Plantar Pressure Characteristics in Hallux Valgus Feet

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ABSTRACT: Due to the pathoanatomical changes in hallux valgus feet, the plantar flexion moment of the first metatarsophalangeal joint is reduced. Therefore, load bearing of the hallux is decreased during push-off. We assessed loading parameters in hallux valgus feet. Based on dorsal-plantar weight bearing radiographs of 61 feet, the intermetatarsal-, hallux valgus-, distal metatarsal articulation-angle, and sesamoid position were evaluated. Plantar pressure assessment was performed with the emed® system during level walking. We found negative correlations between hallux valgus angle and peak pressure in the great toe ($r = -0.301$, $p < 0.023$), the maximum force of the hallux ($r = -0.481$, $p < 0.001$), and contact time of the great toe ($r = -0.448$, $p < 0.001$), and positive correlations for force time integral ($r = 0.348$, $p < 0.001$), contact area ($r = 0.307$, $p < 0.020$), maximum force ($r = 0.430$, $p < 0.001$), and peak pressure ($r = 0.361$, $p < 0.006$) of the fifth metatarsal head. A positive correlation between the sesamoid and the metatarsal subluxation regarding maximum force ($r = 0.294$, $p < 0.034$), and a negative correlation between the contact area of the hallux ($r = -0.232$, $p < 0.020$) was shown. Depending on the severity, hallux valgus angle, and sesamoid subluxation, load shows significant lateral transmission in hallux valgus feet. © 2014 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 32:1688–1693, 2014.

Keywords: hallux valgus; plantar pressure distribution

Hallux valgus is a common pathologic, gradually progressive condition of the musculoskeletal system. Due to the weakness of the medial collateral ligament and capsule, the proximal phalanx drifts into valgus, and the metatarsal head drifts into varus. With increasing deviation of the first metatarsal, the medial sesamoid shifts under the metatarsal head, and the lateral sesamoid shifts into the space between the first and the second metatarsal head. As a consequence, the tendons of the extensor hallucis longus and the flexor hallucis longus are shifted laterally, becoming abductors and thereby exacerbating the deformity.[1,2,3]

During normal gait at the end of stance the first ray, especially the hallux obtains the highest loads of the foot.[4] Jacob et al. reported that 29% of the body weight is acting under the first metatarsal head, and 24% is acting under the big toe.[5] Recent studies suggested that forefoot kinematics are altered by morphologic changes associated with hallux valgus deformity.[6] These changes alter the kinematics of the first metatarsophalangeal (MTP) joint, leading to reduced force generation capacity of the plantar flexors[7] and therefore causing decreased weight bearing by the great toe and the first ray. Load transfer during stance phase of gait is increased over the metatarsal heads of the lesser toes. Several authors reported this phenomenon as the reason for lesser toe metatarsalgia.[8,9,10]

Pathologies of the foot alter the plantar pressure distribution and can be easily measured under dynamic conditions by pedobarography. Pedobarography expands the static radiological diagnostics that show only structural changes. Several authors used plantar pressure assessment to investigate biomechanical changes after reconstructive procedures in the foot and ankle,[11,12,13] but also to characterize loading patterns in healthy, respectively[14] pathologic feet.[15,16] Hillstrom et al. reported significant differences with respect to plantar pressure parameters across different foot types. Bryant et al. investigated the influence between static radiographic measurements and plantar pressure distribution in feet with hallux valgus or hallux limitus deformity, but did not find a relationship between both measurements.[17] A recent review of studies analyzing plantar pressure characteristics in hallux valgus feet reported inconsistent results, due to the lack of appropriate classification of the severity of deformity and different systems for plantar pressure assessment.[18]

We assessed loading parameters in hallux valgus feet and correlated these measurements to the severity of the deformity based on plane radiographs. We hypothesized that a strong relationship exists between structural and dynamic conditions in hallux valgus feet in terms of a lateral shift of load from the medial to the lateral aspect of the foot.

PATIENTS AND METHODS

Patients with symptomatic hallux valgus deformity were referred to the study by a fellowship trained foot and ankle surgeon before surgical treatment. Between 01/2006 and 01/2007, 55 patients were included, and 20 patients were excluded: patients with concurrent forefoot deformities, fixed-foot deformities, rheumatic disease, diabetes mellitus, varus valgus deformity of the leg, or history of trauma were excluded. No patient was suffering from other pathologic conditions of the musculoskeletal system that might influence normal gait patterns. A total of 61 feet of 55 patients, of which 52 were female, were included. Mean age was 57.7 years (SD 11.3, range 20–79); there were 30 right and 31 left feet. The mean hallux valgus angle was 34.1° (SD 7.9; min 20°, max 56°), the mean intermetatarsal angle 14.7° (SD 2.6; min 11°, max 23°), and the mean sesamoid

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subluxation (SL) was 2.4 (SD 0.6). There were 35.2% mild, 55.6% moderate, and 9.3% severe hallux valgus deformities. All patients received standardized full weight bearing radiographs in the dorsoplantar and lateral views, and a plantar pressure assessment was obtained during level walking. The validity, repeatability, and reliability of the emed system are high if more than three measurements are taken and if the mid gait method is used.[19,20,21] In our study, five measurements were taken, and the mid gait method was chosen because the mid gait method is more representative for normal gait.[22,23] An independent observer performed all measurements. Prior to collecting data, all patients signed an informed consent approved by the Institutional Review Board. The rights of the patients were protected all the times.

Radiographic assessments of the hallux valgus angle and the intermetatarsal angle were performed according to the method of Miller et al. (Fig. 1).[24] This method is the most precise method and offers a high grade of reliability and repeatability.[25] The hallux valgus angle was determined by the intersection of the longitudinal axes of the first metatarsal and the proximal phalanx. The intermetatarsal angle was formed by the intersection of the longitudinal axes of the first and the second metatarsal bone. The severity of the hallux valgus deformity was classified on weight-bearing dorsoplantar radiographs and divided into mild (hallux valgus angle [HVA] up to 19° and intermetatarsal angle [IMA] up to 13° moderate (HVA of 20° to 40° and IMA 14° to 20°), and severe (HVA > 40° and IMA > 20°.[3] The sesamoid position was evaluated by measuring the position of the medial sesamoid relative to the bisecting line of the first metatarsal shaft and was classified as grade 0 to 3.[26] Grade 0 is defined as no displacement of the sesamoid relative to the longitudinal axis of the first metatarsal. Grade 1 is defined as an overlap of 50% of the sesamoid to the longitudinal axis. Grade 2 is defined as overlap of >50% of the sesamoid to the longitudinal axis. Grade 3 is defined as complete displacement of the sesamoid across the longitudinal axis of the first metatarsal.

Figure 1. Radiological assessment of the hallux valgus angle (intersection of the longitudinal axes of metatarsal 1 and the proximal phalanx), intermetatarsal angle (intersection of the longitudinal axes of the first and second metatarsal), and sesamoid luxation (position of the medial sesamoid relative to the bisecting line of the first metatarsal shaft was graded from 0 to 3) on a weight bearing dorsoplantar radiograph.

Dynamic pedobarography was performed using a capacitive pressure measurement platform (emed-at platform, novel GmbH, Munich, Germany) with a total area of 610 mm × 323 mm enclosing a 240 mm × 380 mm sensor area with a total of 1,760 sensors (2 sensors/cm^2), sampling at a rate of 60 Hz, and auto triggered upon first contact. The platform has a maximum measurable force of 67 kN with a hysteresis of <3%, and the pressure threshold is 10 kPa, ranging up to 1,270 kPa. The platform with a depth of 18 mm is embedded in a polyethylene ramp with a length of 10 m. Patients were able to cross the emed-at platform in both directions. Patients were told to walk at a normal, constant velocity. The data were collected, and the analysis was performed with the emed/D software.[27] The foot was divided into the following geometric regions of interest: total object, heel, medial and lateral metatarsus, forefoot, great toe, second toe and toe three to five, first metatarsal head (MH 1), second metatarsal head (MH 2), third metatarsal head (MH 3), metatarsal head four (MH 4), and metatarsal head five (MH 5) (Fig. 2). For each region, the peak pressure (kPa), the maximum force (N), the contact area (cm^2), the contact time (ms), and the force-time integral (N*s) was generated by the emed software. For each region of interest (called: mask), the time course of maximum pressure, force, and loaded area inside this mask were analyzed. For each parameter, the maximum was selected and displayed. The force-time integral was calculated as the area underneath the force over time curve. An average of the five datasets was calculated by the software.

Statistical Analysis

The Kolmogorov–Smirnov test for normal distribution and Pearson correlation were performed to investigate the influence of radiographic parameters of plantar pressure distribution. Analysis was performed using SPSS version 11.3 (SPSS Inc., Chicago, IL) and Excel for Mac (The Microsoft Corp., Redmond, WA). The level of significance was defined as alpha <0.05.

RESULTS

The mean results of the plantar pressure assessment for peak pressure (kPa), maximum force (N), contact time (%ROP), contact area (cm^2), and force time integral (N•s) for each region of interest are listed in Table 1. Table 2 indicates all significant correlations between radiological data (hallux valgus angle, intermetatarsal angle, and sesamoid luxation) and plantar pressure parameters (kPa, N, %ROP, cm^2, N•s).

Peak Pressure

We found a positive correlation between the hallux valgus angle and the head of metatarsal five ($r = 0.361$, $p < 0.006$) and a negative correlation of the hallux ($r = -0.301$, $p < 0.023$). A positive correlation was also identified between the sesamoid subluxation and toes three to five.

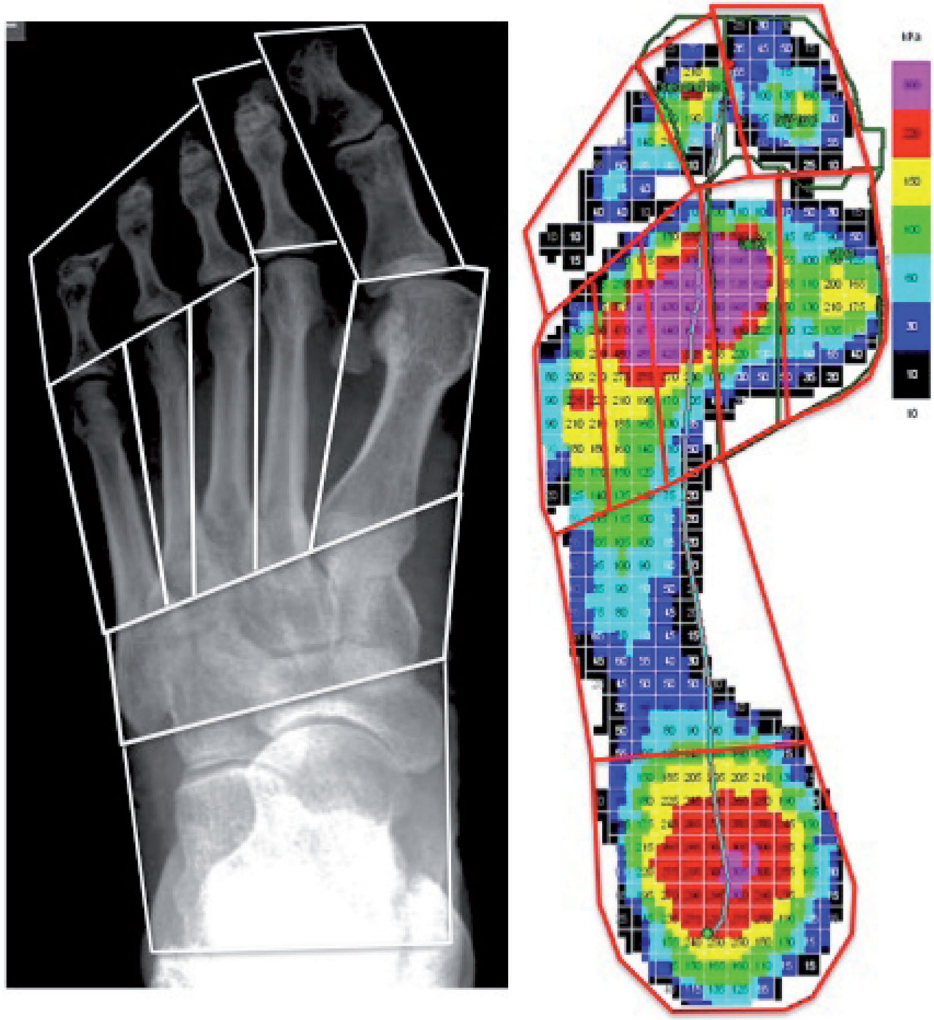

Figure 2. The region of interest in a plantar pressure image and the corresponding regions on a dorsoplantar radiograph. Regions: total object, heel, lateral midfoot, medial midfoot, forefoot, hallux, 2 toe, 3–5 toe, and metatarsal head 1 to 5.

Maximum Force

Positive correlation was found between the hallux valgus angle and the head of metatarsal five ($r = 0.430$, $p < 0.001$) and an inverse correlation for the hallux ($r = -0.481$, $p < 0.001$). Positive correlation was found between the sesamoid subluxation and metatarsal head one.

Contact Time

Negative correlation was found between the hallux valgus angle and the hallux ($r = -0.448$, $p < 0.001$) and a positive correlation between the sesamoid subluxation and toes three to five.

Contact Area

We found a negative correlation between the hallux and the hallux valgus angle ($r = -0.581$, $p < 0.001$) and the sesamoid subluxation ($r = -0.323$, $p < 0.020$). A positive correlation was found between the hallux valgus angle and metatarsal head five ($r = 0.307$, $p < 0.020$) and between the hallux valgus and metatarsal head five ($r = 0.289$, $p < 0.037$).

Force-Time Integral

The correlation between the hallux valgus angle and the hallux was negative ($r = -0.435$, $p < 0.001$) and positive for the metatarsal head five ($r = 0.348$, $p < 0.008$).

DISCUSSION

The hallux valgus deformity is associated with altered loading patterns of the forefoot, particularly of the first ray.[28] Studies focused on plantar pressure parameters, but their results were inconsistent.[29,18,10,30] Our aim was to specify plantar pressure characteristics of different regions of hallux valgus feet and to correlate them with the radiological parameters HVA, IMA (severity), and the sesamoid subluxation.

Three major results emerged from our study. First, we found a significant negative correlation between the

Table 1. Mean Results of the Plantar Pressure Assessment for Peak Pressure (kPa), Maximum Force (N), Contact Time (%ROP), Contact Area (cm^2), and Force-Time Integral (N•s) for Each Region of Interest (MH1 = Metatarsal Head One; MH2 = Metatarsal Head Two; MH3 = Metatarsal Head Three; MH4 = Metatarsal Head Four; and MH5 = Metatarsal Head Five)

	Peak Pressure (kPa) ± STD	Maximum Force (N) ± STD	Contact Time (%ROP) ± STD	Contact Area (cm^2) ± STD	Force Time Integral (N•s) ± STD
Total object	705.54 ± 195.05	741.33 ± 110.16	114.75 ± 115.23	119.34 ± 11.70	450.05 ± 108.83
Heel	312.79 ± 86.13	519.12 ± 674.80	58.75 ± 7.97	30.89 ± 2.59	123.43 ± 37.99
Lateral midfoot	143.03 ± 63.84	122.04 ± 65.96	60.16 ± 8.31	19.73 ± 4.84	37.62 ± 26.25
Medial midfoot	104.10 ± 26.87	20.41 ± 12.58	44.11 ± 10.36	3.81 ± 2.16	5.51 ± 4.49
Forefoot	681.02 ± 199.74	618.31 ± 93.20	83.02 ± 3.88	47.99 ± 5.11	245.79 ± 65.91
Hallux	336.63 ± 189.57	66.93 ± 36.56	59.93 ± 19.90	7.33 ± 2.53	19.45 ± 13.46
second toe	156.68 ± 89.12	23.78 ± 14.71	56.02 ± 35.13	3.42 ± 1.14	6.26 ± 5.14
Toe three to five	138.70 ± 62.50	33.22 ± 18.07	62.95 ± 14.67	6.03 ± 2.09	10.10 ± 6.55
MH1	361.18 ± 303.26	131.68 ± 64.41	71.63 ± 6.02	11.69 ± 2.07	50.98 ± 46.04
MH2	567.99 ± 208.96	168.34 ± 43.33	79.60 ± 4.11	10.94 ± 9.86	65.40 ± 18.36
MH3	474.23 ± 137.22	181.67 ± 37.67	81.88 ± 3.85	11.09 ± 1.13	73.59 ± 18.36
MH4	284.76 ± 98.52	112.78 ± 28.60	80.67 ± 3.73	24.80 ± 119.40	47.25 ± 13.01
MH5	272.53 ± 177.87	61.99 ± 25.79	74.27 ± 5.22	6.02 ± 0.74	22.37 ± 10.39

HVA and the hallux region in terms of peak pressure, maximal force, contact time, contact area, and force-time integral. Second, we found a significant positive correlation between the HVA and metatarsal head five in terms of peak pressure, maximal force, contact area, and force-time integral. Third, we found a significant positive correlation between the subluxation of the sesamoids and peak pressure, and contact time under toes three to five and maximal force under the head of the metatarsal one. These results confirm our hypotheses that with increasing hallux valgus angle load is shifted from the medial to the lateral aspect of the foot.

Table 2. All Significant Correlations Between Plantar Pressure Parameters of Each Region of Interest and Hallux Valgus-, Intermetatarsal-Angle, and Sesamoid Subluxation are Listed. The Correlations were Calculated by Use of the Pearson's Correlation Coefficient (r). The Level of Significance was Set at 0.05. (MH 1 = Metatarsal Head One; MH 5 = Metatarsal Head Five)

	Intermetatarsal Angle	Sesamoid Subluxation	Hallux Valgus Angle
Sesamoid subluxation	$r = 0.540$, $p < 0.001$		
Hallux valgus angle	$r = 0.540$, $p < 0.001$		
Intermetatarsal angle		$r = 0.561$, $p < 0.001$	$r = 0.484$, $p < 0.001$
Severity	$r = 0.909$, $p < 0.001$	$r = 0.451$, $p < 0.001$	$r = 0.478$, $p < 0.001$
Peak pressure total			$r = 0.285$, $p < 0.032$
Peak pressure lateral midfoot			$r = 0.341$, $p < 0.009$
Peak pressure forefoot			$r = 0.336$, $p < 0.011$
Peak pressure hallux			$r = -0.301$, $p < 0.023$
Peak pressure MH 5			$r = 0.361$, $p < 0.006$
Peak pressure toe three to five		$r = 0.279$, $p < 0.045$	
Max force lateral midfoot			$r = 0.431$, $p < 0.001$
Max force hallux			$r = -0.481$, $p < 0.001$
Max force MH 1		$r = 0.294$, $p < 0.034$	
Max force MH 5			$r = 0.430$, $p < 0.001$
Contact time medial midfoot			$r = 0.297$, $p < 0.025$
Contact time Hallux			$r = -0.448$, $p < 0.001$
Contact time toe three to five		$r = 0.283$, $p < 0.042$	
Contact area lateral midfoot			$r = 0.303$, $p < 0.022$
Contact area hallux		$r = -0.323$, $p < 0.020$	$r = -0.581$, $p < 0.001$
Contact area MH 5		$r = 0.289$, $p < 0.037$	$r = 0.307$, $p < 0.020$
Force time integral lateral midfoot			$r = 0.431$, $p < 0.001$
Force time integral hallux			$r = -0.435$, $p < 0.001$
Force time integral MH 5			$r = 0.348$, $p < 0.001$

There are several limitations with the present study. First, we included a small number of patients ($n = 55$; 61 feet). Second, only a small percentage (9.3%) of patients with severe hallux valgus deformity were included. Third, we did not include a control group, though the main goal was to correlate plantar pressure characteristics of hallux valgus feet and dorsoplantar radiographs. Keeping this in mind, it is not justifiable to expose healthy subjects to unnecessary radiation exposure. Fourth, we did not address velocity in the plantar pressure distribution assessment due to the fact that the mid gait method provides the record of the most natural gait patterns in the assessment of plantar pressure distribution.[31,23] However, to our knowledge, this is the first study focusing on peak pressure, maximum force, contact time, contact area, and force-time integral of different regions of interest in hallux valgus feet.

Hallux valgus deformity is a dynamic process with an increasing adduction of the first metatarsal, abduction of the hallux, and an increasing distance between the first and second metatarsals. From a functional standpoint, a reduced force-generation capacity of the plantar flexor of the first ray due to the lateral deviation of the great toe is present. Decreased weight bearing of the great toe was reported to be the reason for lesser toe metatarsalgia.[6,1,32,33,9] Martinez-Nova et al. reported a significant increase of plantar pressure under the hallux and the first metatarsal head in patients with mild hallux valgus, but they generated the data from an in-shoe system[29] that was different from our emed system. The in-shoe system is appropriate to evaluate the interaction between foot and shoe, but not the supporting surface.[21] This might explain the reason for the different results.

Menz et al. stated that increased length of the lesser metatarsal is not associated with elevated peak pressure, but higher peak pressure under the lateral metatarsal heads was measured when patients suffered forefoot pain.[34] They further demonstrated that patients with metatarsalgia were more likely to suffer hallux valgus, showed significant increase of plantar peak pressure under metatarsal heads three to five, and showed a negative association between hallux valgus and hallux loading.[35] Our study showed increased peak pressure under metatarsal heads three to five with increased sesamoid subluxation. The peak pressure increased under the metatarsal head five with increasing hallux valgus angle and it decreased under the hallux. Thus, our results are in agreement with those of Menz et al.

Kaipel et al. correlated metatarsal lengths and plantar loading patterns in patients with and without metatarsalgia.[36] Patients with concomitant foot abnormalities like hallux valgus were excluded. Maximal force under the first metatarsal head decreased, but no difference was found in maximal peak pressure between both groups. The authors concluded that metatarsal length does not influence plantar loading parameters. Zammit et al. reported that patients with hallux rigidus/limitus had a significant increase of maximum force and peak pressure under the hallux and the lesser toes.[30] They concluded that osteoarthritis of the metatarsophalangeal joint, associated with a limited range of motion, leads to significant changes in plantar pressure characteristics of the foot. Both foot pathologies, hallux rigidus/limitus and metatarsal length are not associated with a tibial deviation of the first metatarsal, whereas tibial deviation is a characteristic for hallux valgus, and in our opinion is responsible for the lateral shift of loading. We correlated loading patterns with increasing hallux valgus, intermetatarsal angle, and sesamoid subluxation, and we showed a significant load transfer from the medial to the lateral aspect of the foot. The load transfer is concluded from the many negative correlations under the big toe and the positive correlation in the region of metatarsal head five in regard to peak pressure, maximal force, contact time, contact area, and force-time integral (Table 2).

As already described, the metatarsal head slips of the sesamoid complex medially, and the medial sesamoid lies below the metatarsal head because of the insufficiency of the medial ligament.[1,2,3] With increasing hallux valgus deformity, the sesamoid complex shifts laterally. The elevated peak pressure and contact time under toes 3 to 5 and the elevated contact area under metatarsal head five, with a decreasing contact area under the hallux, reflects this pathologic process. Interestingly, we found a significant increase of maximal force under the first metatarsal head, which can be attributed to the medial sesamoid that lies below the first metatarsal head.

Based on our results, with an increasing hallux valgus angle the plantar pressure parameters are transferred from the medial aspect to the lateral aspect of the forefoot. Furthermore, attention has to be paid to the position of the sesamoid complex that alters the pressure parameters when it is subluxated laterally and the load is shifted.

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