Clinical implications of foot pressures during normal gait

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ARTICLE POINTS

1 In patients with diabetes, neuropathy and previous ulceration are associated with higher foot pressures.

2 A pressure of >8 kg/cm^2 (785 kPa) may greatly increase the risk of ulceration.

3 Patients with diabetic neuropathy, particularly those with previous ulceration, have poorer control of their diabetes.

4 Diabetes is associated with a shift to medial loading.

5 The load shift may explain why ulcers occur with high frequency at the first and second metatarsals.

KEY WORDS
- **Diabetic neuropathy**
- **Foot ulcer**
- **Plantar pressure**
- **Gait analysis**

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Introduction

The clinical usefulness of foot pressure measurement to identify the at-risk diabetic foot is controversial. This article describes a study that supports the clinical use of this technique. Results showed that in patients with diabetes, plantar pressures were higher in those with neuropathy (and especially in those with a history of previous ulceration) than those without neuropathy. The changes in pressure were associated with a medial load shift (to areas where neuropathic ulcers commonly occur). Explanations are put forward for the load shift and the link between poor diabetes control and ulceration.

Foot ulcers have been shown to occur at sites of high pressure in patients with diabetic neuropathy (Boulton et al, 1987a; Fernando et al, 1991). High plantar pressure alone without associated neuropathy does not appear to result in foot ulceration. In a 30-month prospective study, Veves et al (1992) found that diabetes patients with normal peak pressures did not develop plantar ulcers. High plantar pressures are therefore a risk factor for subsequent foot ulceration in the neuropathic diabetic foot.

Aims

The aim of this study was to investigate the pattern of plantar pressure and time parameters in diabetic neuropathic patients with and without a history of plantar ulceration. We hypothesised that patients with neuropathy would have higher and more sustained plantar pressures and that, when retested, the site of peak pressures would shift to the medial metatarsal heads, where ulceration commonly occurs.

Methods

Foot pressure was measured in 200 subjects: 160 patients with diabetes and 40 controls.

There were four groups:

- 40 controls (people without diabetes): Co group
  50 diabetes patients without neuropathy: Di group
- 90 diabetes patients with neuropathy: DiN group
- 20 patients with diabetes and neuropathy and a history of plantar ulceration: DiNU group.

All subject groups were of similar weight and age. The patient groups were consecutive patients meeting the inclusion criteria; the controls were members of staff in the diabetes centre. Neuropathy was defined as vibration perception threshold greater than 25 volts and insensitivity to a 10-g monofilament. Ethical approval for the study was granted by the Merton, Sutton and Wandsworth Health Authority District Medical Ethical Committee.

Measurement system

The advantages of different systems for foot pressure measurement have been summarised previously in this journal (Booth et al. 1998; West and Barnett, 1999). We used a system of barefoot measurement against a force plate (Musgrave™ system, Musgrave Systems, UK). The platform is set in a specially constructed recess in the floor of the diabetes centre. All subjects were able to walk comfortably unaided at their own pace. Any plantar callosities were removed prior to footprint measurement.

Patients with active ulceration were excluded from the study. We followed guidelines for the measurement of foot pressures as previously agreed by the Foot Pressure Interest Group (Barnett, 1998).

Four sensors were chosen to represent each area for analysis. The combined area of the sensors was approximately 1 cm^2.

Data collected

Six dynamic footprints (three from each foot) were recorded. For the purposes of this study, only data obtained from under the metatarsal heads were used for analysis.

For each footprint, the following data were recorded at the metatarsal heads:

- Peak pressure
- Time to peak pressure
- Contact time (duration of peak pressure)
- Contact time as percent of the total stance phase ('% stance phase').

The highest pressure from the five metatarsal heads was selected as the 'peak pressure'. When analysing the pattern of loading, these pressures were ranked in order of magnitude to create a forefoot pressure pattern for each foot (e.g. 2, 3, 4, 1, 5). A detailed method for pattern recognition can be found in Plank and Potter (1995) and Hughes et al (1989). All pressures were recorded as kg/cm^2 and

Table 1. Characteristics of patients in the different groups

	Co group	*Di* group	*DiN* group	*DiNU* group
Number of subjects (n)	40	50	90	20
Age in years (range)	47 (22-73)	59 (24-81)	62 (31-83)	56 (30-72)
Mean weight in kg (s.d.)	71.2 (12.1)	77.5 (14.9)	80.6 (18.0)	84 (13.6)
Number of males/females	19/21	27/23	58/32	17/3
Number of people with type 1/type 2 diabetes	n/a	16/34	39/51	15/5
Median duration of diabetes (yrs)	n/a	8.6	14.5	26.8
Latest HbA_{1c} result (mean±s.d.)	n/a	7.4±0.31	8.1±0.21	8.7±0.17

n/a = not applicable
s.d. = standard deviation
Co group = people without diabetes
Di group = diabetes patients without neuropathy
DiN group = diabetes patients with neuropathy
DiNU group = diabetes patients with neuropathy and a history of plantar ulceration

Table 2. Summary of peak pressure and time parameter data for each group

Co group	*Di* group	*DiN* group	*DiNU* group	
Number of subject (n)	40	50	90	20
Mean (range) of peak pressure (kPa)	569.9 (294.3-765.2)	637.7 (399.3-971.2)	833.9† (341.4-1471.5)	1014.4# (649.4-1353.8)
Time to peak pressure (ms)	524	588	603	595
Contact time (ms)	625	701.6*	736*	751*
% stance phase	75.5	79.3	78.9	79.9

n/a = not applicable
s.d. = standard deviation
Co group = people without diabetes
Di group = diabetes patients without neuropathy
DiN group = diabetes patients with neuropathy
DiNU group = diabetes patients with neuropathy and a history of plantar ulceration

* P<0.05 vs Co group
† P<0.05 vs Co group
\# P<0.05 vs DiN or Co group

PAGE POINTS

1 Neuropathic patients have higher and more sustained plantar pressures compared with non-neuropaths.

2 In healthy controls, the pattern of loading over the metatarsal heads remained constant over time.

3 All the neuropathic patients with a history of previous ulceration showed a shift to medial loading.

4 In nearly half of all patients with previous ulceration, the peak pressure was at a different site.

then converted to kPa.

The site of maximum pressure loading was recorded at baseline and patients were invited to return for a repeat measurement after at least nine months (range 9–16 months).

Results

Group characteristics are shown in *Table 1*. The within-patient and between-patient co-efficients of variation for pressure measurements were 9.4% and 11.2% respectively.

Table 2 shows the mean and range of peak pressure and time parameters for each group.

Peak pressure

The mean peak pressures in the four groups were progressively higher — the DiNU group had the highest values. A representative dynamic footprint obtained from a DN patient is shown in *Figure 1*. For comparison, *Figure 2* shows a typical footprint from someone without diabetes.

Time to peak pressure

Time to peak pressure was similar in neuropaths (DiN, DiNU) and non-neuropaths (Di) and not significantly different from controls (Co) (P=0.12).

Contact times

The contact times for the diabetes groups (Di, DiN, DiNU) were similar and all were significantly higher than the contact time for the Co group.

% stance phase

The mean contact time in neuropaths (DiN, DiNU) represented 79% of the stance phase which was not significantly different from that of the Co group.

Site of maximum pressure at the metatarsal heads

From the original cohort of patients, the following were reassessed:

- 31 neuropaths (6 with previous ulceration) at a mean period of 12 months (range 9–16 months) after.
- 22 diabetes patients without neuropathy at a mean period of 12 months (9–14 months).
- 10 controls (aged 26–53 years) at a period of 9–13 months.

At baseline, the site of maximum pressure loading was under the first metatarsal in 22% of neuropaths and 40% of those with previous ulceration, compared with only 10% of controls and 12% of non-neuropaths (P=0.007).

The pattern of loading remained constant in all control subjects when repeated. In the diabetes groups, there was a shift to medial loading (i.e. maximum loading at first or second metatarsal) in the non-neuropathic group (25% patients) and in the neuropaths (43% patients) and in all six patients with a history of previous ulceration.

It was also found that in patients with a history of previous ulceration, the highest pressure was at the site of the previous ulcer in only 58% of them.

Other clinical considerations

Table 1 shows that the DiNU group had

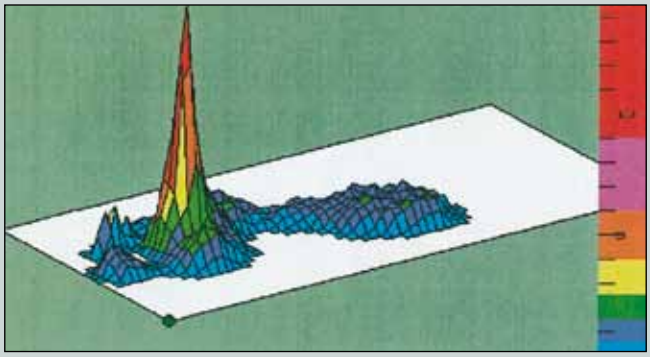

Figure 1. A representative dynamic pressure footprint from a person with diabetes and neuropathy.

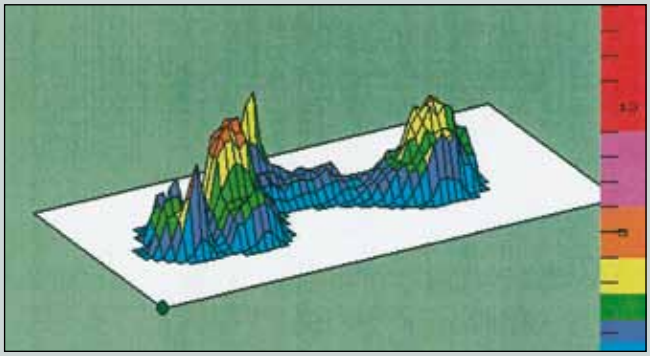

Figure 2. A representative dynamic pressure footprint from a person without diabetes.

the longest duration of diabetes and the poorest diabetes control. The mean ± standard deviation HbA_{1c} values of DiNU and Di (8.7 ± 0.17 and 7.4 ± 0.31, respectively) were significantly different (P=0.017).

Discussion

In keeping with previous studies, peak plantar pressures in patients with diabetes were higher in patients with neuropathy than those without neuropathy, and highest in those with a history of previous ulceration.

Threshold pressure

Several investigators have tried to ascertain whether there is a critical level of plantar foot pressure above which patients will ulcerate. Boulton et al (1983) found foot pressures to be greater than 110 kPa in every subject with a neuropathic foot ulcer, suggesting a threshold pressure for ulceration.

Lavery et al (1998) showed that subjects with diabetes and peak plantar pressures above 65 kPa were at six times greater risk for ulceration than those with pressures below this value. The same group, however, could not demonstrate a threshold pressure for foot ulcers and concluded that the higher the peak pressure, the higher the risk of ulceration (Armstrong et al, 1998).

It is likely that each region of the foot has a different threshold pressure above which injury can occur depending upon basic structure and tissue viability (Cavanagh and Ulbrecht, 1994). At the present time, the clinical importance of the cumulative load, which is the integration of the foot pressure with time of loading, is not known. For example, a relatively long duration of a moderately high pressure at a vulnerable site in the foot could be more damaging than a short duration of a very high pressure.

The highest peak pressure obtained in the control group without diabetes was 7.8 kg/cm^2 (765.2 kPa); this is consistent with results obtained by Bennett et al (1996) using a similar system suggesting a threshold abnormal pressure of about 8 kg/cm^2 (785 kPa).

Time and pressure

Duration of peak pressure was increased in all the diabetes groups compared to healthy controls and may contribute to an increased cumulative load at vulnerable sites in the foot. The increased contact time in patients with diabetes is probably explained by a lower walking speed than healthy controls.

The mean contact time in neuropaths represented 78% of the stance phase which was not significantly different from that of the healthy control group implying that there was no change in the proportions of the stance phase.

Distribution of pressure load

Nearly half of the neuropathic group showed a shift to medial loading when retested after 12 months. This change was associated with a tendency to loading over the first and second metatarsals, the areas that are most likely to ulcerate. Other workers have also noted a change in site of peak pressures in neuropathic feet over time. Boulton et al (1987b) found a change in 43% of neuropathic patients — similar to the results of this study.

The changing pattern of walking may relate to progression of neuropathy and absence of feedback information with progressive loss of joint position sense (Cavanagh and Ulbrecht, 1994). Changes in joint mobility have also been suggested (Cavanagh et al, 1991). The effect is to favour loading over the first and second metatarsals, which are the common sites for plantar ulceration.

Influence of diabetes

The study results showed that duration of diabetes was progressively higher in non-neuropaths, neuropaths and neuropaths with previous ulceration. Furthermore, diabetes control, as measured by HbA_{1c}, was worse in neuropaths with previous ulceration. Bennett et al (1996) have shown similar results for patients with a history of ulceration.

It has been suggested that the high HbA_{1c} is a reflection of increased rates of non-enzymatic glycosylation generally, including in the connective tissue of the foot and that this reduces the shock absorbing capacity of the plantar tissues. This could provide a mechanism for the link between hyperglycaemia and foot ulceration.

PAGE POINTS

1 Measures to reduce peak pressures at vulnerable sites may help prevent recurrence of ulcers.

2 Future studies will examine the benefits of teaching patients to walk differently to avoid loading over sites in the foot at high risk.

Conclusions

Measurements of parameters such as pressure and time may eventually allow accurate prediction of who will get a plantar ulcer and where it will occur. Future studies are planned which will investigate measures to relieve pressures at vulnerable sites. We plan to establish whether patients can be taught to walk in ways which will avoid the generation of high pressures at high-risk sites in the foot. ■

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