CHAPTER 1

Three-Dimensional Weightbearing Computed Tomography Image Analysis of Hallux Rigidus

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INTRODUCTION

In 1887, Davies-Colley originally described a localized form of arthritis of the first metatarsophalangeal joint and referred to it as "hallux flexus" (1). Cotterill later coined the term hallux rigidus, which has remained the most commonly used terminology (2). The subjective symptoms and objective information from the physical and radiographic examination are well documented in the literature. However, there have been many disputed findings with regards to the epidemiology as well as physical and radiographic findings of hallux rigidus.

The disparity in radiographic findings with regards to hallux rigidus may be due to the difficulty in obtaining accurate measurements and views with the standard diagnostic full weightbearing radiographs. With advances in technology, three-dimensional relationships of the bones in the foot can accurately be analyzed and measured. Three-dimensional weightbearing computed tomography (3D-WBCT) is a new technology that allows for more exact and efficient ways to measure and compare anatomic relationships of the foot and ankle. This is crucial to the podiatric surgeon as proper analysis of the anatomic structure such as bone quality and articular shape of the first metatarsal head will contribute to preoperative planning and intraoperative techniques for surgical treatment of hallux rigidus.

LITERATURE REVIEW

In the literature, there is conflicting demographic information on patients with a hallux rigidus diagnosis (3). Furthermore, there is widespread disagreement on many radiographic parameters including whether the first metatarsal articular shape or a hallux valgus deformity is associated with hallux rigidus (3). There has also been controversy about whether or not a long, short, or equal first metatarsal length had an association with hallux rigidus (3). In a radiographic study of the size of the first metatarsophalangeal segment, Munuera et al in 2007 found that the absolute or anatomic first metatarsal length in hallux rigidus patients is not greater than in normal feet as some studies have found (4). They also concluded that the first metatarsal protrusion distance in relation to the second metatarsal is increased in this foot type (4). One of the main limitations of the study is the use of two-dimensional images to evaluate three-dimensional elements.

Richter et al did a recent study comparing PedCAT 3D-WBCT, CT, and radiographs. They found that image acquisition with 3D-WBCT to be 70% faster than with radiographs and 35% faster than with CT (5). When considering the potential of the 3D-WBCT as faster image acquisition and more accurate bone imaging than radiographs and CT with acceptable radiation dose and cost-effectiveness, it could be implicated that the 3D-WBCT may have the potential to become the standard diagnostic imaging in foot and ankle surgery.

The aim of this study is to address the controversy in the literature about the influence of the size of the first metatarsal and hallux as a causal factor of hallux rigidus. Using 3D-WBCT, we will effectively confirm whether the absolute lengths of the first metatarsal and hallux are greater than normal in patients with hallux rigidus. We hypothesize that the lengths of the metatarsal and hallux are greater in patients with hallux rigidus. Because of the clarity in imaging that 3D-WBCT provides compared with plain radiographs, we will also be able to provide reference values for the size of the first metatarsal and hallux, which would be helpful for preoperative diagnosis and planning.

METHODS

A retrospective review was performed of 3D-WBCT images from 18 anonymous patients who were evaluated between 2012 and 2014 from the principle author's office. The sample for this study comprised 18 feet belonging to 9 patients in the control and 9 patients in the hallux rigidus group. There were 5 males and 4 females in the hallux rigidus group, with an average age of 60.4 years (range 50-64 years). The inclusion criteria for the patients in the sample included: never to have undergone first metatarsophalangeal joint surgery of the foot, never to have experienced trauma to the foot that may have altered its anatomic morphology, and not to have neuromuscular disease and seronegative arthridities that could affect the results of the study.

The sample was divided into a control group and a group with hallux rigidus. The control group subjects required a hallux dorsiflexion of >70 degrees. The subjects in the hallux rigidus group required a hallux dorsiflexion of ≤50 degrees.

3D-WBCT images were taken of bilateral feet in the patient's relaxed calcaneal stance position using the CurveBeam, LLC Version 2.2.0.2 scanner and CubeVue 2011-2012 program software. Slices obtained from the CurveBeam were combined with the CubeVue software into a 3-dimensional image that could be analyzed. The following 3D-WBCT parameters were measured and compared between the 2 groups using the CubeVue software: first metatarsal protrusion, first metatarsal length and width, second metatarsal length, proximal phalanx of hallux length and width, distal phalanx of hallux length, and the total length of the hallux.

Hardy and Clapham described the method used to measure the relative first metatarsal protrusion distance, which is the method recommended by the American Orthopedic Foot and Ankle Society. This measurement consists of a transverse line connecting the posterior tubercle of the navicular with distal end of the calcaneus. The point where the bisection of the second metatarsal intersects this transverse line is the center of 2 arcs that pass through the most distal aspects of the first and second metatarsal heads. The protrusion between these 2 metatarsals is obtained by measuring the distance between the 2 arcs.

To obtain the lengths of the first and second metatarsals and the hallux phalanges, the lengths of their respective longitudinal axes were measured. The width of the first metatarsal and proximal phalanx of the hallux was measured by using a line perpendicular to the longitudinal axis of the metatarsal at the midpoint of its length. The overall hallux length was recorded as the distance from the proximal end of the longitudinal axis of the proximal phalanx to the most distal end of the distal phalanx of the hallux.

RESULTS

The 3D-WBCT measurements were first assembled according to group assignment and descriptive statistics consisting of means and standard deviations for quantitative data. Frequencies for the categorical data were also calculated for each of the study groups. SPSS software package was used to analyze the data. Paired sample *t*-tests were used to determine if there was a statistical difference between the 2 groups with respect to the measurements analyzed. *P* values less than or equal to 0.05 were considered significant.

Table 1 lists the mean and standard deviations of the 7 measurements obtained from the 3D-WBCT images of the 2 groups. The mean metatarsal protrusion distance was 3.43 ± 0.49 mm for the halllux rigidus group and 2.34 ± 1.04 mm for the control group. The mean first metatarsal length was 64.56 ± 7.92 mm for the hallux rigidus group, and 61.87 ± 4.53 mm for the control group. Mean measurements of second metatarsal length were 75.34 ± 8.24 mm and 73.63 ± 5.08 mm in the hallux rigidus and control groups, respectively.

For the digital measurements, the mean proximal phalanx lengths were 29.96 ± 3.98 mm and 27.66 ± 3.49 mm for the hallux rigidus and control groups, respectively. The mean of the distal phalanx length was 24.13 ± 3.55 mm for the hallux rigidus group and 23.81 ± 2.77 mm for the control group. Mean measurements for the first metatarsal width were 13.53 ± 1.70 mm and 12.74 ± 1.26 mm, respectively. The mean proximal phalanx width was 14.20 ± 1.46 for the hallux rigidus group and 13.95 ± 1.26 for the control group. Of all of these 3D-WBCT parameters, only the first metatarsal protrusion distance was found to be statistically significant ($P < 0.025$) between the 2 groups.

Table 1. Measurements obtained from the three-dimensional weightbearing computed tomography images

	Control **Mean ± SD**	**Hallux rigidus** **Mean ± SD**
1st metatarsal length (mm)	61.87 ± 4.53	64.56 ± 7.92
1st metatarsal width (mm)	12.74 ± 1.26	13.53 ± 1.70
Proximal phalanx length (mm)	27.66 ±3.49	29.96 ± 3.98
Proximal phalanx width (mm)	13.95 ± 1.26	14.20 ± 1.46
Distal phalanx length (mm)	23.81 ± 2.77	24.13 ± 3.55
2nd metatarsal length (mm)	73.63 ± 5.08	75.34 ±8.24
1st metatarsal protrusion distance (mm)	+2.34 ± 1.04	+3.43 ± 0.49*

*($P = 0.025$)

DISCUSSION

Based on our study, we found that the first metatarsophalangeal segment in hallux rigidus patients to be longer than normal including a long hallux, increased first metatarsal protrusion distance, and a first metatarsal that tends to be anatomically longer than normal. We found that the first metatarsal protrusion distance to be significantly greater in the hallux rigidus group compared with the control. The difference between the control and hallux rigidus groups might be clinically insignificant because there are relatively small differences when separately analyzing the first metatarsal length, proximal and distal phalanx lengths and total length of the hallux. However, these differences should not be taken into account alone.

When these different parameters are combined, the results would be a longer than usual first metatarsophalangeal segment. In order for there to be adequate dorsiflexion of the hallux, there must be a slight difference in the second metatarsal protrusion with respect to the first metatarsal (6). Thus while the second metatarsal is bearing weight, the first metatarsal can plantarflex and allow the rotational axis of the joint to be transferred posterior-ward. A long first metatarsal with respect to the second metatarsal constrains the plantarflexion in the propulsive phase of gait (7). This makes the first metatarsophalangeal joint very stable in the transverse plane of square morphology. This could cause excessive compression of the joint in the propulsive phase of gait when the ground reactive force acting on the hallux increases (8). This retrograde effect on the joint could explain the decrease in intra-articular space observed.

We can relate the excessive functional length of the first metatarsal to the etiology of hallux rigidus as the relative first metatarsal protrusion distance was greater in the hallux rigidus group than in the control. This is in agreement with several studies including Munera et al and Zgonis et al (4). Although the trend was for the first metatarsal to be slightly larger in the hallux rigidus group, the difference was not statistically significant. However, the difference between the groups with regards to the first metatarsal width is noteworthy. It has been postulated that excessive width could make the first metatarsal morphologically squarer (9). If that squaring affects the entire metatarsal, including the head, there could be a relationship with the development of this deformity as the association between hallux rigidus and a square shaped first metatarsal head has been accepted.

The results of this study have important implications for preoperative planning and intra-operative decision-making. The dynamic 3-dimensional evaluation of this pathology using WBCT allows the surgeon to preoperatively evaluate the foot and ankle more accurately than with plain film radiographs. This technology may allow the surgeon to make precise assessments of relative bone positions and angulations for treating hallux rigidus. The quality of bone including the absence or presence of bony cysts that are not usually appreciated on plain films can better assist the surgeon at preoperative planning. The foot and ankle can be studied in all 3 planes of weightbearing and the status of any bone can be measured.

The main limitation of this study is the small sample size available to extract our data. Another limitation is that it is a retrospective review. We are unable to determine whether the control group subjects with positive metatarsal protrusion distance values or longer first metatarsals went on to develop hallux rigidus. Also, the demographic differences between the 2 groups including age and sex may be a limitation. We hope that this first study using 3D-WBCT to evaluate hallux rigidus will encourage further long-term prospective studies evaluating the various 3D-WBCT parameters that would be of benefit in understanding the etiology of hallux rigidus.

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