

# Research Progress on the Application of Weight-Bearing CT in Hallux Valgus

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## Abstract

Hallux valgus, as a common foot deformity, severely impacts patients' quality of life. Accurate diagnosis and assessment are crucial for formulating treatment plans. Traditional imaging methods have certain limitations in the diagnosis and evaluation of hallux valgus, making it difficult to fully reflect the true morphology of foot bones and joints under weight-bearing conditions. Weight-bearing CT (WBCT), as an advanced three-dimensional imaging technique, can accurately present the foot skeletal structure and its dynamic changes while the patient is standing and bearing weight, thereby enhancing the understanding of the pathological mechanisms of hallux valgus and the accuracy of clinical diagnosis. This article reviews the recent application progress of WBCT in the diagnosis, pathological mechanism analysis, surgical planning, and efficacy evaluation of hallux valgus. Combining the latest research findings, it analyzes its advantages and limitations in clinical practice and looks forward to future technological trends. The review aims to provide theoretical support and practical guidance for clinicians, promote the widespread application of WBCT technology in hallux valgus management, and contribute to the improvement of patient outcomes.

## Keywords

Weight-Bearing CT, Hallux Valgus, Three-Dimensional Imaging, Diagnosis, Surgical Planning, Efficacy Evaluation

## 1. Introduction

Hallux valgus is a common foot deformity characterized primarily by lateral deviation of the first metatarsophalangeal (MTP) joint and medial deviation of the first metatarsal, with a higher incidence in women [1]. Its pathological mechanism involves multiple factors, including rotational abnormalities of the first metatarsal,

joint instability, and soft tissue imbalance. For example, pronation of the first metatarsal is considered an important factor leading to sesamoid position abnormalities and deformity recurrence [2] [3]. Additionally, elevation of the first metatarsal (metatarsus primus elevatus) and stiffness of the MTP joint (hallux rigidus) are also closely related to hallux valgus, further exacerbating the pathological state [4] [5].

In clinical diagnosis, X-ray radiography remains the primary imaging method. However, its two-dimensional images limit the comprehensive assessment of three-dimensional bone structures and are inadequate for accurately reflecting dynamic changes under weight-bearing conditions [1]. For instance, angle measurements of hallux valgus (such as the hallux valgus angle and intermetatarsal angle) in non-weight-bearing images are often underestimated and do not fully reflect the degree of deformity under actual weight-bearing [6]. Furthermore, two-dimensional radiographs struggle to capture the rotational angle of the first metatarsal and changes in soft tissue structures, leading to insufficient assessment of deformity severity and recurrence risk [3] [7].

With advancements in imaging technology, the application of Weight-Bearing CT (WBCT) has become increasingly widespread, showing significant advantages, particularly in the diagnosis and evaluation of foot and ankle diseases [8] [9]. WBCT can acquire three-dimensional volumetric data of the foot while the patient is standing and bearing weight, effectively simulating physiological loading conditions and accurately reflecting the spatial relationships of bone alignment, joint spaces, and related soft tissues [10] [11]. Studies have shown that WBCT can more accurately measure the rotational angle of the first metatarsal, the position of the MTP joint and sesamoids, assisting in assessing the severity of hallux valgus and treatment plans [3] [12]. CT images under weight-bearing conditions can also reveal joint instability and subtle fractures that are difficult to detect with conventional radiographs, providing more objective data support for surgical positioning and postoperative evaluation [13] [14]. WBCT, combined with advanced image processing and deep learning technologies, has gradually enabled automated 3D bone model reconstruction and automatic measurement of key parameters, greatly improving measurement accuracy and repeatability [10] [11]. This helps in quantitatively analyzing the three-dimensional deformity characteristics of hallux valgus, providing a scientific basis for individualized surgical design and assisting in the development of more precise correction plans [15] [16].

In summary, the accurate diagnosis and assessment of hallux valgus urgently need to overcome the limitations of traditional 2D radiographs. WBCT technology demonstrates significant advantages in evaluating the three-dimensional structure of the foot, capable of truly reflecting the dynamic characteristics of bones, joints, and soft tissues under weight-bearing conditions, thereby offering more precise diagnostic information and treatment guidance for clinical practice [8] [17]. In the future, WBCT integrated with artificial intelligence technology will further advance the digital diagnosis and treatment of hallux valgus, achieving a leap from elucidating pathological mechanisms to precise personalized therapy.

## 2. WBCT Technology and Its Imaging Advantages in Hallux Valgus

### 2.1. Technical Principles and Imaging Characteristics of WBCT

Weight-Bearing CT (WBCT) is an imaging technique performed while the patient is in a standing or simulated weight-bearing posture, allowing it to truly reflect the spatial relationships of foot bones under body weight loading. Compared to traditional supine CT, the greatest advantage of this technology lies in its ability to capture the three-dimensional morphology and alignment of bone structures under physiological load, thus enabling a more accurate assessment of dynamic changes in complex foot deformities like hallux valgus [17] [18].

Specifically, WBCT utilizes high-resolution imaging systems to scan the foot circumferentially while the patient is standing. Combined with advanced three-dimensional reconstruction techniques, it can clearly display bone structures and their spatial relationships, avoiding the limitations caused by bone overlap and projection errors inherent in traditional 2D imaging [7] [19]. The reconstructed 3D images can accurately show the rotational angle of the first metatarsal, the hallux valgus angle, and changes in joint space, enabling physicians to perform precise quantitative analysis to support clinical diagnosis and treatment planning [3] [20].

Furthermore, the high spatial resolution and multi-planar imaging capability of WBCT make a comprehensive assessment of first metatarsal rotation, joint dislocation, and complex three-dimensional deformities between metatarsals possible. This is significant for understanding the three-dimensional pathological mechanism of hallux valgus and helps reveal the multi-planar characteristics and dynamic changes of bone deformities in hallux valgus [21] [22]. Overall, through three-dimensional imaging under true weight-bearing conditions, WBCT significantly enhances the precision and clinical value of hallux valgus imaging.

### 2.2. Comparison of WBCT with Traditional Imaging

Compared to traditional weight-bearing X-rays, WBCT demonstrates significant advantages in the accuracy of hallux valgus angle measurements. Traditional X-rays are limited by two-dimensional projection and bone overlap, making it difficult to accurately reflect the rotation of the first metatarsal and dislocation of joint surfaces, leading to insufficient diagnostic sensitivity and specificity [7] [22]. In contrast, WBCT can precisely measure the first metatarsal rotation angle and hallux valgus angle through 3D reconstruction, and shows higher inter-observer and intra-observer reliability in postoperative evaluation, significantly reducing measurement errors [7].

Additionally, WBCT can reveal pathological changes difficult to detect with traditional imaging, such as rotation of the first metatarsal, joint surface dislocation, metatarsal rotation, and valgus of the metatarsal head, which is particularly important for the comprehensive assessment of complex hallux valgus cases [3] [17]. For example, studies show that WBCT can quantitatively analyze the distribution of first metatarsal rotation and the valgus angle of the metatarsal head in hallux

valgus patients, providing precise three-dimensional data support for surgical correction [21].

Moreover, the three-dimensional presentation of intra-articular bone structures, fascial and ligament attachment points by WBCT further deepens the understanding of the pathological mechanisms of hallux valgus, aiding in the development of individualized treatment plans and reducing recurrence rates [22] [23]. In summary, with its three-dimensional, weight-bearing imaging advantages, WBCT has become an indispensable advanced tool in the imaging assessment of hallux valgus, clearly superior to traditional 2D X-ray imaging.

### **2.3. Current Application Status of WBCT in Clinical Practice**

WBCT technology has been widely introduced in recent years by numerous orthopedic and foot-ankle specialty centers as an important imaging tool for preoperative assessment and postoperative follow-up of hallux valgus [7] [17]. Clinical studies indicate that surgical planning assisted by WBCT can significantly improve correction outcomes. By accurately assessing first metatarsal rotation, metatarsal head valgus, and changes in joint space, it reduces the risk of postoperative recurrence of hallux valgus [3] [22].

Preoperatively, WBCT helps surgeons gain a detailed understanding of the three-dimensional structure of the lesion, including the rotational angle of the first metatarsal, displacement of the metatarsal head, and stability of the MTP joint. This information aids in selecting more appropriate surgical approaches and osteotomy angles [16] [22]. Furthermore, WBCT can monitor postoperative bone healing and the stability of the correction, promptly detecting potential signs of recurrence and providing a basis for clinical decision-making [7].

The application of WBCT has also promoted in-depth research into the pathological mechanisms of hallux valgus. For instance, observing the relationship between first metatarsal rotation and metatarsal head valgus reveals the role of multiple factors in the formation and development of hallux valgus [21] [24]. Simultaneously, with the development of artificial intelligence technology, automated WBCT image analysis methods are gradually emerging, further improving the efficiency and accuracy of imaging assessment [24].

Overall, WBCT has become a key technology in the diagnosis and treatment of hallux valgus, driving advancements in related surgical techniques and treatment concepts, and serving as an important cornerstone for achieving refined and individualized treatment [17] [18].

## **3. Application of WBCT in the Study of Hallux Valgus Pathological Mechanisms**

### **3.1. Three-Dimensional Assessment of Bone Structure Abnormalities**

WBCT technology enables precise three-dimensional assessment of the bone structure in hallux valgus patients under natural weight-bearing conditions, re-

vealing the multi-dimensional pathological deformity characteristics of hallux valgus. WBCT can accurately measure the varus angle of the first metatarsal, the valgus of the first MTP joint, and the rotation of the metatarsals. The reliability of these parameters is significantly better than that of traditional radiographs, especially in postoperative assessment [7]. Through 3D reconstruction, WBCT can analyze changes in metatarsal deformation and joint surface contact status in detail, revealing the mechanical basis of hallux valgus. Specifically, the rotation of the first metatarsal (i.e., pronation) is significantly correlated with valgus of the metatarsal head, and this rotation is influenced by the pronated position of the heel and metatarsal torsion [3] [17]. Additionally, WBCT shows that the first metatarsal undergoes significant rotational changes under load, which is an important component of the pathogenesis of hallux valgus [20]. Through precise three-dimensional analysis of bone alignment, WBCT provides a powerful tool for understanding the multifaceted bone abnormalities in hallux valgus, enabling better guidance for surgical planning and reducing postoperative recurrence rates [22].

### **3.2. Observation of Articular Cartilage and Joint Space Changes**

WBCT, combined with soft tissue imaging techniques, can dynamically assess the wear of articular cartilage and the narrowing of joint space in hallux valgus patients. Studies have found that the joint space of the first MTP joint undergoes dynamic changes under weight-bearing, and these changes are closely related to the progression of hallux valgus [17]. WBCT can display the thickness of the articular cartilage and its degree of degeneration, helping to assess the extent of cartilage damage. WBCT scans show that degeneration of the articular cartilage of the first MTP joint in hallux valgus patients is closely related to osteophyte formation and bone changes [23]. In postoperative assessment, WBCT can more clearly reflect the recovery of articular cartilage and changes in joint space, providing accurate feedback on cartilage protection and repair outcomes for clinicians [22]. By observing the contact status and gap changes between articular cartilage and bone surfaces, WBCT offers a new perspective for understanding the mechanism of cartilage degeneration and its interaction with bone abnormalities.

### **3.3. Quantitative Analysis of Bone Changes and Osteophyte Formation**

WBCT enables quantitative analysis of osteoporosis and osteophyte formation in hallux valgus patients, providing an in-depth understanding of their degenerative pathological processes. Studies show that WBCT uses three-dimensional quantitative methods to assess the degree of osteoporosis and the size of osteophytes, finding that osteophyte formation is closely related to metatarsal head rotation and joint instability [25]. Quantitative analysis of osteophytes by WBCT aids in staging the pathological phase, providing a basis for individualized treatment. For hallux valgus at different pathological stages, WBCT can accurately measure osteophyte volume and changes in bone density, guiding the extent of surgical re-

section and the choice of surgical technique [22]. Regarding osteoporosis, WBCT can reveal microscopic changes in the bone quality of the first metatarsal, suggesting the relationship between degradation of bone structure and abnormal mechanical load [26]. Combined with quantitative data on osteophytes and bone changes, WBCT provides a scientific basis for the study of degenerative bone changes in hallux valgus and clinical intervention, promoting the development of precision medicine.

## **4. Application of WBCT in Surgical Planning and Efficacy Evaluation of Hallux Valgus**

### **4.1. Three-Dimensional Localization and Simulation in Surgical Planning**

Weight-Bearing CT (WBCT) provides an extremely precise bone model for hallux valgus surgical planning by acquiring three-dimensional images of the foot bones under natural weight-bearing conditions. Compared to traditional non-weight-bearing CT, WBCT can truly reflect the impact of load on the bone structure, offering significant advantages especially in the assessment of complex three-dimensional deformities [17] [18]. Using the 3D skeletal model constructed with WBCT, surgeons can accurately measure key parameters such as the rotational angle of the first metatarsal, the osteotomy angle, and joint space, thereby assisting in formulating reasonable osteotomy directions and fixation plans to effectively correct multi-planar hallux valgus deformities [16].

Furthermore, WBCT supports virtual surgical simulation. Through digital osteotomy and reconstruction, it predicts postoperative bone alignment and joint function recovery. For example, using 3D printing technology combined with WBCT data, studies have shown that triplane Chevron osteotomy (TCO) can more precisely adjust the distal tilt angle of the metatarsal compared to traditional Chevron osteotomy, achieving three-dimensional correction while preserving or increasing the length of the first metatarsal and reducing the occurrence of transfer metatarsalgia [16]. WBCT can also assess changes in the posture of the first metatarsal and the rotation of the metatarsal head after osteotomy, guiding the refined design of the osteotomy plan, improving surgical success rates, and reducing the risk of postoperative recurrence [3].

For complex or recurrent hallux valgus cases, WBCT can better reveal the details of bone deformities, such as the degree of metatarsal rotation, valgus of the metatarsal head, intermetatarsal angle, osteotomy line, and joint surface dislocation, helping to formulate individualized secondary surgical plans [3] [7]. Through WBCT, surgeons can better understand the three-dimensional characteristics of the deformity and combine clinical manifestations to develop more scientific osteotomy angles and fixation strategies, thereby optimizing treatment outcomes.

In summary, by providing precise three-dimensional bone models under weight-bearing conditions and virtual surgical simulation technology, WBCT greatly enhances the scientific and personalized level of hallux valgus surgical planning,

offering a powerful auxiliary tool for clinicians.

## 4.2. Objective Evaluation of Postoperative Efficacy

Postoperative efficacy evaluation is a crucial part of the hallux valgus treatment process, and WBCT demonstrates unique advantages in this aspect. Traditional X-rays are limited by their two-dimensional nature and cannot accurately reflect the three-dimensional alignment of bones and changes in joint space after surgery. In contrast, WBCT can clearly display the bone structure under weight-bearing conditions, providing quantitative data on postoperative bone alignment [7]. WBCT can precisely measure the postoperative rotational angle of the first metatarsal, the intermetatarsal angle, and the relative position between the metatarsal head and the talus, objectively reflecting the reduction degree of hallux valgus and the corrective effect of the osteotomy. Assessing the rotation of the first metatarsal and the valgus angle of the metatarsal head with WBCT can reveal whether there is residual rotational deformity after surgery, which is closely related to the risk of hallux valgus recurrence [7]. Through 3D reconstruction, WBCT displays the alignment relationship between the metatarsal head and the metatarsal base, assisting in judging the stability of the osteotomy fixation and the recovery of joint function.

Combined with clinical symptoms and functional scores (such as VAS pain score, AOFAS ankle-hindfoot score, etc.), WBCT provides important imaging evidence, making efficacy evaluation more comprehensive and objective [27]. For example, the reduction in patient pain and improvement in activity function postoperatively are positively correlated with the restoration of bone alignment shown by WBCT, supporting WBCT as an important tool for postoperative follow-up [27].

Additionally, WBCT shows high sensitivity in monitoring postoperative complications (such as poor fracture healing, joint space narrowing, bone hyperplasia, etc.), providing a basis for timely adjustment of treatment plans [28]. Through regular WBCT examinations, doctors can dynamically understand the postoperative bone change process, achieving precise management.

Therefore, with its high resolution and three-dimensional quantitative capabilities, WBCT provides reliable objective indicators for the evaluation of postoperative efficacy in hallux valgus, promoting postoperative rehabilitation and the optimization of long-term outcomes.

## 4.3. Application of WBCT in Complex and Recurrent Hallux Valgus

Complex and recurrent hallux valgus cases involve more complicated bone deformities and soft tissue damage, making them difficult to assess comprehensively with traditional 2D imaging. WBCT, through its 3D reconstruction technology, accurately identifies characteristics of bone deformity and joint damage, providing key support for planning secondary surgical procedures for complex cases [7] [17].

WBCT can clearly display the rotation degree of the first metatarsal, the inter-metatarsal angle, dislocation between the metatarsal head and base, and the positional relationship between the metatarsal head and the talar joint surface, helping surgeons accurately determine the cause of recurrence, such as insufficient osteotomy correction, unstable fixation, or abnormal joint space [3]. Furthermore, WBCT also has advantages in identifying subchondral bone lesions and soft tissue calcification, assisting in the comprehensive assessment of the pathological mechanism of recurrent hallux valgus [29].

By quantitatively analyzing WBCT indicators combined with clinical symptoms, doctors can formulate personalized secondary surgical plans, such as adjusting the osteotomy angle, optimizing fixation methods, and addressing soft tissue issues, thereby minimizing the risk of postoperative recurrence. Simultaneously, WBCT helps assess the specific reasons for the failure of the previous surgery, providing a scientific basis for preoperative decision-making [7].

In summary, for complex and recurrent hallux valgus cases, WBCT relying on its ability to accurately display three-dimensional bone and joint surface details, serves as a powerful tool for guiding secondary surgical planning and optimizing treatment strategies, significantly improving treatment outcomes and patient prognosis.

## 5. Conclusions

As a significant breakthrough in the field of imaging in recent years, Weight-Bearing CT has brought new perspectives and methods to the diagnosis and treatment of hallux valgus, a common foot deformity. Its three-dimensional imaging capability greatly enhances the understanding of the pathological mechanisms of hallux valgus. It not only more accurately reflects the true anatomical relationships of bones and soft tissues under weight-bearing conditions but also reveals complex structural changes that are difficult to capture with traditional two-dimensional imaging. This technological advantage undoubtedly promotes the precision of hallux valgus diagnosis, reduces the risk of misdiagnosis and missed diagnosis, and provides a solid imaging basis for clinical decision-making.

In terms of surgical planning and efficacy evaluation, the introduction of WBCT enables surgeons to design more scientific and reasonable surgical plans based on individual anatomical characteristics, avoiding the shortcomings of a “one-size-fits-all” treatment approach. Through preoperative precise measurement of lesion angles and bone alignment, combined with postoperative imaging assessment under weight-bearing conditions, clinicians can more comprehensively evaluate surgical outcomes and recurrence risks. This not only improves patient treatment satisfaction and quality of life but also provides valuable data support for the optimization of future treatment strategies. The application of WBCT in individualized medicine fully reflects the development trend of “precision diagnosis and treatment” in modern medicine.

As an advanced three-dimensional imaging technology, WBCT has already

demonstrated great potential in the diagnosis and treatment of hallux valgus. By balancing technological advantages with clinical practical needs and coordinating findings from different studies, WBCT is expected to become a standard imaging tool for hallux valgus management. In the future, with the reduction of equipment costs and continuous technological improvement, its clinical application scope will further expand, promoting hallux valgus treatment into a new stage of greater precision and personalization. As experts in the medical field, we should actively promote the development of research related to WBCT, strengthen interdisciplinary cooperation, promote the standardized application of this technology in clinical practice, and ultimately achieve the goal of providing patients with more scientific and efficient diagnostic and therapeutic services.

Although weight-bearing CT (WBCT) has significant advantages in the diagnosis and treatment of hallux valgus, it also has certain limitations. The high cost of the equipment, higher radiation dose compared to traditional X-rays, and the complex process that requires patients to stand under load restrict its popularization in primary hospitals and limit its applicability to some patients. Technically, there is a lack of unified measurement standards, resulting in poor comparability of parameters among different studies. The assisted analysis by artificial intelligence has yet to be verified in its ability to identify complex deformities and relies on doctors' experience. Moreover, it can only provide static skeletal structure information and cannot dynamically evaluate the kinematics of the ankle-foot. In clinical applications, it may lead to over-examination in early-stage mild patients, increasing unnecessary radiation exposure and economic burden. For complex cases, it may cause excessive reliance on imaging data and neglect of individualized functional needs. There is also a controversy regarding the cost-effectiveness of postoperative follow-up. Stratified strategies need to be formulated for different cases. Therefore, when promoting this technology, its technical advantages and actual clinical applicability should be weighed.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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