about simulating the WB effect, most loading devices were considered full WB although just a portion of full body weight was loaded [3,8–11]. Studies by Kido et al. [4,12,13] were limited in that the load tended to extend over the hindfoot with failure of tension on the gastrocnemius, which reproduced a non-physiological condition. Devices developed in Zhang et al. [14] and Kimura et al. [15,16] were bulky, not easy to set up, and cumbersome due to the heavy weight plate compared to the device in our study, despite the fact that they simulated full body weight.

The strengths of our study are that it is the first study on the effectiveness of axial loading CT as a substitute for full WB 3D CT by comparing bony alignments with full WB radiographs in the standing position unlike other studies on weight loading device. This is also the first study to compare reproducibility according to the degree of load. In our results, none of the angles of the foot and ankle were different significantly between the standing radiographs and axial loading CT when >70% axial load was applied, suggesting that WB can be produced if >70% of axial load is given even if 100% axial load is not added. According to these results, we recently inserted two soft pads under the shoulder bar to relieve shoulder pain when the load was given, intending to apply >70% of axial load.

The advantages of axial loading CT are as follows. First, both right and left 3D images can be acquired with one shot; therefore, abnormal lesions can be compared to normal anatomy (Fig. 3). This is not possible with the Planmed Verity Extremity. Second, it is much less expensive than full WB CT and is available to existing CT machines. This facilitates commercialization and more updated diagnosis criteria for disease entities such as osteoarthritis and other deformities will be made. Third, it is applicable to other WB parts, such as the knee, hip and spine, which is not possible with PedCAT.

Some disadvantages of using axial loading CT should also be mentioned. First, the radiation dose is higher than that used for WB CT. The dose for adults for three radiographs for one foot (anteroposterior/Lateral/oblique) is 0.7 mSv, the dose for a bilateral pedCAT scan is 4.3 mSv, and the dose for conventional CT of one foot/ankle is 25 mSv [2,5]. Second, because patients have to fully extend their leg to get an axial load, it is not available to patients with flexion contracture of the knee and hip or kyphosis.

The limitations of our study are as follows. First, we assumed that angle measurements on standing radiographs would be similar to angle measurements on WB CT, as both methods were performed while patients were standing. According to Richter et al. [5], T1MA and IMA1–2 differ between standing radiographs and pedCAT but not CPA. Second, we only compared six parameters of the foot and ankle. More parameters such as hindfoot alignment, rotation and translation of the talus, subtalar vertical angle, and other angles must be compared. Third, we were unable to isolate factors associated with an inaccurate foot position or inaccurate

projection of the radiograph [5]. Fourth, we did not subdivide the intervals of degree of axial load. Finally, the foot pathologies of the subjects were not analyzed [5] and specified such as flatfoot. Additional studies on the angular difference among weight bearing plain radiographs, axial loading CT and WB CT using various parameters and detailed axial load intervals are necessary. Also, further studies on the specific angular difference among three modalities in specific pathology such as flatfoot would be necessary.

## 5. Conclusions

Higher agreement between the two imaging methods was realized when >70% axial load was applied. This results indicate that axial loading 3D CT with >70% axial load has WB and standing effects with various advantages, and can be substituted for the more expensive full WB 3D CT.

## Conflict of interest statement

No potential conflict of interest relevant to this article is reported.

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