CHAPTER 1

COMPUTED TOMOGRAPHY 3-DIMENSIONAL IMAGE ANALYSIS OF THE SAGITTAL PLANE WEIGHT-BEARING SURFACES OF THE METATARSALS

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INTRODUCTION

Metatarsalgia and other generalized forefoot complaints are one of the most common problems plaguing the podiatric physician. Furthermore, this metatarsalgia often leads to, or is accompanied by painful progressive digital deformities. More specifically, these complaints are commonly centered around the plantar aspects of first, second, and third metatarsal heads. Recent literature has been examining plantar plate attenuation/rupture; while stress fractures, capsulitis, bursitis, neuromas, etc., are all well researched pathologies in the forefoot. Shortening osteotomies of the lesser metatarsals, i.e., the Weil osteotomy, are in vogue presently, and much research is focused on examining this and other procedures. Correlations have been found between a long second metatarsal and increased plantar plate ruptures (1). Yet other research has shown that an increase in metatarsal length is not correlated with increased plantar pressures based on force plate studies (2). Much of this research revolves around reducing the length of the metatarsals, based on the dorsal plantar view of the radiograph.

Dreeban et al in 1989, found that a dorsiflexory osteotomy of ~4 mm in a lesser metatarsal relieved plantar pressures based on pedobarographic analysis (3). Despite this however, a paucity of research evaluates the sagittal plane deformities of the metatarsals, with the exception of the first ray. The research disparity on this topic is most likely due to the difficulty obtaining accurate dynamic measures during gait, but also the added trouble of viewing this plane from a lateral radiograph secondary to overlap of the metatarsals. As new technology surfaces, such as weight-bearing computed tomography (CT) imaging, it will allow for a more efficient and precise way to measure the sagittal plane anatomy of the metatarsals. It is important to identify proper metatarsal alignment to assist in preoperative planning and intraoperative techniques for metatarsal osteotomies.

Reasons for many of the forefoot pathologies can be attributed to "abnormal" metatarsal parabola (i.e., long second/short first/short third, etc.) and systemic arthritides, but much of the pathology may also be due to plantarflexed or dorsiflexed positions of certain metatarsals. There is a multitude of literature on plantar pressures of the human foot, and some new research is emerging with geometrically constructed models of the foot in simulated weightbearing, based on magnetic resonance imaging (MRI) scans. To date, and to the best of our knowledge, there is no study using patient's actual weight-bearing CT image to assess the sagittal plane weight-bearing surfaces of the metatarsals.

In this study, we have examined the relative metatarsal head distances from the ground and their heights relative to each other. These weight-bearing CT measurements from 50 patients and 50 feet provide a more accurate insight into the anatomic position of the metatarsals in the sagittal plane. Hopefully, more precise assumptions can then be made as to where to place the metatarsal heads in common surgeries such as distal first metatarsal osteotomies, the Weil, the Lapidus, and other related procedures. The purpose of this study is to evaluate the weight-bearing surfaces of the metatarsal heads, as well as the sesamoids, with reference to the ground and each other, using weight-bearing 3-D CT images. We hypothesize there is no difference between the sagittal plane height of the most plantar aspect of the sesamoids and all metatarsals.

METHODS

Weight-bearing CT images from 50 anonymous patients, who were evaluated between 2011 and 2013, were retrospectively analyzed by one investigator at Oasis Surgical Center, San Diego, California. Patient ages ranged from 14 to 78 years, and there were 24 females and 26 males who each presented with various foot complaints based on diagnosis. Greater than 50% of the patients had an

associated pronated foot type. Using the CubeVue 2011-2012 program software, and the CurveBeam, LLC Version 2.2.0.2 scanner, weight-bearing CT images were taken of bilateral feet in the patient's relaxed calcaneal stance position. Images were taken in less than 1 minute (approximately 9 seconds of radiation exposure to the patient), with slices of 0.3 mm, and a relatively small radiation dose (~2μSv). Slices were then combined via CubeVue software, into a 3-dimensional image to be viewed. On the digital image within the computer program, the lowest point of the metatarsal head was chosen from a frontal plane image slice, which was then correlated and confirmed with the lowest aspect in the sagittal plane image slice.

The distance in millimeters was then measured from that lowest point of the metatarsal to the ground surface on the image. This measuring process was used for each metatarsal as well as the lowest sesamoid. The first intermetatarsal angle (>12 degrees), sesamoid size, Seiberg's Index, and hallux position (>15 degrees) were also measured and included in analysis. Metatarsal protrusion distance was also measured by means of Coughlin's Method, as well as the more common method of bisecting the second metatarsal and comparing perpendicular lines from the first and second distal articular surfaces to that bisection. All measures where then charted and analyzed to ascertain a possible "normal distance," and where each metatarsal is relative to each other. Patients were also separated into a group with hallux abducto valgus and patients with a rectus hallux, to establish possible correlations to sagittal plane position. We excluded any subjects who had previous foot surgery, as well as patients who had past fractures, dislocations, Charcot, significant arthritides, and malignancies in the bone or surrounding soft tissues.

RESULTS

SPSS software was used for all statistical analysis. The paired sample t-test, Pearson R correlation coefficient for determining association between variables, 1-way ANOVA, and 2-way ANOVA were all used to analyze the data. *P* values less than or equal to 0.05, or (5%), were considered significant. All data were within ± 2 standard deviations, and followed a normal bell curve, indicating an appropriate sample population.

When including all patients, the mean distance from ground to first metatarsal head was found to be 9.22 mm, and the range was 4.33 mm to 13.32 mm. The mean distance from ground to second metatarsal head was 6.40 mm, with a range of 2.40 mm to 11.70 mm. The mean distance from ground to the third metatarsal was 5.32 mm, with a range of 1.50 mm to 12.30 mm. The mean distance from the ground to the fourth metatarsal was 4.76 mm, with a range of 1.57 mm to 9.54 mm. The mean distance from the ground to the fifth metatarsal was 3.55 mm, with a range of 0.46 mm to 7.52 mm. The mean distance from ground to the most plantar sesamoid was 3.79 mm, with a range of 0.30 mm to 8.50 mm.

Grouped by patients with a rectus hallux, a slight decrease in distance to the ground was found, with respect to all metatarsals and the sesamoids. The mean distance from ground to first metatarsal head was found to be 8.48 mm, and the range was 4.33 mm to 13.32 mm. The mean distance from ground to second metatarsal head was 5.53 mm, with a range of 2.40 mm to 10.70 mm. The mean distance from ground to the third metatarsal was 4.72 mm, with a range of 1.91 mm to 7.56 mm. The mean distance from the ground to the fourth metatarsal was 4.24 mm, with a range of 1.57 mm to 7.66 mm. The mean distance from the ground to the fifth metatarsal was 2.94 mm, with a range of 0.46 mm to 6.61 mm. The mean distance from ground to the most plantar sesamoid was 2.98 mm, with a range of 0.30 mm to 7.81 mm.

The results of the hallux valgus group, revealed a slight ~2 mm elevation of all metatarsals and sesamoids, compared to the rectus hallux group. The mean distance from ground to first metatarsal head was found to be 9.79 mm, and the range was 6.37 mm to 12.86 mm. The mean distance from ground to second metatarsal head was 7.08 mm, with a range of 3.30 mm to 11.70 mm. The mean distance from ground to the third metatarsal was 5.80 mm, with a range of 1.50 mm to 12.10 mm. The mean distance from the ground to the fourth metatarsal was 5.19 mm, with a range of 2.52 mm to 9.54 mm. The mean distance from the ground to the fifth metatarsal was 4.02 mm, with a range of 0.86 mm to 7.52 mm. The mean distance from ground to the most plantar sesamoid was 4.43 mm, with a range of 0.94 mm to 9.13 mm.

Although there were only four patients with pathological hallux limitus, and therefore no statistical inferences can be drawn, the trend of medial column measures were slightly more elevated than both groups included in the analysis. Mean distance from the ground to the first metatarsal was 10.57 mm; second metatarsal 8.17 mm; third metatarsal 7.87 mm; fourth metatarsal 6.30 mm; fifth metatarsal 3.75 mm; and sesamoids 4.49 mm.

Patients with valgus position of the hallux, tended to have ~2 mm more elevation of each metatarsal and sesamoids, then the rectus group. Even this marginal distance of ~2 mm was found to be statistically significant between groups, with a *P* value of <0.05.

There were very high correlations found between the

distances from the ground to the first metatarsal and sesamoids; second and third metatarsals; and fourth and fifth metatarsals. Biomechanically, this should be intuitive since the first metatarsal and sesamoids move as one complex, and the second and third/fourth and fifth metatarsals are part of the medial and lateral columns respectively, and as such, move together in their respective columns. A high correlation was also found between the distances from the ground to each of the metatarsals and sesamoids. Therefore, if one metatarsal was found to be elevated, all of the metatarsals and sesamoids were found to be elevated.

Age was strongly and inversely correlated with the distance from ground to sesamoids and metatarsal heads, with a Pearson r of 0.492. There was no correlation found between the first intermetatarsal angle, Seiberg's Index, or metatarsal protrusion distance, and the distance from ground to sesamoids and the metatarsal heads in all patients, and hallux abducto valgus/rectus groups.

There was a moderate correlation between Coughlin's method and the more common metatarsal protrusion distance measures. The average metatarsal protrusion distance via Coughin's method was -4.4 mm and with the more common method was -3.7 mm.

The average sesamoid size was found to be 6.44 mm.

DISCUSSION

Most pathology of the forefoot can be attributed to either abnormally long or short or excessively plantarflexed or doriflexed metatarsals. These traits will then predispose the foot to increased callus formation, ulcerations, digital muscle imbalance and therefore contracted digits, and lastly significant pain. Most of the current and past peer-reviewed literature revolves around the enigma of the "normal" metatarsal parabola, and each specific metatarsal length. A multitude of articles can be found citing the correlation between increased metatarsal length and increased callus formation and rate of plantar plate rupture with associated hammered digits. However, there have been few studies attempting to analyze the sagittal plane "normal" anatomy of the metatarsals, and even less that have measured distances of metatarsal heads to the ground. No studies, to the best of our knowledge, exist that ascertain these measures using actual patient's weight-bearing CT images.

Assessing sagittal plane normality for metatarsals by any means is a difficult task. Not only is there limited research to build upon, but also the means of visualizing these measures were limited to radiographs. With the advent of the weight-bearing CT scans, it allows for more precise and reproducible measures of sagittal plane distance and possible normal measures.

The distance measures obtained in this study were unable to be compared to other measurements in literature, as this is a pilot study in this area. Perhaps these distances may be considered normal for patients in their RCSP. The importance of these data will have significant implications for preoperative planning, as well as intraoperative decision-making when completing metatarsal osteotomies.

Although most surgeons use static weight-bearing radiographs of patients in RCSP for preoperative planning, it is important to remember that these measures are not dynamic. It would be beneficial in future studies, to perhaps include a stress lateral dorsiflexion CT image in the data analysis. This view could give more insight into where the metatarsal heads are after mid-stance and into the propulsive phase. Conceivably, the metatarsals could remain the same relative distances to each other, but likely move closer to the ground causing increased pressure under the metatarsal heads. Pathologies of the forefoot are then most certainly a combination of metatarsal length, declination, and dynamic rotation forces during gait. They are not simply a length or a declination issue, but a combined entity.

The hallux abducto valgus group in this present study had metatarsals and sesamoids with increased distance from the ground. This is contrary to the belief that patients with hallux abducto valgus and increased intermetatarsal angles, have more first ray elevation and therefore pressure is transferred to the lesser metatarsals, mostly the second. First we must remember that these values likely change with dynamics. Secondly, it is feasible with an unstable first ray and associated excessive pronation, more weight-bearing forces are placed on the medial arch relieving the metatarsal heads of some pressure and therefore they are more elevated.

A strong inverse correlation was found between age and distance from ground to metatarsal heads. This finding should be intuitive considering the atrophy of the fat pad with increasing age. As age increased, the metatarsal heads became closer to the ground. This should be a reminder that in the older population, it is extremely important to cushion the metatarsal heads in order to prevent an additional related pathologies as discussed above.

Metatarsal protrusion was not found to correlate with sagittal plane distance to the ground. These results indicate that despite having a longer or shorter metatarsal, this does not predispose it to being closer to the ground or more elevated in RCSP. Again, it is important to note that these measurements may change during gait. There was a moderate correlation found between the two methods of measurement, but on average Coughlin's method produced an ~1 mm longer measure of the second metatarsal. Seiberg's Index also had no correlation with sagittal plane distances to the ground. This may indicate that despite the

first ray being elevated or plantarflexed relative to the second metatarsal, does not indicate that each of the metatarsals is actually closer or father away from the ground.

We recognize that a retrospective study in itself is a limitation of the study. Another limitation is that there are no normal or controls to compare to, as well as no subjective patient information. Perhaps the largest limitation is the lack of a dynamic or functional measure of the sagittal distances. Hopefully, this pilot study will encourage new studies to investigate further.

CONCLUSION

In this study our goal was to assess a possible normal sagittal plane metatarsal head distance for all metatarsals and sesamoids. We reject our null hypothesis that there is no difference between the sesamoids and metatarsal heads in sagittal plane distance from the ground. Additionally, patients with hallux abduct ovalgus deformities were found to have slightly more elevated metatarsal heads in RCSP, than their non-pathologic counterparts, with approximately 2 mm on average. Though metatarsal protrusion distances did not correlate with a more plantar oriented metatarsal head, clinical judgment must be used intra-operatively when positioning the metatarsals in the sagittal plane. In older patients care must be taken to provide proper forefoot cushioning to prevent "metatarsalgia" and concomitant progressive digital deformities.

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