

"Pressure Gradient" as an Indicator of Plantar Skin Injury

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OBJECTIVE — Peak plantar pressures (PPPs) have been studied extensively as a contributing factor to skin breakdown, especially in the forefoot where most plantar neuropathic ulcers occur. The purposes of this article were to 1) describe an additional pressure variable, the peak pressure gradient (PPG), 2) determine whether the PPG is higher in the forefoot than in the rearfoot (even when compared with PPP), and 3) determine the correlation between the PPG and PPP at the forefoot and rearfoot in subjects with diabetes, peripheral neuropathy, and a history of plantar ulcer.

RESEARCH DESIGN AND METHODS — Twenty subjects (12 male and 8 female) with diabetes, peripheral neuropathy, and a mean \pm SD age of 57 ± 9 years participated. Plantar pressures were collected during walking in footwear. The PPP and the PPG (defined as the spatial change in plantar pressure across adjacent sites of the foot surface around the PPP) were determined for the forefoot and rearfoot, and the forefoot-to-rearfoot ratios for each variable were calculated.

RESULTS — The mean PPG was 143% higher in the forefoot than in the rearfoot, whereas the mean PPP was only 36% higher in the forefoot than in the rearfoot ($P < 0.0001$). The PPG forefoot-to-rearfoot ratio (2.84 ± 1.36) was nearly two times greater than the PPP forefoot-to-rearfoot ratio (1.48 ± 0.58) ($P < 0.0001$). The correlation between PPP and PPG was $r = 0.59$ at the forefoot and $r = 0.75$ at the rearfoot.

CONCLUSIONS — The PPG was substantially higher in the forefoot than in the rearfoot even when compared with the PPP. The PPG appears to be providing additional information about the stresses experienced by the soft tissues of the foot, especially in the forefoot. The PPG may be a useful indicator of skin trauma because spatial changes in high plantar pressures may identify high stress concentrations within the soft tissue.

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Peak plantar pressure (PPP) has been investigated extensively in the literature as a surrogate measure of trauma to the plantar foot and is known to be an important contributing factor to skin breakdown in people with diabetes and peripheral neuropathy (1–3). High PPP repeated many times has been associated with the location of skin breakdown (4). There does not, however, appear to be a specific threshold of PPP that predicts skin breakdown (5). If one considers only mechanical trauma to the

foot, other important variables besides PPP include direction of stress (normal versus shear), number of repetitions (steps), and duration of plantar pressures (sometimes estimated as the pressure time integral) (6). This threshold of injury also appears to vary among individuals, depending upon other factors that include amount of foot deformity (7), prior activity level (8,9), type of footwear, vascular status (3), history of ulcer (6), and type of measuring device.

Besides these variables, we believe

that the peak pressure gradient (PPG) is another important pressure variable to consider. We define the PPG as the spatial change in plantar pressure around the PPP location. We speculate that pressures that change substantially across adjacent areas on the surface of the foot, i.e., have a high pressure gradient, are more damaging to the plantar soft tissues than high pressures spread evenly across the foot. As one simple example, underwater divers experience very high hydrostatic pressures; however, these pressures do not result in skin breakdown because the high pressures are distributed evenly across the surface of their skin. We speculate that large pressure gradients contribute to skin breakdown because they generate large shearing stresses within the soft tissues (10).

One preliminary way to test this speculation that PPG is a useful indicator of trauma to the skin is to investigate the relationships among PPP, PPG, and the incidence of skin breakdown in the forefoot compared with that in the rearfoot. Skin breakdown typically is located at the forefoot under the metatarsal heads rather than at the heel in patients with diabetes and severe neuropathy (2,11). During barefoot walking, forefoot pressures are much higher than rearfoot pressures (forefoot-to-rearfoot pressure ratio 2.3 ± 2.4 [mean \pm SD]) in subjects with diabetes and severe neuropathy (2). During walking in shoes, however, PPPs under the forefoot tend to be similar to those in the rearfoot (242 ± 25 kPa in the forefoot compared with 240 ± 28 kPa in the rearfoot) (3).

Based on these previous studies and the characteristics of the PPG, we hypothesized that the PPG would be higher in the forefoot than in the heel of patients with diabetes, peripheral neuropathy, and a history of a plantar ulcer, even during walking with footwear. Furthermore, we speculated that the PPG forefoot-to-rearfoot ratio would be greater than the PPP forefoot-to-rearfoot ratio. Such a relationship would suggest that further investigation into the PPG as an indicator of skin trauma is warranted. Therefore, the purposes of this article were to 1) describe an alternative pressure variable, the PPG, 2) determine whether the PPG is substan-

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Abbreviations: PPG, peak pressure gradient; PPP, peak plantar pressure; VPT, vibratory perception threshold.

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

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tially higher in the forefoot than in the rearfoot (even when compared with the PPP), and 3) determine the correlation between the PPG and PPP at the forefoot and rearfoot in subjects with diabetes, peripheral neuropathy, and a history of plantar ulcer.

RESEARCH DESIGN AND METHODS

Subjects were recruited as part of a larger study seeking to develop a computational model of the diabetic foot. As the computational model was being developed, it became apparent that the change in pressures across the plantar foot at the location of the PPP, or the PPG, may be an important variable. The preliminary data from our computational model demonstrated potentially damaging shear stresses occurring inside the soft tissues where there was a large difference (or gradient) in pressure between two adjacent sites on the plantar foot.

Subjects were recruited from the Diabetic Foot Center, Volunteers for Health, the Diabetes Research Training Center at Washington University School of Medicine, and the BJC Health System in St. Louis, Missouri. Criteria for entry into the study were a history of diabetes, evidence of peripheral neuropathy (inability to sense the 5.07 Semmes Weinstein monofilament and vibratory perception threshold [VPT] >25 V), a palpable pedal pulse, and a history of a midfoot or forefoot plantar ulcer. Nonambulatory patients or patients with severe midfoot or rearfoot Charcot neuroarthropathy were excluded.

Sensation was tested using the 5.07 Semmes Weinstein monofilament and a Bio-Thesimeter (Bio-Medical Instrument, Newbury, OH). All subjects were unable to sense the 5.07 Semmes Weinstein monofilament on at least two sites on the plantar foot as described elsewhere (12). Sensation also was quantified with a Bio-Thesimeter. The head of the Bio-Thesimeter was held perpendicular to the plantar surface of the great toe, and the amplitude of the vibration was increased gradually. The VPT was defined as the lowest voltage the patient could perceive using a mean of three trials (2). A value of 50 V was assigned to those subjects unable to perceive the voltage even when turned to its maximum amplitude. The mean \pm SD value for this group was 48.3 ± 4.1 V, indicating a severe level of neuropathy (Table 1). Ankle dorsiflexion range of motion was measured with the subject in a prone position, the knee ex-

Table 1—Patient characteristics

n	20
Age (years)	57.3 ± 9.3
Men/women (% men)	12/8 (60)
BMI (kg/m^2)	32.5 ± 7.4
Type 1/type 2 diabetes (n)	5/15
Diabetes duration (years)	16.1 ± 10.5
A1C (%)	8.1 ± 1.9
VPT (V)	48.3 ± 4.1
Dorsiflexion range of motion with knee extended (degrees)	1.8 ± 6.3
Ulcer location (no.)	
Metatarsal head 1	7
Metatarsal head 3	2
Metatarsal head 5	2
Great toe	6
Midfoot	3

Data are means \pm SD or n (%).

tended, and the subtalar joint in a neutral position as described previously (12). All reported ulcers had occurred on the plantar surface of the midfoot or forefoot as described with other subject characteristics in Table 1. All subjects read and signed the informed medical consent according to the institutional review board approved protocol before entrance into the study.

Plantar pressure assessment

Plantar pressures were recorded during walking using the F-Scan system (Tekscan, Boston, MA) and previously validated methods (3,13,14). All subjects wore Soletech shoes (Advance orthopedic footwear, style number E3010) that were fitted by a certified pedorthist or orthotist.

The footwear was selected because it is used widely in clinical practices, meets all the guidelines of the “therapeutic shoe bill” (Medicare Part B), and can accommodate forefoot deformities or a custom orthotic device. For the purposes of this study, the shoe was worn with its standard insert and a thin cotton sock. Excessive callus that might affect pressure measures was trimmed before testing.

Each F-scan in-shoe sensor contains 960 sensing locations or pixels. Each pixel is 5.08×5.08 mm. A new sensor was trimmed to fit the shape of the subject's foot and was placed between the subject's sock and the insole. Subjects wore the sensor inside the shoe for several minutes and took about 40 steps before calibration for adequate sensor “break in” (3,13). The sensor was calibrated according to the manufacturer's guidelines and was consistent with other investigators (3,13,14). Subjects were allowed to walk at their chosen walking speed, and data were collected at 50 Hz during two walking trials immediately after calibration. A mean of three steps chosen during the midportion of the walking trials was used for the PPP and PPG variables.

Determination of plantar pressure variables

The PPP and PPG were determined using custom software. ASCII files containing all frames of data from three steps were processed by the software. The foot was divided in half from the distal toe to the proximal heel to determine the forefoot and rearfoot. The software selected the PPP at the rearfoot and forefoot. This

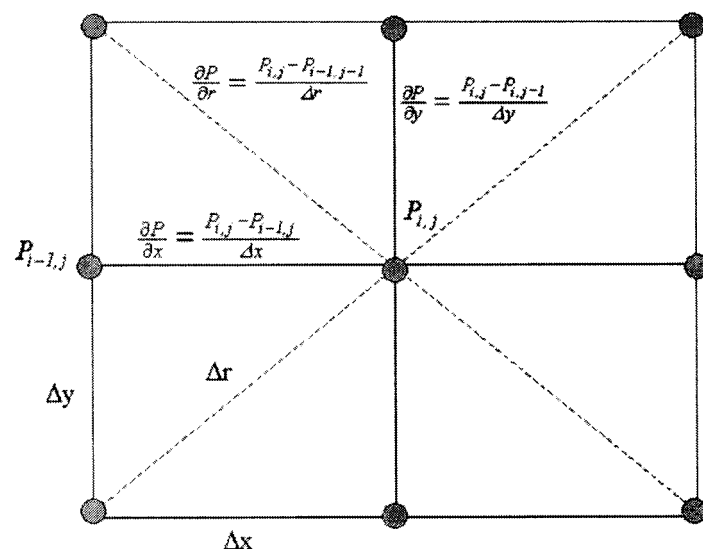


Figure 1—Calculation of the PPG.

Table 2—PPP and PPG at forefoot and rearfoot and individual forefoot-to-rearfoot ratios

	Value
PPP (kPa)	
Forefoot	371 ± 76
Rearfoot	272 ± 86
PPG (kPa/mm)	
Forefoot	34 ± 13
Rearfoot	14 ± 6
Ratio*	
(PPP forefoot)/ (PPP rearfoot)	1.48 ± 0.58
(PPG forefoot)/ (PPG rearfoot)	2.84 ± 1.36

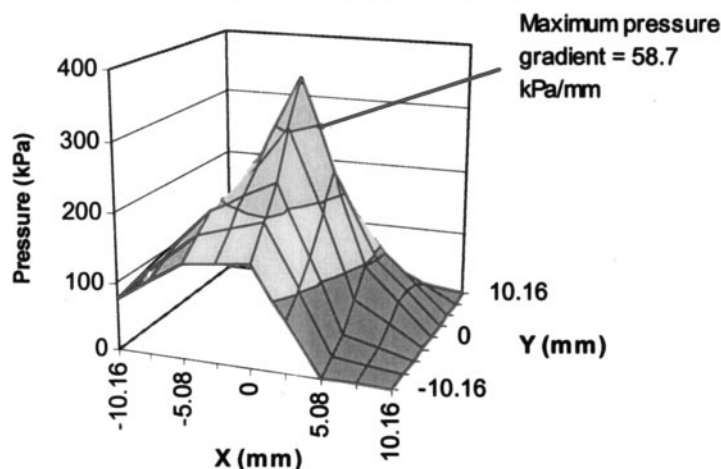
Data are means ± SD. * $P < 0.0001$ (paired t test).

value was checked with the PPP values obtained from the F-Scan software. A bicubic polynomial spline smoothing function was applied to the raw data before the PPG was determined to eliminate individual pixel outliers and to estimate pressure values at nodes located half the length between each sensor pixel. The reason for adding nodes between the sensor pixels was to increase the accuracy of the PPG calculation. The PPG then was determined in a defined area (3×3 F-Scan sensor pixels [231.3 mm^2]) around the PPP by calculating the highest change in pressure (pressure gradient) from one node (half pixel apart) to the next according to rows and columns and by diagonal (Fig. 1). The pressure gradient values were calculated by subtracting the pressure in each node around the PPP from that in the adjacent node and dividing by the distance between the centers of the nodes.

Statistical analysis

The PPP and PPG in the forefoot and rearfoot were recorded for each subject. A PPP forefoot-to-rearfoot ratio was calculated by dividing the PPP in the forefoot by the PPP in the rearfoot (2). Likewise, a PPG forefoot-to-rearfoot ratio was calculated by dividing the PPG in the forefoot by the PPG in the rearfoot. Differences between PPP and PPG in the forefoot and in the rearfoot and the difference between the PPP and PPG forefoot-to-rearfoot ratio were determined using two-tailed paired t tests. The correlations between the PPP and PPG at the forefoot and rearfoot were determined using a Pearson product-moment correlation.

A Pressure distribution on forefoot



B Pressure distribution on rearfoot

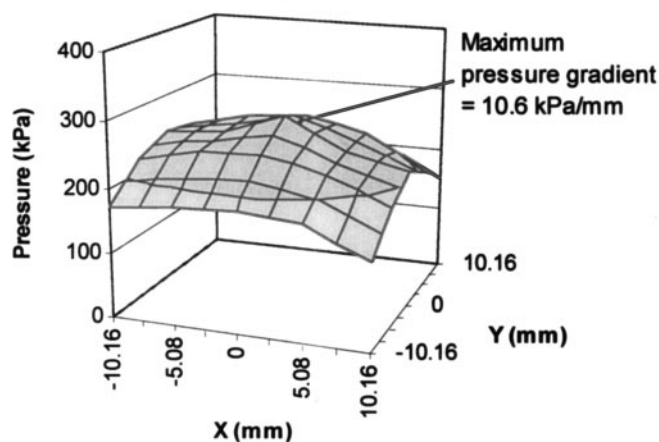


Figure 2—Peak pressures are similar, but the maximum pressure gradient under the forefoot (A) is much greater than the maximum pressure gradient under the rearfoot (B) for this representative subject.

RESULTS— The mean PPG was 143% higher in the forefoot than in the rearfoot whereas the mean PPP was only 36% higher in the forefoot than in the rearfoot (Table 2) ($P < 0.0001$). Figure 2 illustrates an example of the PPP and the PPG at the forefoot and the rearfoot of a representative subject. The PPG forefoot-to-rearfoot ratio (2.84 ± 1.36) was nearly two times greater than the PPP forefoot-to-rearfoot ratio (1.48 ± 0.58) ($P < 0.0001$) (Table 2). The correlation between PPP and PPG was $r = 0.59$ at the forefoot and $r = 0.75$ at the rearfoot.

CONCLUSIONS— The primary results of this study indicate that the PPG is much higher in the forefoot than in the rearfoot (forefoot-to-rearfoot ratio), even when compared with the PPP forefoot-to-rearfoot ratio. These results may be important because the incidence of skin

breakdown is much higher in the forefoot than in the rearfoot (2,11). Perhaps the PPG is an important indicator of tissue trauma because it indicates high levels of stress concentration in the soft tissues that may lead to skin breakdown.

The correlation between PPG and PPP was considerably higher in the rearfoot than in the forefoot ($r = 0.75$ vs. 0.59). PPP accounted for 57% of the variance of PPG at the heel but only 35% of the variance at the forefoot. There are several possible reasons that the PPG may be much higher in the forefoot than the rearfoot (even when compared with the PPP forefoot-to-rearfoot ratio) and that the PPG is more highly correlated to the PPP in the rearfoot than in the forefoot. First, the soft tissue thickness is 36–48% greater under the heel than that under the metatarsal heads (15). This increased soft tissue thickness probably helps to distribute

plantar pressures to increased areas and attenuate peak pressures and pressure gradients (15,16). Furthermore, although the shape of the calcaneus tends to remain fairly intact after complications of peripheral neuropathy, the metatarsal heads are often deformed by an increased metatarsal phalangeal joint angle (hammer toe deformity) and arthropathy that can contribute to a high PPP (17) and PPG. Therefore, the structure of the calcaneus and the thickness of the soft tissue may provide a more consistent pressure gradient in the rearfoot than in the metatarsal heads in the forefoot. The primary difference between the PPG and the PPP is that the PPG represents the spatial change in the pressure in the region of the peak pressure. From a mechanical standpoint, a sharp change in high pressure, i.e., a high PPG, may lead to internal stress concentrations and shearing of soft tissues, causing injury. This higher change in peak pressure may be one reason that the forefoot experiences a higher incidence of skin breakdown than does the heel despite relatively similar PPPs during walking in shoes.

Another important reason for the higher incidence of skin breakdown in the forefoot than in the rearfoot is that the PPPs are higher in the forefoot than in the rearfoot during barefoot ambulation (2). Caselli et al. (2) studied the forefoot-to-rearfoot plantar pressure ratio in several patient groups including subjects with diabetes and severe neuropathy similar to that described in this study ($VPT 48.3 \pm 6.2$ V). The forefoot PPP (6.2 kg/cm^2 [608 kPa]) and PPP forefoot-to-rearfoot ratio (2.3 ± 2.4) were much higher than the values reported in our study. Although the pressure sensor characteristics were similar to ones used in our study, the higher values reported in that study probably occurred because the subjects walked barefoot across a mat rather than walking in therapeutic footwear. PPPs in our study are similar to those reported by Pitei et al. (3), who reported forefoot and heel PPPs of 242 ± 25 and 240 ± 28 kPa, respectively. These values are slightly lower than the values reported in our study (Table 2), probably because Pitei et al. had subjects walk in therapeutic shoes that included multilayer inserts whereas subjects in this study walked in a standard insert.

We are aware of no other research studies that have specifically examined the PPG. The concept of a pressure gradient contributing to internal stress, how-

ever, is documented in the engineering literature (10). In addition, Prabhu et al. (18) described a parameter called the "power ratio," which was used to accurately discriminate among groups of patients with neuropathy and to predict risk for skin breakdown. The power ratio is defined as the ratio of high-frequency power to total power in an image generated by a pedobarograph and appears to be influenced by plantar pressures that change rapidly across the surface of the foot (18). Hence, the power ratio and the PPG each appear to be measures of the change in pressure across the surface of the foot.

Mechanical stresses contributing to plantar skin breakdown appear to be a composite value of several indicators (19). The magnitude of stress clearly has been associated with the location of skin breakdown and is measured as the PPP (1–4), but the PPP alone cannot clearly predict skin breakdown (5). We believe the PPG is an indicator of plantar skin trauma that is related, but not identical, to the PPP, as reflected by the results of this study. The duration of pressure application to the skin also is thought to be important and is estimated by the pressure time integral (6). Direction of stress and the number of repetitions also are thought to be important (6,9). Although it was not the primary purpose of this study, we performed a post hoc analysis to determine whether there was an association of the location of the PPP, pressure time integral, and PPG to location of ulcer. In this small sample size, PPP, pressure time integral, and PPG occurred at the healed ulcer site in 56, 69, and 31% of the occurrences, respectively. One of the three variables was associated with the location of skin breakdown 81% of the time. We believe that all of these variables are related to one another but contain unique information to help predict trauma and skin breakdown.

This study is a first step in investigating the importance of the PPG as an indicator of plantar skin injury on the neuropathic foot. Clearly there are many mechanical and biological factors that contribute to skin breakdown (7). This study was a cross-sectional analysis of a single group of patients with diabetes, severe peripheral neuropathy, and a history of ulcers. Additional studies are required to determine the benefits and limitations of using PPG as an indicator of tissue injury and skin breakdown. Computational models could investigate the relationship

between pressure gradients on the surface of the foot to stress concentrations within the soft tissues of the foot. PPG should be investigated in groups of subjects with various levels of neuropathy and histories of ulcers. Finally, prospective studies should be conducted to determine whether the PPG can be used with the PPP and the pressure time integral to help predict skin breakdown. Although additional studies are required, the results of this study indicate that the PPG may be an important variable to identify where stress concentrations that may lead to skin breakdown are located on the plantar foot.

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