The Forefoot-to-Rearfoot Plantar Pressure Ratio Is Increased in Severe Diabetic Neuropathy and Can Predict Foot Ulceration

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OBJECTIVE — We have previously demonstrated that high plantar pressures can predict foot ulceration in diabetic patients. The aim of the present study was to evaluate both the relationship between forefoot and rearfoot plantar pressure in diabetic patients with different degrees of peripheral neuropathy and their role in ulcer development.

RESEARCH DESIGN AND METHODS — Diabetic patients of a 30-month prospective study were classified according to the neuropathy disability score: scores of 0, 1–5, 6–16, and 17–28 are defined as absent ($n = 20$), mild ($n = 66$), moderate ($n = 95$), and severe ($n = 57$) neuropathy, respectively. The F-Scan mat system was used to measure dynamic plantar pressures. The peak pressures under the forefoot and the rearfoot were selectively measured for each foot, and the forefoot-to-rearfoot ratio (F/R ratio) was calculated.

RESULTS — Foot ulcers developed in 73 (19%) feet. The peak pressures were increased in the forefoot of the severe and moderate neuropathic groups compared with the mild neuropathic and nonneuropathic groups (6.2 ± 4.5 and 3.8 ± 2.7 vs. 3.0 ± 2.1 and 3.3 ± 2.1 kg/cm^2 [mean ± SD], respectively; $P < 0.0001$). The rearfoot pressures were also higher in the severe and moderate neuropathic groups compared with the mild neuropathic and nonneuropathic groups (3.2 ± 2.0 and 3.2 ± 1.9 vs. 2.5 ± 1.3 and 2.3 ± 1.0, respectively; $P < 0.0001$). The F/R ratio was increased only in the severe group compared with the moderate and mild neuropathic and nonneuropathic groups (2.3 ± 2.4 vs. 1.5 ± 1.2, 1.3 ± 0.9, and 1.6 ± 1.0, respectively; $P < 0.0001$). In a logistic regression analysis, both forefoot pressure (odds ratio 1.19 [95% CI 1.11–1.28], $P < 0.0001$) and the F/R ratio (1.37 [1.16–1.61], $P < 0.0001$) were related to risk of foot ulceration, whereas rearfoot pressure was not.

CONCLUSIONS — Both the rearfoot and forefoot pressures are increased in the diabetic neuropathic foot, whereas the F/R ratio is increased only in severe diabetic neuropathy, indicating an imbalance in pressure distribution with increasing degrees of neuropathy. This may lend further evidence toward the concept that equinus develops in the latest stages of peripheral neuropathy and may play an important role in the etiology of diabetic foot ulceration.

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The combination of high plantar pressures and sensory deficit is mainly responsible for ulcer development in neuropathic diabetic patients (1,2). Increased foot plantar pressures have been described in the diabetic neuropathic patients and shown to be related to the development of foot ulceration (3–5). In a recent multicenter prospective clinical trail, we showed that the measurement of high peak plantar pressure (>6 kg/cm^2) has the highest specificity in identifying patients at risk of foot ulceration (6).

Most of the studies describing foot pressures refer to peak plantar pressure, irrespective of the region of the foot under which it is recorded (3–8). Furthermore, limited data are available regarding the pressure pattern under the rearfoot and its relationship with the forefoot (9). In the present study, we hypothesized that an imbalance exists in pressure distribution between the rearfoot and the forefoot in the diabetic neuropathic foot, and that this imbalance is related to the development of foot ulceration. To this end, we have measured the peak plantar pressures under the forefoot and the rearfoot and examined their relationship in a large diabetic population with increasing degrees of diabetic neuropathy. In addition, we have evaluated the association between the forefoot-to-rearfoot peak pressure ratio (F/R ratio) and the risk of ulceration.

RESEARCH DESIGN AND METHODS

The data for 248 individuals with diabetes enrolled in a large multicenter 30-month prospective study were included in this study (6). The patients were recruited from the Joslin Beth Israel Deaconess Foot Center and a primary foot care clinic in Boston, Massachusetts; the University of Texas Health Science in San Antonio, Texas; and the California College of Podiatric Medicine in San Francisco, California. Patients were enrolled consecutively in their respective clinics. The diagnosis of diabetes had been made before enrollment and confirmed by either communication with primary care providers or a review of the medical records. The study protocol was approved by the institutional review boards of each participating center.

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Abbreviations: CPPT, cutaneous pressure perception threshold; F/R ratio, forefoot-to-rearfoot ratio; GRF, ground reactive force; MTPJ, metatarsophalangeal joint; NDS, neuropathy disability score; OR, odds ratio; STJ, subtalar joint; VPT, vibration perception threshold.

A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

Table 1—*Demographic data*

	No neuropathy	Mild neuropathy	Moderate neuropathy	Severe neuropathy
n	20	66	95	57
Age (years)	50.2 ± 16.2	56.6 ± 12.3*	60.1 ± 11.3*†	59.7 ± 11.7*†
M/F (% male)	7/13 (35%)	21/45 (32%)	44/51 (46%)	42/15 (74%)
BMI (kgm^2)	27.9 ± 4.1	31.9 ± 6.1*	31.7 ± 8.6*	28.9 ± 5.8†‡
Type 1/type 2 diabetic (n)	1/19	6/60	25/70	14/43
Diabetes duration (years)	8.4 ± 10.4	9.9 ± 8.9	16.2 ± 10.7*†	16.4 ± 10.9*†
NDS	0.00	2.5 ± 1.1*	11.7 ± 2.8*†	21.1 ± 2.9*†‡
VPT	9.8 ± 7.0	15.9 ± 11.1*	30.9 ± 14.8*†	48.3 ± 6.2*†‡
CPPT	4.2 ± 0.7	4.7 ± 0.9*	5.4 ± 1.5*†	6.6 ± 1.1*†‡
First MTPJ ROM (degrees)	85.9 ± 22.4	83.3 ± 21.3	67.9 ± 23.1*†	64.7 ± 23.1*†
STJ ROM (degrees)	25.6 ± 7.2	27.6 ± 10.4	23.6 ± 9.3*	20.1 ± 7.6*†‡
Force (N)	83.2 ± 25.3	87.9 ± 24.4	95.2 ± 27.7*†	94.4 ± 27.7*

Data are means ± SD, unless otherwise indicated. ROM, range of motion; N, Newton. *$P < 0.001$ vs. nonneuropathic group; †$P < 0.001$ vs. mild neuropathy group; ‡$P < 0.001$ vs. moderate neuropathy group.

Neuropathy evaluation

Patients were stratified in four groups according to their neuropathy disability score (NDS). The NDS was obtained from physical examination and was based on the examination of tendon reflexes and sensory modalities as previously described (10). The patella and Achilles tendon reflexes were examined. A score of 0 was given if the reflex was normal. A score of 1 was given if the reflex could be elicited with reinforcement. A score of 2 was given if the reflex was absent. The total sum represented the reflex score.

Sensory tests included pinprick using a pointed metal or wooden pin, light touch using a strip of cotton ball, vibration using a tuning fork, and temperature perception using a test tube filled with cold water. A score was given according to the anatomical location where the patient could not identify the stimuli introduced. If the patient perceived the stimulus at all levels, a score of 0 was given. A score of 1 was given if the patient failed to perceive the stimulus at the base of the toe, 2 if the patient failed to perceive the sensory at the midfoot, 3 if the patient failed to perceive the stimulus at the heel, 4 if the patient failed to perceive the stimulus at the lower leg, and 5 if the patient failed to perceive the stimulus at the knee. The average score of both feet was entered as the sensory score. The summation of reflex and sensory scores for each modality was entered as the NDS. An NDS score of 0 indicated absence of neuropathy, 1–5 mild neuropathy, 6–16 moderate neuropathy, and 17–28 severe neuropathy (11).

The vibration perception threshold (VPT) and the cutaneous pressure perception threshold (CPPT) were also determined as previously described (6). VPT was evaluated by the use of a biothesiometer (Biomedical Instruments, Newbury, OH). The lower voltage at which the patient could perceive the vibration stimulus on the pulp of the toe was recorded, and the mean of three readings for each foot was entered for final data analysis. The CPPT was evaluated by the use of a set of eight Semmes-Weinstein monofilaments that apply a pressure from 1 to 100 g. The lowest pressure the patient could feel at the top of the toe was recorded and used for analysis.

Joint mobility evaluation

The passive range of motion of the first metatarsophalangeal joint (MTPJ) and the subtalar joint (STJ) were measured by the use of a goniometer. The maximal range of motion was measured from the maximal inversion to the maximal eversion of the foot for the STJ. The mean of three evaluations in each foot was calculated for analysis.

Plantar pressure measurements

Dynamic plantar pressures were recorded in patients walking barefoot, using the F-Scan mat system, software version 3.711 (Tekscan, Boston, MA), as previously described. This computerized system consists of a floor mat on which an ultra-thin Tekscan sensor of 960 sensor cells (5 mm^2 each) is placed. The mat was calibrated for each patient using that patient's own weight before each testing session. The patients walked without shoes over the mat, and the maximum plantar peak pressure for the entire foot was obtained. Several practice runs were made to familiarize patients with the system and to ensure the recording of natural gait. The mean reading of three midgait steps was entered for final data analysis. The maximum peak pressures under the forefoot and the rearfoot were separately measured for each foot, and the ratio was calculated (F/R). The rearfoot was defined as the posterior one-third of the foot, and the forefoot was considered the metatarsal heads and toes. The day-to-day coefficient of variation of the measurements obtained by the instrument is 7.8%, whereas the variability between different steps is 2.6% (12). Similar results have been obtained from measurements in healthy and diabetic subjects in our unit.

Statistical analysis

The Minitab statistical package (Minitab, State College, PA) for personal computers was used for the statistical analysis. For parametrically distributed data, the ANOVA test was used, followed by Fisher's test to identify differences among the various groups. For nonparametrically distributed data, the Kruskal-Wallis test was used. Univariate and multivariate logistical regression analysis was used in a stepwise fashion to assess variables that were independent predictors of regional peak plantar pressure and ulceration. All tests were two-tailed, with an α set at 0.05. Data are presented as the means ± SD.

RESULTS — The demographical characteristics of the diabetic population are

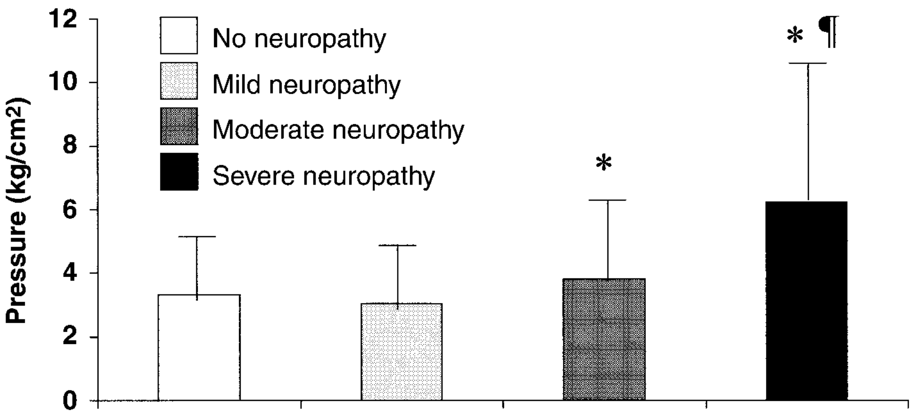

Figure 1—*Forefoot peak plantar pressure in diabetic patients without and with mild, moderate, and severe peripheral neuropathy. *Severe and moderate neuropathy groups vs. mild neuropathy and nonneuropathic groups, respectively* ($P < 0.001$)*; ¶Severe vs. moderate neuropathy group* ($P < 0.001$).

summarized in Table 1. The groups with moderate or severe neuropathy were older, with a greater BMI, a higher prevalence of male sex, a longer duration of diabetes, a lower range of motion of the first MTP and ST joints, and a higher peak vertical force than their counterparts with mild or no neuropathy.

The forefoot peak pressure increased colinearly with the severity of neuropathy. More specifically, it was significantly higher in the severe and moderate neuropathic groups compared with the mild and nonneuropathic groups (6.2 ± 4.5 and 3.8 ± 2.7 vs. 3.0 ± 2.1 and 3.3 ± 2.1 kg/cm^2, respectively; $P < 0.0001$) (Fig. 1). The rearfoot peak pressure was also higher in the moderate and severe neuropathic groups compared with the mild and nonneuropathic groups (3.2 ± 2.0 and 3.2 ± 1.9 vs. 2.5 ± 1.3 and 2.3 ± 1.0 kg/cm^2, respectively; $P < 0.0001$) (Fig. 2). The F/R pressure ratio was significantly higher in the severe neuropathy group when compared with the moderate, mild, and nonneuropathic groups (2.3 ± 2.4 vs. 1.5 ± 1.2, 1.3 ± 0.9, and 1.6 ± 1.0, respectively; $P < 0.0001$) (Fig. 3).

A significant correlation between forefoot peak pressures and age, duration of diabetes, BMI, NDS, VPT, CPPT, and first MTPJ and STJ mobilities was found ($P < 0.05$). However, in multivariate regression analysis, age, BMI, VPT, and the vertical component of the ground reactive force (GRF; the force generated by the foot-to-floor interaction) were the only factors that showed statistical significance ($P < 0.05$).

For the rearfoot pressures, first MTPJ mobility, NDS, VPT, and the vertical force were the only parameters significantly related ($P < 0.05$). No correlation was found with age, duration of diabetes, BMI, and STJ mobility. In multivariate analysis, the only significant predictor of rearfoot pressures was the vertical component of GRF ($P < 0.001$). Stepwise regression analysis indicated that all of the above factors were able to explain only 12.6 and 27.1% of the variance for the rearfoot and forefoot peak plantar pressures, respectively.

Foot ulcers developed in 95 (19%) feet, or 73 (29%) patients, during the 30-month follow-up. Of these wounds, 98% were localized under the forefoot. Univariate logistical regression analysis yielded a statistically significant odds ratio (OR) for both forefoot peak pressures and F/R peak plantar pressure ratios, whereas no significant OR was found for rearfoot peak pressures (Table 2). However, in multivariate logistic regression analysis, the only significant factors were high CPPT (≥5.07), VPT (≥25 V), and foot pressure (≥6 kg/cm^2) or F/R ratio (≥2), depending on which of the two latter parameters was entered in the model. Finally, an F/R ratio ≥2 was slightly more specific than a peak plantar pressure ≥6 kg/cm^2 in identifying patients who develop foot ulceration (76 vs. 69%), although it was less sensitive (46 vs. 59%). The positive predictive value was 31% for both of the diagnostic tests.

As more than one ulcer could have occurred in the same patient, thus allowing that particular patient's characteristics to highly affect the final results, we performed the same analysis considering the ulcer development per single patient, i.e., the incidence of first ulceration in each patient. The results of the univariate analysis were similar to those obtained when the ulcer rate was entered for the analysis. Thus, the OR was 1.22 (95% CI 1.11–1.34, $P < 0.001$) for forefoot peak pressure, 1.08 (0.93–1.25, P = NS) for the rearfoot, 2.52 (1.42–4.48, $P < 0.01$) for peak pressure (≥6 kg/cm^2), and 3.17 (1.71–5.89, $P < 0.001$) for an F/R ratio ≥2. The multivariate logistic regression analysis also showed results similar to the ones reported above (data not shown). The sensitivity, specificity, and positive predictive value per patient (43, 81, and 48%, respectively) of an F/R ratio ≥2 in

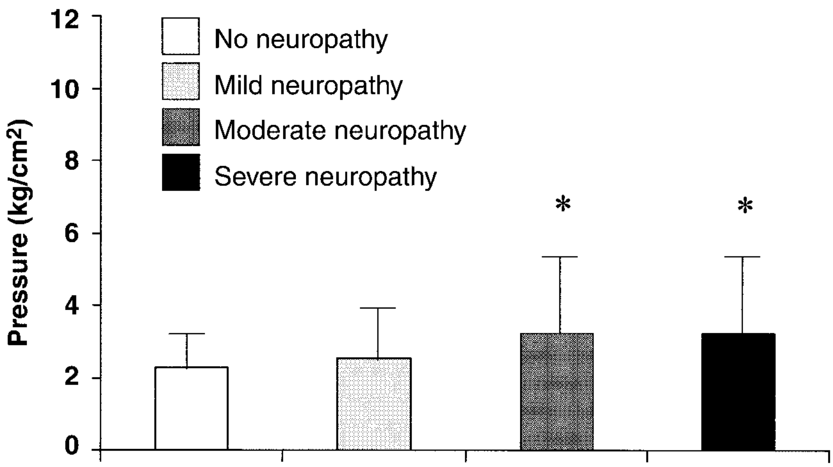

Figure 2—*Rearfoot peak plantar pressure in diabetic patients without and with mild, moderate, and severe peripheral neuropathy. *Severe and moderate neuropathy groups vs. mild neuropathy and nonneuropathic groups* ($P < 0.001$).

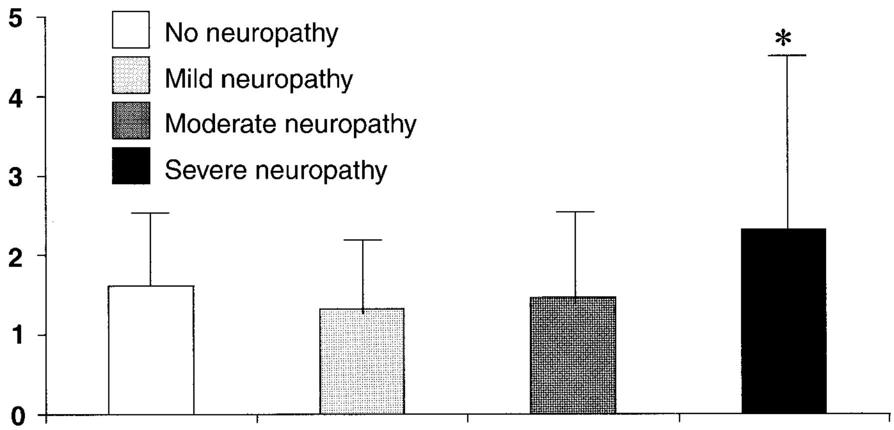

Figure 3—*F/R peak plantar pressure ratio in diabetic patients without and with mild, moderate, and severe peripheral neuropathy. *Severe vs. moderate and mild neuropathy and nonneuropathic groups* (P < *0.001*).

identifying the first ulcer occurrence were also similar to those reported previously.

CONCLUSIONS— In this large multicenter study, the data suggest that both forefoot and rearfoot peak plantar pressures are increased in diabetic patients with peripheral neuropathy, but the F/R peak plantar pressure ratio was significantly higher only in patients with severe neuropathy. Furthermore, we found that an F/R ratio >2 was able to predict ulcer development with the same specificity as a peak pressure >6 kg/cm^2.

The great majority of the studies describing the pressure pattern under the diabetic foot refer only to forefoot peak plantar pressures because this is the area where neuropathic ulcers commonly develop (1–8). Sensory impairment, foot deformities, limited joint mobility, presence of callus, and reduced plantar tissue thickness have all been related to high forefoot plantar pressures (13–16). This is the first study to specifically show that there is also a significant peak pressure increase under the rearfoot in the presence of diabetic neuropathy. In our population, the vertical component of the GRF was the only independent predictor of peak pressures at the rearfoot. We believe that the loss of proprioceptive sensitivity may affect the foot-to-floor impact at the beginning of stance phase and therefore lead to increased force during the heel-strike. In agreement with our hypothesis, in a large cross-sectional study, a significant correlation between measurements of sensory neuropathy and heel peak pressures, but not forefoot pressure, was described (17). Furthermore, increased forces during the heel contact rather than during the push-off phase of the gait cycle have already been described in diabetic neuropathic patients (18). In healthy subjects, available data also suggest that peak pressure at the rearfoot is mostly affected by events before or during heel-strike (19). Interestingly, limited subtalar joint mobility was not related to rearfoot peak pressures, challenging the old belief that the inability of this joint to absorb the shock produced by the heel-strike results in the development of high foot pressures. Other factors, such as changes of the heel pad mechanical characteristics (20) and/or limited ankle joint mobility (14,21), may also play a role in the development of high pressures under the rearfoot.

The relationship between the forefoot and rearfoot loading pattern and the severity of peripheral neuropathy was also examined in this study. We found that although peak plantar pressures are increased in the whole foot in neuropathic patients, the F/R plantar pressure ratio is increased only in the most severely neuropathic patients. This indicates that an imbalance in pressure distribution occurs only in advanced peripheral neuropathy. A homogeneous pressure distribution between the forefoot and the rearfoot has been reported in healthy subjects (22), whereas the inability to uniformly distribute the load throughout the foot is one of the first abnormalities noticed in pathological conditions. One can only speculate about the possible reasons for the occurrence of a pressure imbalance in the later stages of diabetic neuropathy. Motor impairment, the functional shortening of the Achilles' tendon (potentially by way of advanced glycation of soft tissues), and the possible rupture of the plantar fascia occurring in advanced stages of diabetes may all lead to a drop of the forefoot (equinus deformity) and therefore to a significant increase of the load under this foot subarea (21,23,24). Further studies are needed to elucidate the biomechanical changes occurring in the diabetic foot with increasing degrees of nerve damage.

Our findings also suggest that only patients with diabetes and severe neuropathy may need to have robust efforts made at redistribution of force evenly throughout the foot. The load distribution is one of the most important preventive measures in the insensitive foot, and total-contact, custom-made foot insoles designed to accommodate the foot are crucial to this aim (25). There is still no consensus regarding when the health care provider should prescribe orthoses as a part of the prophylactic measures in neuropathic patients. Furthermore, recent evidence suggests that not all neuropathic patients benefit from footwear for the

Table 2—*Risk factors for ulceration (logistic regression analysis)*

Risk factor	OR	95% CI	*P*
Univariate			
Forefoot pressure	1.2	1.1–1.3	0.001
Rearfoot pressure	1.1	0.9–1.20	0.344
Pressure ≥6 kg/cm^2	3.2	2.0–5.1	0.001
F/R ratio >2	2.7	1.7–4.3	0.001
Multivariate			
VPT ≥25	2.7	1.3–5.7	0.01
CPPT ≥5.07	2.6	1.1–6.3	0.04
Pressure ≥6 kg/cm^2	1.8	1.0–3.0	0.03
F/R ratio >2	1.8	1.1–3.2	0.03

prevention of ulceration (26). We believe that the analysis of the F/R ratio may be a useful criterion to identify those patients who can benefit from accommodative orthoses or other treatments to correct the load imbalance. This parameter might also be used to verify the effectiveness of such treatments in redistributing the pressure throughout the foot. More research, using pressure measurement at the foot-insole interface rather than at the foot-to-floor interface, is needed to test the latter possible application of the F/R ratio.

The F/R ratio was shown to predict foot ulceration, and an F/R ratio >2 is as specific, if not better, as a peak pressure >6 kg/cm^2 in identifying patients who will develop a foot ulceration. Several attempts have been made to identify a pressure threshold above which ulcers develop, but the absolute magnitude of pressure values among different studies is not consistent (27,28). The great variety of measurements systems, units of measure, calibration methods, and analyses used is one of the reasons for the observed discrepancies and makes comparison among studies difficult. The F/R ratio has the advantage of being a relative value, and different units of measure, calibration methods, and sensor resolutions do not affect it. Therefore, we believe that the F/R peak pressure ratio may represent a useful tool to standardize foot pressure measurements and to compare data coming from centers using different techniques.

The relationship between neuropathy and F/R ratio is curvilinear in diabetic patients with different degrees of neuropathy. Because there is no standard definition of diabetic neuropathy, a nondiabetic control group might have been of use. However, this was a prospective study to mainly investigate the incidence of foot ulceration, a condition that is almost nonexistent in healthy nondiabetic subjects. Therefore, we believe that the inclusion of a healthy control group would have not added any additional significant information in this study.

In summary, we have shown that both forefoot and rearfoot peak plantar pressures increase with increasing degrees of nerve damage, but the F/R peak plantar ratio is increased only in advanced peripheral neuropathy. This finding confirmed our hypothesis that an imbalance in pressure distribution, causing the forefoot to be more loaded than the rearfoot, occurs only in severely neuropathic patients. Furthermore, an F/R ratio >2 appears to be highly specific in identifying patients at risk of ulceration, and it may be used as an alternative to specific evaluation of peak plantar pressures to standardize pressure measurements for multicenter studies.

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