Joint Diseases and Related Surgery

Jt Dis Relat Surg
2026;37(x):i-ix

ORIGINAL ARTICLE

Volumetric relationships of foot bones and the role of the talus in hallux valgus

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ABSTRACT

Objectives: This study aims to evaluate the foot as a whole, to compare the foot bones in terms of volume, and investigate the role of the foot bones in the formation of hallux valgus (HV).

Patients and methods: Between February 2024 and September 2024, a total of 21 patients (6 males, 15 females; mean age: 29.04 ± 5.21 years; range, 19 to 38 years) with an HVA of ≥30° and intermetatarsal angle (IMA) of ≥ 13° were included in this prospective study. The control group consisted of 18 patients (5 males, 13 females; mean age: 28.94 ± 5.56 years; range, 20 to 39 years) with an HVA of <15°. Computed tomography (CT) images were uploaded to the 3D Slicer program, and the volumes of the foot bones were measured and calculated as percentages.

Results: In terms of volume percentage, the mean talus (22.68 ± 1.62 *vs*. 21.37 ± 1.81; d = 0.78; 95% CI 0.10–1.44) and the fifth metatarsal (4.63 ± 0.85 *vs*. 4.15 ± 0.52; d = 0.65; 95% CI -0.01–1.29) were higher, while the mean cuboid volume (5.31 ± 0.71 *vs*. 5.89 ± 0.55; d = 0.90; 95% CI 0.23–1.57) was lower in the HV group, indicating a statistically significant difference (p<0.05). No significant difference was observed in the volume ratios between the bones of the medial and lateral rays (p ≥ 0.05). When medial ray bones were combined, the ratios of talus/medial cuneiform (d = 0.92) and (talus + 1st metatarsal)/medial cuneiform (d = 0.82; 95% CI 0.20–1.52) were found to be significantly higher in the HV group (p < 0.05).

Conclusion: Although genetic factors are widely considered to play a key role in HV development, we propose that the process originates more proximally, most likely at the level of the talus. Based on our study results, we conclude that an increase in talar volume may lead to a compensatory reduction in the volumes of the cuboid and medial cuneiform bones, initiating a sequence in which soft-tissue forces contribute to progressive pronation of the first metatarsal, ultimately resulting in HV.

Keywords: Computed tomography, hallux valgus, talus, tarsal bones, three-dimensional imaging, volume measurement.

Foot and ankle pathologies represent significant public health concerns due to their adverse impact on patients' quality of life and their increasing prevalence.[1,2] Given its high prevalence and clinical significance within the population, it has been the subject of extensive investigation in recent years. Although many hypotheses have been put forward regarding its etiopathogenesis over the years, a clear cause has still not been established yet.[3,4]

Various theories have been proposed ranging from genetic predisposition and footwear types to structural alterations in the sesamoids, as well as changes in the tendons and ligaments that influence the first ray over time.[1,5-7] Some have blamed hypermobility of the first ray as a significant factor in the development of hallux valgus (HV) and have recommended first metatarsal-cuneiform joint arthrodesis to correct HV.[8]

Received: August 05, 2025
Accepted: November 19, 2025
Published online: March 11, 2026

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Doi: 10.52312/jdrs.2026.2537

Citation: Ekinci Y, Payas A, Sarıaslan AY, Kaya Erten Z, Arat F, Batın S. Volumetric relationships of foot bones and the role of the talus in hallux valgus. Jt Dis Relat Surg 2026;37(x):i-ix. doi: 10.52312/jdrs.2026.2537.

Since the main causes cannot be fully explained by local factors, the pathology is thought to begin further back and be more complex. The biomechanics of the structures forming the medial ray have been considered the most important structure in explaining the etiopathogenesis of HV.[9,10] Recently, it has been widely adopted that the medial cuneiform angle is disrupted in patients with HV, and the metatarsus adductus angle increases due to tendon force directions and sesamoid displacement, resulting in angular and rotational deformity. This is even considered a characteristic indicator of HV.[10] While studies report an inverse relationship between the distal medial cuneiform angle and the severity of the HV angle (HVA), some studies argue that this angle is not significant.[3,6,10-12] Three-dimensional (3D) imaging further clarifies that the talus moves mostly in a single axis, while the calcaneus, navicular, and cuboid bones move in at least two, and often even three, planes. The calcaneus can directly affect the lateral ray, while the talus can directly affect the medial ray.[13]

To date, no studies have examined the relationship between volumetric changes in foot bones and the development of deformities such as HV. Although numerous hypotheses have been proposed regarding HV, the uncertainty surrounding its etiopathogenesis has prompted researchers to explore new perspectives. In the present study, we hypothesized that not only the first ray or soft tissues, but also other components of the foot could play a role in the formation of HV. We, therefore, aimed to evaluate the foot as a whole, to compare the foot bones in terms of volume, and investigate the role of the foot bones in the formation of HV.

PATIENTS AND METHODS

This single-center, cross-sectional, prospective study was conducted at University of Health Sciences, Kayseri City Training and Research Hospital, Department of Orthopedics and Traumatology between February 2024 and September 2024. Inclusion criteria were as follows: age between 18 and 40 years; an HVA of ≥ 30° and intermetatarsal angle (IMA) of ≥ 13° (HV group) or HVA of < 15° (control group); and complete data. Exclusion criteria were as follows: age < 18 and > 40 years; congenital foot deformities (pes planus, pes cavus, tarsal coalition, etc.); space-occupying lesion or tumor on the foot; history of previous foot surgery; severe arthritis; pregnancy; wearing narrow-toed shoes regularly and frequently. A written informed consent was obtained from each patient. The study protocol was approved by the Kayseri City Hospital Clinical Research Ethics Committee (Date: 19.09.2023, No: 2023/908). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Weight-bearing radiography (WBR) is the most common imaging method used both in the diagnosis and treatment of HV. However, considering that the deformity is 3D, it is obvious that it is insufficient in defining the deformity.[14] Among the patients with HV who were admitted to our clinic and who had HVA ≥ 30° in weight-bearing anteroposterior X-ray view and who were indicated for surgery,[5,15] a total of 21 patients (6 males, 15 females; mean age: 29.04 ± 5.21 years; range, 19 to 38 years) who had computed tomography (CT) scanning during preoperative evaluation and who met the criteria were included in the study. The control group (n=18, 5 males, 13 females; mean age: 28.94 ± 5.56 years; range, 20 to 39 years) included patients who underwent foot CT scanning in our clinic for other reasons and met the criteria. The CT images were obtained using a General Electric IQ model 32-detector CT device with a 0.625 mm slice thickness in accordance with the prespecified bone protocol. All X-rays and CT scans were reviewed separately by two experienced orthopedic surgeons and cases that did not meet the acceptance criteria were excluded. Disagreements between surgeons were resolved through discussion.

The age (years), HVA (°), height (m), and weight (kg) of all participants were recorded, and body mass index (BMI) (kg/m^2) was calculated as weight in kg divided by the square of height in meters (kg/m^2).

Image process and data analysis

All DiCOM files from the foot CT scans taken of the participants were imported into the 3D Slicer software for foot bone segmentation. The volume (mm^3) information was accessed through the "Quantification" tab under the "Modules" tab. Finally, the total volume of all foot bones was calculated. Since the volume of each foot and its constituent bones is unique to the individual, all measurements were calculated as a percentage of the total volume and recorded separately for each bone (Figure 1 and 2).

Statistical analysis

Study power analysis and sample size calculation were performed using the G*Power version 3.1 software (Heinrich Heine University Düsseldorf, Düsseldorf, Germany) based on the effect size

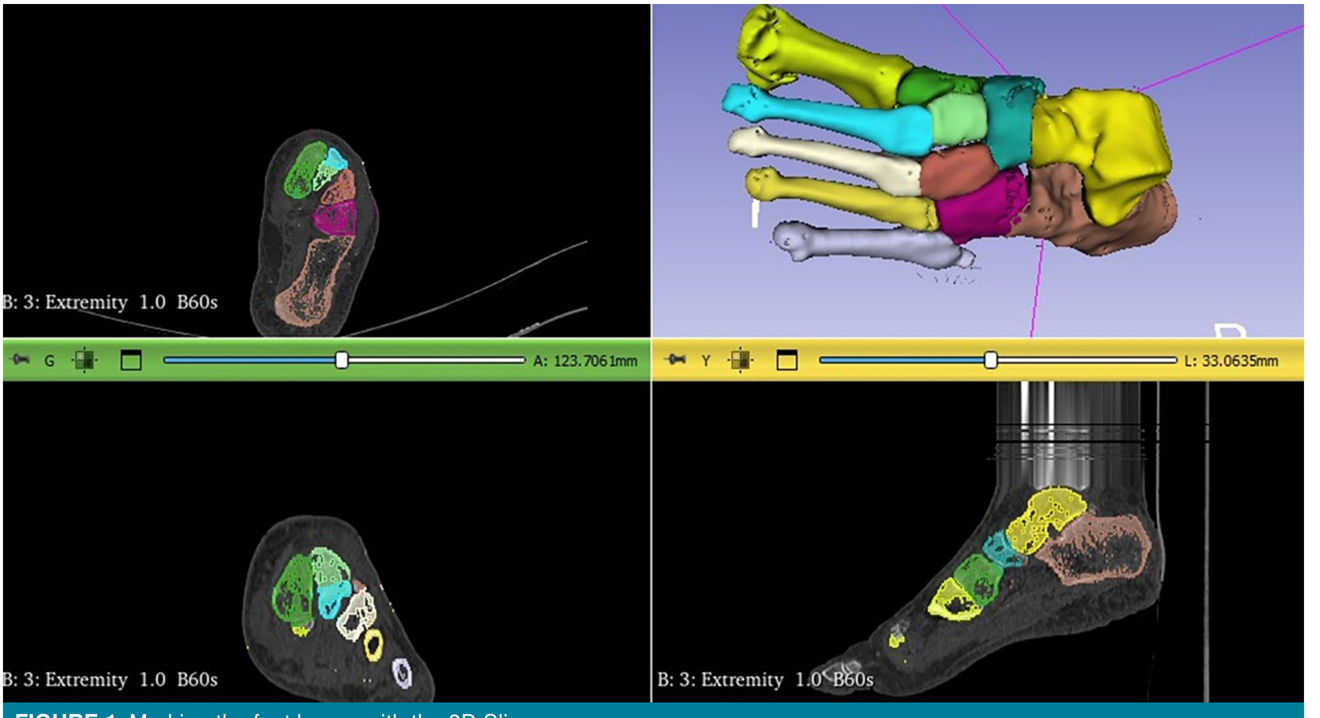

FIGURE 1. Marking the foot bones with the 3D Slicer program.

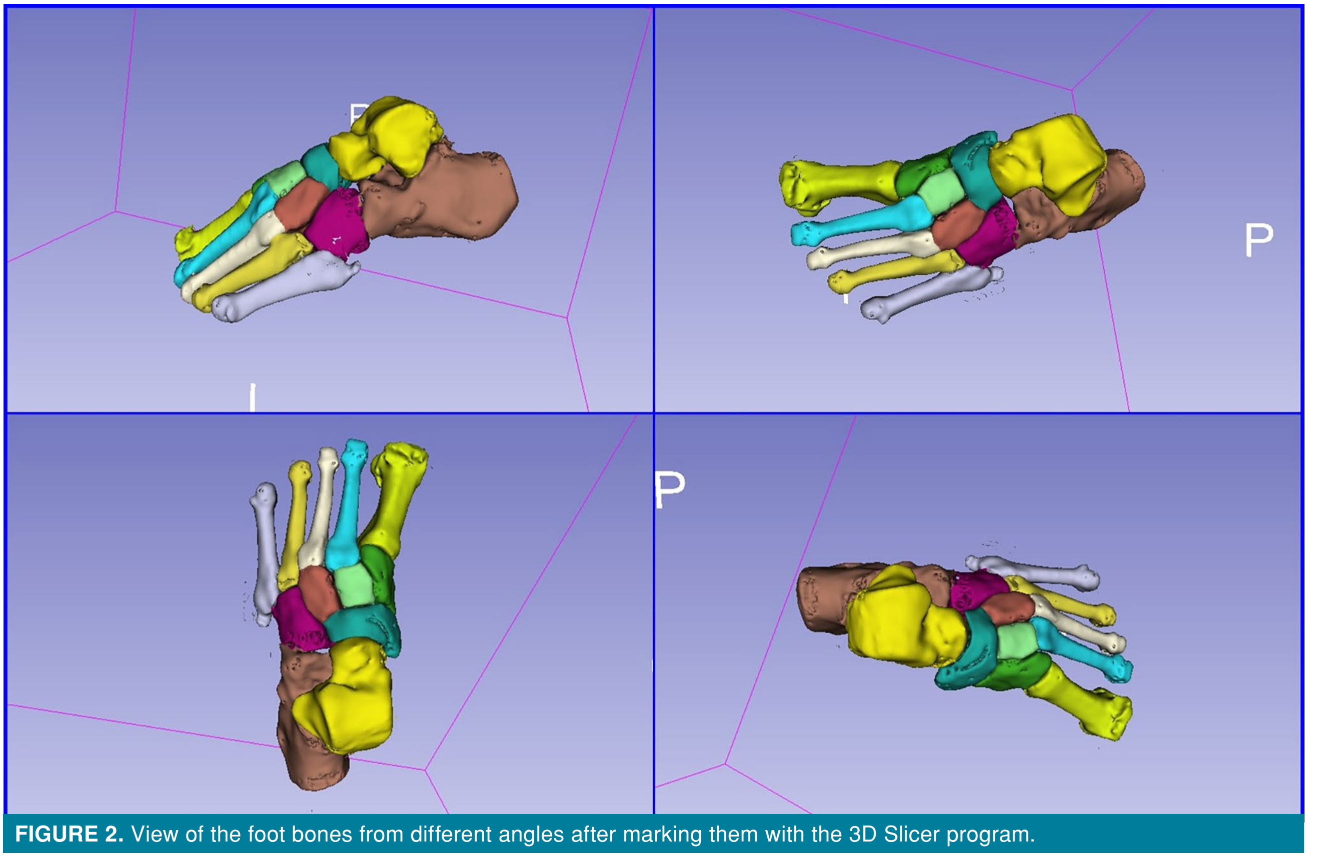

FIGURE 2. View of the foot bones from different angles after marking them with the 3D Slicer program.

TABLE I
Demographic information of subjects in groups

	HV group (n = 21)			Control group (n = 18)			
	n	%	Mean ± SD	n	%	Mean ± SD	*p*
Age (year)			29.04 ± 5.21			28.94 ± 5.56	0.92
Sex							
Female	15	71.4		13	72.2		
Male	6	28.6		5	27.8		
BMI (kg/m²)			27.96 ± 3.13			27.11 ± 2.93	0.84

SD, standard deviation.

(Cohen's d = 1.0) reported in a systematic review examining the relationship between HV and foot structure.[16] A two-sided t-test with α = 0.05 and 95% study power was used for two independent groups (HV and control), and the total sample size was determined to be minimum 36 (18 individuals in each group).

Statistical analysis was performed using the IBM SPSS version 26.0 software (IBM Corp., Armonk, NY, USA). Continuous data were presented in mean ± standard deviation (SD), while categorical data were presented in number and frequency. The independent samples t-test was used to compare means, assuming normal distribution of data as confirmed by the Kolmogorov-Smirnov test. A two-way mixed-effects model and intraclass correlation coefficients (ICCs) were used to evaluate agreement and differences between intra- and inter-observer measurements. A *p*-value of < 0.05 was considered statistically significant with 95% confidence interval (CI). In addition to p-values, effect sizes (Cohen's d) were calculated to evaluate the magnitude of between-group differences. The interpretation of effect size followed Cohen's conventional thresholds: small = 0.2, medium = 0.5, and large = 0.8.[17]

RESULTS

There was no significant difference in the baseline demographic and clinical characteristics of the HV group and control group (p>0.05) (Table I).

The mean foot volume was 118.38 ± 36.72 mm^3 and 142.74 ± 48.56 mm^3 in the HV group and control group, respectively (p = 0.091). When the volumes of the cases were calculated as percentages and the two groups were compared, the talus (d = 0.78; 95% CI 0.10–1.44) and fifth metatarsal (d = 0.64; 95% CI –0.01–1.29) volumes were significantly larger (p = 0.025 and p = 0.038) in the HV group, while the cuboidal volume (d = 0.90; 95% CI 0.23-1.57) was smaller (p = 0.006) (Table II).

When the volumes of the medial ray (1^{st} metatarsal + medial cuneiform + navicular + talus) and lateral ray (5^{th} metatarsal + cuboid + calcaneus) bones were measured and compared as percentages, no statistically significant difference was found between the two groups (p = 0.86; d = 0.07; 95% CI –0.55–0.70) (Table III). When the bone ratios were examined, the talus/medial cuneiform ratio (p = 0.005; d = 0.92; 95% CI 0.28–1.60), (talus + 1^{st} metatarsal) / medial cuneiform ratio (p = 0.009; d = 0.82; 95% CI (0.20–1.52), and (1st metatarsal + medial cuneiform)/talus ratio (p = 0.038; d = 0.66; 95% CI –1.31 to –0.02) were found to be significantly higher in the HV group.

Intra- and inter-observer reliability of morphometric measurement results were determined to be excellent (ICC: 0.967–0.974) and good (ICC: 0.910–0.986), respectively.

DISCUSSION

In the present study, we evaluated the foot as a whole and compared the foot bones in terms of volume in order to examine the role of the foot bones in the formation of HV. The results of our study showed that there are volumetric changes in the foot bones in HV cases, and the increase in talus volume is particularly noteworthy. Therefore, we can assume that HV and the talus are closely related.

The foot has a complex structure consisting of many interrelated bones, muscles, tendons and ligaments. The foot is one of the most important parts of the body, as it not only carries the entire load of the locomotor system but also transfers the load flawlessly, ensuring perfect

TABLE II
Distributions of foot bone volumes between groups

	Mean ± SD	Cohen's d	Effect size	95% CI	t**	*p*
Total volumes of bones (mm^3)						
HV group	118.38 ± 36.72	0.56	Medium	–0.09-1.21	–1.745	0.091
Control group	142.74 ± 48.56					
Talus (%)						
HV group	22.68 ± 1.62	**0.81**	**Large**	0.10-1.44	2.36	**0.025***
Control group	21.37 ± 1.81					
Calcaneus (%)						
HV group	28.38 ± 2.1	0.36	Small	–0.29-1.01	–1.127	0.287
Control group	29.52 ± 3.8					
Navicular (%)						
HV group	6.33 ± 0.69	0.06	Negligible	–0.57-0.69	0.202	0.841
Control group	6.29 ± 0.55					
Cuboideum (%)						
HV group	5.31 ± 0.71	**0.90**	**Large**	0.23-1.57	–2.89	**0.006***
Control group	5.89 ± 0.55					
Medial cuneiform (%)						
HV group	5.38 ± 0.82	0.47	Medium	–0.18-1.12	–1.52	0.135
Control group	5.73 ± 0.59					
Intermediate cuneiform (%)						
HV group	2.62 ± 0.32	0.10	Negligible	–0.53-0.73	–0.351	0.736
Control group	2.66 ± 0.46					
Lateral cuneiform (%)						
HV group	3.00 ± 0.42	0.46	Medium	–0.19-1.11	–1.343	0.187
Control group	3.20 ± 0.45					
1^{st} Metatars (%)						
HV group	8.60 ± 0.68	0.05	Negligible	–0.58-0.68	–0.180	0.859
Control group	8.65 ± 1.25					
2^{nd} Metatars (%)						
HV group	4.89 ± 0.46	0.36	Small	–0.29-1.01	1.081	0.287
Control group	4.74 ± 0.36					
3^{th} Metatars (%)						
HV group	3.9 ± 0.10	0.25	Small	–0.38-0.88	0.168	0.867
Control group	3.99 ± 0.48					
4^{th} Metatars (%)						
HV group	4.00 ± 0.42	0.46	Medium	–0.19-1.11	1.518	0.138
Control group	3.78 ± 0.50					
5^{th} Metatars (%)						
HV group	4.63 ± 0.85	0.64	Medium	–0.01-1.29	2.165	**0.038***
Control group	4.15 ± 0.52					

SD, standard deviation; CI, confidence intervals; HV, hallux valgus; * $p < 0.05$; **, independent t test.

continuity of movement. Therefore, it would not be a correct approach to expect a deformity that develops in the foot to be caused by a single factor. The most important factor in the failure to reveal the etiopathogenesis of a deformity such as HV is undoubtedly this complex structure. Since one of the most important parameters reflecting the relationship between the bones is the volumetric relationship, it would be possible to have more information about HV with volume measurement.

Genetic transmission has been emphasized for many years in the development of HV.

TABLE III
Distribution of foot bone volume ratios between groups

	Mean ± SD	Cohen's d	Effect size	95% CI	t**	*p*
Talus / calcaneus						
HV group	0.80 ± 0.09	**0.98**	**Large**	**0.38-1.72**	–1.66	0.109
Control group	0.73 ± 0.01					
Talus / navicular						
HV group	3.64 ± 0.61	0.39	Small	–0.24-1.03	1.21	0.231
Control group	3.42 ± 0.48					
Talus / medial cuneiform						
HV group	4.30 ± 0.69	**0.92**	**Large**	**0.28-1.60**	2.991	**0.005***
Control group	3.75 ± 0.43					
Calcaneus / medial cuneiform						
HV group	5.43 ± 1.24	0.16	Small	–0.47-0.79	0.505	0.617
Control group	5.23 ± 1.21					
Navicular / medial cuneiform						
HV group	1.19 ± 0.20	0.56	Medium	–0.08-1.21	1.918	0.065
Control group	1.10 ± 0.09					
(1st Metatarsal + medial cuneiform) / talus						
HV group	0.62 ± 0.06	0.66	Medium	**–1.31-(–0.02)**	–2.171	**0.038***
Control group	0.67 ± 0.09					
(1st Metatarsal + talus) / medial Cuneiform						
HV group	5.93 ± 0.930	**0.82**	**Large**	**0.20-1.52**	2.776	**0.009***
Control group	5.27 ± 0.520					
Medial ray / lateral ray						
HV group	1.12 ± 0.90	0.07	Negligible	–0.01-0.70	1,354	0.186
Control group	1.07 ± 0.10					

SD, standard deviation; CI, confidence intervals; HV, hallux valgus; * $p < 0.05$; **, independent t test.

Piqué-Vidal et al.[18] reported that more than 90% of 350 White patients had at least one relative with HV. Of note, HV is more common in women, who have been reported to exhibit more adducted metatarsals, smaller metatarsal dimensions, and reduced joint surface area.[19] Consistent with the literature, HV was more common in female patients in our study.

The first ray exhibits a hypermobile character, particularly under load. The first metatarsal performs pronation during flexion and supination during extension. However, it remains unclear whether the resulting hypermobility is a cause or an effect. Despite studies both supporting and refuting the existence of first ray hypermobility, high-level evidence is still lacking.[20] Kimura et al.[21] reported that first metatarsal pronation in cases with HV was not observed in healthy individuals or in cases with hallux rigidus and, therefore, the first metatarsal pronation was a torsional movement specific to HV. Although hallux rigidus is also a deformity affecting the first metatarsophalangeal joint, its mechanism is not as complex as HV. The presence of forces which create rotation and the fact that the acting forces originate more proximally are probably the most significant features distinguishing HV from other deformities. Consistent with the literature, our study results support that the pathology originates more proximally by evaluating the volumetric characteristics of the bony structures contributing to these forces.

In a cadaveric study, Krause et al.[22] recorded static tibiotalar pressure changes in pes cavus deformities created by placing a wedge at the first tarsometatarsal joint. They found that as the severity of pes cavus increased, tibiotalar pressure also increased and the center of force shifted anteriorly. This shift led to long-term anteromedial ankle arthrosis, suggesting that the severity of the deformity was directly proportional to the increase in pressure. Of note, this study is of utmost importance as it demonstrates that other bones are also affected by changes occurring in the foot bones. In our study, we measured significantly greater talus volume and lower cuboid volume in patients with HV. This suggests an increased load on the medial support structures, and the resulting volumetric imbalance may cause tension, even insufficiency, in the medial soft tissues, potentially leading to deformity. However, it is evident that further pressure measurement studies are needed in cases with HV to clarify the biomechanical effects. In addition, the dorsal metatarsophalangeal joint capsule contributes minimally to stability, as it is not reinforced by any tendon, unlike other regions.[23] It is obvious that, once insufficiency occurs, dominant forces can lead to deformity. However, the underlying cause of this insufficiency has not been fully elucidated.

In their study, Mancuso et al.[24] reported that the first metatarsal was longer than the second metatarsal in almost all 110 cases with HV, whereas the second metatarsal was longer in almost all cases in the control group. They concluded that the longer first metatarsal led to dorsoflexion restriction at the metatarsophalangeal joint, thereby resulting in instability and ultimately HV. However, in our study, the first metatarsal volumes of the patients with HV were similar to those in the control group. Therefore, the volume of the first metatarsal may not be a factor in the development of HV. In another study, Mason and Tanaka[9] defined three different types based on the number of facets on the proximal articular surface of the first metatarsal. Although they associated the unifacial joint structure specifically with HV, they reported that HV could also be seen with bifacial joints in some cases. Thus, an increased number of facets was proposed to have protective effects against the development of HV, since an increased number of facets indicates more contact points and enhanced stability.

One of the commonly proposed factors contributing to the development of HV is the obliquity of the first metatarsal-medial cuneiform joint.[6,11,23,25] However, Sovilj et al.[5] reported that 55.9% of patients with a transverse shape had mild HV and 50.3% of patients with oblique shape had moderate HV. Therefore, we cannot speculate that the shape of the first metatarsal-medial cuneiform joint has a clear effect on HV.

The midfoot and hindfoot bones undergo both translational and rotational movements during plantar flexion and dorsiflexion. In their study analyzing adult foot movements with a 3D virtual model, Mattingly et al.[13] reported that the talus exhibited almost three times more biplanar movement than the calcaneus. In contrast, the movements of the calcaneus, navicular, and cuboidal bones occurred in biaxial rotation and sometimes biplane translation. When the foot was plantarflexed, the cuboid rotates relative to the calcaneus, and the navicular rotated relative to the talus. The navicular and cuboid bones moved together during translational movements; similarly, the talus and calcaneus moved in synchrony. Additionally, in our study, the talus/medial cuneiform ratio and (talus + 1st metatarsal)/medial cuneiform ratio were found to be significantly higher in the HV group, supporting the role of the talus in load transfer to the medial arch. In general, we expect to find similar changes in the calcaneus in response to the increase in talus volume. However, in our study, no changes were found in the calcaneus at the expected level. We can interpret the volume decrease in the cuboid volume as a reflection of the expected rotational movement on the lateral side. Conversely, while we expected a rotational effect on the medial side in the navicular, our measurements indicated that the affected bone was the medial cuneiform rather than the navicular. We believe that these changes, which begin with the talus, are reflected distally through a domino effect, and the addition of soft tissue influences leads to the first metatarsal pronation, leading to HV. The lack of clinical evidence of the relationship between the calcaneus and talus can be explained by the role of the hindfoot in weight-bearing.

In their studies examining changes in talus morphology, Flury et al.[26] suggested that these changes might be associated with flatfoot, while Gorman et al.[27] emphasized the importance of relating the depth, width, and radius of the talus to BMI. In our study, we also attempted to standardize our foot bone measurements by including individuals with similar BMI and without foot deformities in our study.

It has been well established that HV deformity is a gradually progressive deformity. Therefore, understanding the volumetric changes in the talus would change the clinical approach. Reducing talus volume may not be possible. However, taking precautions before the deformity develops may lead to improved clinical outcomes. Although many procedures have been described in HV surgery, there is no consensus on which technique should be applied to each patient. While each technique has certain advantages and disadvantages, the major concern is recurrence. In particular, juvenile HV cases have a much higher recurrence rate.[28] This is likely because changes in adolescent foot bone volumes persist after surgery. Another contribution that may be important in preventing recurrences would be the addition of cuboid-related planning to surgical treatment. Understanding the volumetric impact of foot bones on the development of HV would aid in the development of ergonomic shoe designs and foot orthoses. Indeed, with the introduction of AI into our lives, it would be possible in the near future to better analyze individuals' foot structures through smartphone applications, without even needing to receive radiation, and to prevent possible deformities.

Nonetheless, there are some limitations to our study. The small sample size is the first limitation. Although we used power analysis to examine a sufficient number of patients, future studies with larger patient and control groups would provide more valuable data to the body of knowledge in the literature. Second, although we measured volume in our study with groups that were homogeneous in terms of age and BMI, it would be more beneficial to measure volumes using actual numerical values rather than ratios by working with individuals having the same foot size. Moreover, our measurements are based solely on static images. To determine the deformity process, future studies would be clinically much more valuable, if they regularly measured the volumetric development of foot bones from childhood. Finally, we were unable to include phalanx measurements in this study due to the fact that the small size of the fifth phalanx could have resulted in inaccurate measurements, which might have negatively affected the outcomes of our study.

In conclusion, the etiology of HV appears to be multifactorial. To date, it remains unclear whether many of the interrelated factors identified are actual causes or consequences of the deformity. Although genetic factors are widely considered to play a key role in HV development, we propose that the process originates more proximally, most likely at the level of the talus. Based on our study results, we conclude that an increase in talar volume may lead to a compensatory reduction in the volumes of the cuboid and medial cuneiform bones, initiating a sequence in which soft-tissue forces contribute to progressive pronation of the first metatarsal, ultimately resulting in HV. Further research focusing on the talus may provide deeper insight into the etiopathogenesis of HV and support the refinement and optimization of treatment protocols.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Y.E., A.P., S.B.: Idea/concept, design; A.Y.S., F.A.: Control/supervision; Y.E., A.P., S.B., A.Y.S.: Data collection and/or processing; Y.E., A.P., S.B., Z.K.E.: Analysis and/or interpretation, literature review, writing the article; Y.E., F.A.: Critical review.

Conflict of Interest: The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Funding: The authors received no financial support for the research and/or authorship of this article.

AI Disclosure: The authors declare that artificial intelligence (AI) tools were not used, or were used solely for language editing, and had no role in data analysis, interpretation, or the formulation of conclusions. All scientific content, data interpretation, and conclusions are the sole responsibility of the authors. The authors further confirm that AI tools were not used to generate, fabricate, or 'hallucinate' references, and that all references have been carefully verified for accuracy.

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