Elevated plantar pressures are an important predictor of diabetic foot ulceration. The objective of this study was to determine which clinical examination variables predict high plantar pressures in diabetic feet. In a cross-sectional study of 152 male veterans with diabetes mellitus, data were collected on demographics, comorbid conditions, disease severity, neuropathy status, vascular disease, and orthopedic and gait examinations. Univariate predictors included height, weight, body surface area, body weight per square inch of foot surface area, bunion deformity, hammer toe, Romberg's sign, insensitivity to monofilament, absent joint position sense, decreased ankle dorsiflexion, and fat pad atrophy. Variables that remained significantly associated with high plantar pressures ($\geq 4$ kg/cm$^2$) in multivariate analysis included height, body weight per square inch of foot surface area, Romberg's sign, and insensitivity to monofilament. These results may be useful in identifying patients who would benefit from interventions designed to decrease plantar foot pressures. (J Am Podiatr Med Assoc 93(5): 367-372, 2003)

Materials and Methods

General Design and Study Population

The study was conducted from July 2000 through May 2001 at the Veterans Affairs Medical and Regional Office Center, Surgical Service #112, White River Junction, VT 05009.
Clinical Examination

One examiner (J.L.D.) and the principal investigator (J.S.W.) underwent training prior to the study to ensure standardization of examination techniques with previously published norms. Age, diabetes duration, smoking status, height, weight, and hemoglobin A1c (HgbA1c) level within the past 6 months were collected prior to the examination. Elevated HgbA1c was defined as greater than 9% in order to reflect current actionable values from Department of Veterans Affairs performance measures. Pedal pulses were palpated, and patients lacking one or more pulses were considered to have arterial insufficiency. Sensitivity to monofilament was determined using a 10-g monofilament. Patients were considered insensate if they were unable to detect the monofilament at one or more of the following plantar sites: first metatarsophalangeal joint, fifth metatarsophalangeal joint, or hallux. Available dorsiflexion at the ankle was measured passively with the patient standing in a relaxed posture. End range of motion in the dorsiflexed position was thought to be a more informative measure given current theory in sagittal plane mechanics of the foot.

With the patient standing, evaluation was performed for bunion deformity, hammer toes, foot architecture, and postural sway. Bunion deformity was defined as abducted great toe position with prominent medial eminence to the first metatarsophalangeal joint. A hammer toe was defined as a contracted toe requiring a dorsiflexory force to move the digit. Evaluation of foot architecture, Romberg’s test, and determination of joint position sense were performed as previously described. The presence of a forefoot weightbearing callus was determined. Plantar forefoot fat pad atrophy was defined as a plurality of prominent metatarsal heads readily palpable on the plantar surface of the foot. An apropulsive gait was determined by visual gait examination. Walking speed was assessed by measuring the time taken to walk a 10-m distance following a 3-m pre-distance to ensure constant velocity. Stride length was determined by measuring the distance a foot travels from initial heel contact to heel contact for the next stride of the same foot. The average of three trials was obtained, with patients instructed to walk at their regular walking speed.

Plantar Pressure Measurement

Mean dynamic foot pressures were measured using the F-Scan mat system, software version 4.12F (Tekscan, Boston, Massachusetts). Reliability of the F-Scan system has been previously described. Patients were evaluated while wearing 4-inch stockinette without shoes. Weightbearing calluses were debrided prior to mat scan measurement. This procedure was followed to avoid alteration of gait patterns by large calluses and the introduction of examination variability, as patients present with different amounts of callus. The mat was calibrated using the patient’s weight. Maximum peak plantar pressures for the entire foot were obtained using the average of five midgait steps. During the first part of the study, mean peak pressure was calculated by averaging the results of three trials, as described in the literature. However, before the completion of the study a new convention for mat studies using five trials was adopted (TG McPoil, personal communication, 2000). Analysis of these data produced identical prediction and point estimates. Thus the data were pooled. Foot surface area was calculated using the F-Scan mat system software.

Statistical Analysis

The unit of analysis was the foot rather than the individual. The dependent variable was binary, with 1 denoting plantar pressure greater than or equal to 4 kg/cm² and 0 denoting plantar pressure less than 4 kg/cm². The 4 kg/cm² threshold was lower than those used in prior studies and is a reflection of the lower pressures observed for the entire population. The threshold was based on the range of plantar pressures measured in this study and represented the top 25% of the distribution. In the first part of the analysis, univariate logistic regression analysis was used to assess the associations between physical examination variables and high plantar pressures. Multivariate models were built using a backward stepwise logistic regression with the criterion for removal being a P value of less than .10. The likelihood ratio test was used to
determine whether variables of borderline statistical significance (P values of .05 to .10) should be retained.

The final model was tested for goodness of fit by comparing the observed and expected outcomes within quintiles of predicted risk using the Hosmer-Lemeshow test. The area under the receiver operating characteristic curve (the C-statistic) was used to determine how well the model discriminates between individuals with and without high peak plantar pressures. The C-statistic ranges from 0.5 (no discrimination) to 1 (perfect discrimination).

**Results**

The patient population characteristics stratified by peak plantar pressure are described in Table 1. Factors associated with high peak plantar pressures in univariate analysis (P < .10) included height, weight, body surface area, body weight per square inch of foot surface area, bunion deformity, hammer toe, Romberg’s sign, insensitivity to monofilament, absent joint position sense, decreased ankle dorsiflexion, and fat pad atrophy.

The final multivariate model included height, body weight per square inch of foot surface area, Romberg’s sign, and insensitivity to monofilament (Table 2). The goodness of fit comparing the observed and expected outcomes of predicted risk using the Hosmer-Lemeshow test was not statistically significant, indicating that the model is well fit throughout the spectrum of predicted risk. The area under the receiver operating characteristic curve was 0.73. The relative contribu-
tion of each clinical finding to explained variation in high plantar pressures is depicted in Figure 1.

**Discussion**

This study identified several clinical examination variables associated with high peak plantar pressures. These patients may be at higher risk for developing diabetic foot ulcers and therefore might benefit from interventions.

The mean peak pressure was somewhat lower than in other studies using the same mat system. The mean ± SD peak pressure in the current study was 4.5 ± 1.2 kg/cm² for neuropathic patients, compared with 6.7 ± 2.9 kg/cm² and 5.4 ± 1.4 kg/cm² in other studies. These differences may be partially explained by the protocol examination's requiring patients to have callus debrided prior to pressure measurement. Callus has been reported to increase peak plantar pressure by up to 29%.

The current findings appear to be consistent with those of previous studies, but they also identify some additional risk factors for elevated peak plantar pressure in patients with diabetes. Cavanagh et al identified weight as a risk factor for elevated peak plantar pressures, accounting for 14% of the variance in peak plantar pressure. The authors believe that the current study is the first to describe the importance of weight indexed to foot surface area as an important predictor of high plantar pressures. Of all the weight-related parameters examined, weight indexed to foot surface area demonstrated the strongest statistical significance. Height also emerged as an independent predictor. Increased height may create a longer lever arm for the center of mass in the body, thus creating greater torque, whereas weight indexed to foot surface area may independently represent increased pressure development over a smaller surface area. Independent effects were also found for the severity of neuropathy. Insensitivity to monofilament and positive Romberg’s sign predicted high pressures independently, which appears to be consistent with previous authors’ observation of increased postural sway for patients with foot ulcers.

The current study could have implications for practicing foot-care providers. It may help identify potential inclusion variables for a prospectively validated clinical prediction rule for foot ulcers. A clinical prediction rule such as this could be beneficial by identifying smaller numbers of high-risk variables for clinicians to monitor, as well as improving identification of an at-risk population. It could also assist in identifying patients who may benefit from targeted interventions. Some of the predictive examination variables are amenable to medical interventions. Effective weight-loss strategies should be encouraged, as weight accounts for 10% to 14% of the variance in plantar pressures. The identification of weight indexed to foot surface area as a major predictor underscores the need to dissipate these pressures over a larger contact surface area with foot orthoses or therapeutic footwear. Various types of shoes and insoles have been described as decreasing plantar pressures. The addition of various configurations of rocker soles can also assist in decreasing plantar pressure. Patients demonstrating clinical gait instability may also benefit from intervention. Although the effect of balance training in neuropathic patients with diabetes has yet to be described, balance training and other activities have been reported to improve balance and decrease falls in other elderly populations.

This analysis has several potential limitations. The results obtained from this homogeneous population of aged, white, male veterans may not be generalizable to other populations. This patient homogeneity

*Figure 1. Relative contribution of each clinical finding to explained variation in plantar pressures.*

### Table 2. Final Multivariate Model Using Backward Stepwise Logistic Regression

<table>
<thead>
<tr>
<th>Multivariate Analysis</th>
<th>Odds Ratio</th>
<th>95% CI</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight per square inch of foot surface area</td>
<td>1.23</td>
<td>1.00–1.51</td>
<td>.049</td>
</tr>
<tr>
<td>Height</td>
<td>1.20</td>
<td>1.07–1.35</td>
<td>.001</td>
</tr>
<tr>
<td>Semmes-Weinstein sign</td>
<td>2.50</td>
<td>1.23–5.05</td>
<td>.011</td>
</tr>
<tr>
<td>Romberg’s sign</td>
<td>2.18</td>
<td>0.87–5.46</td>
<td>.078</td>
</tr>
</tbody>
</table>

Abbreviation: CI, confidence interval.
may be a strength, however, as it has been reported recently that white men have more limited joint mobility, higher plantar pressures, and more foot ulcers than other ethnic groups. In addition, use of a cross-sectional approach to assess elevation of plantar pressures is unable to determine causality to the extent of a prospective design assessing a clinically meaningful endpoint, such as development of foot ulceration. Lower plantar pressure measurements in the current study may be the result of the debridement of foot calluses prior to measurement of plantar pressures that the study protocol required.

Conclusion

A number of factors associated with elevated peak plantar pressures have been identified. This information may be useful for identifying patients who would benefit from interventions to decrease plantar pressures.

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