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Static and Dynamic Plantar Pressure in Diabetic Patients with Advanced Neuropathy

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The purpose of the study was to reveal any abnormal distribution of the static and dynamic plantar pressure in the diabetic patients with advanced neuropathy. Sixteen diabetic patients with advanced neuropathy (Group N) and 16 diabetic patients without advanced neuropathy (Group D) were recruited. Advanced neuropathy was determined by inability to perceive the 5.07 Semmes-Weinstein monofilament at one or more sites in each foot. Static plantar pressure was measured during standing, and dynamic plantar pressure was measured during walking. Static plantar pressure was significantly higher ($p<0.05$) at the posterior part of bilateral central lateral metatarsal heads, while dynamic plantar pressure was significantly higher ($p<0.05$) at the posterior part of left central lateral metatarsal heads, in Group N than in Group D. Both static and dynamic plantar pressure was significantly lower ($p<0.05$) at the left lateral and central lateral toes in Group N than in Group D. Static plantar pressure was significantly lower ($p<0.05$) at the left anterior medial heel, while dynamic plantar pressure was significantly lower ($p<0.05$) at the left posterior central midfoot, in Group N than in Group D. In conclusion, advanced neuropathy tends to increase plantar pressure at lateral metatarsal heads and decrease plantar pressure at lateral toes during both standing and walking, and decrease plantar pressure at anterior heel during standing and at posterior midfoot during walking in the diabetic patients. (J Rehab Med Assoc ROC 2002; 30(2): 65 - 71)

Key words: static, dynamic, plantar pressure, diabetes mellitus, advanced neuropathy

INTRODUCTION

Advanced neuropathy and high plantar pressure have been implicated in the pathogenesis of diabetic foot ulceration, a diabetic complication associated with con-siderable morbidity and costs.[1-4] Advanced neuropathy renders the foot lost of protective sensation. An examination of the insensate foot to assess its structural characte-ristics, and a visual assessment of the patient's gait by a trained physiatrist are certainly helpful, but they are not useful in assessing the risk status of the plantar tissue and in planning therapeutic interventions.

Plantar pressure is the measure of mechanical

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loading to unit surface of the plantar surface, which sustains various weight bearing during standing and walking. Static plantar pressure is measured during standing, and dynamic plantar pressure is measured during walking. Static plantar pressure can reveal the structural variation of foot.[5] Since Duckworth et al reported that dynamic plantar pressure tended to show multiple areas of high pressure better than static plantar pressure, [6] abnormal static plantar pressure has seldom been reported in diabetic patients.

Dynamic plantar pressure has been studied extensively in the Caucatian diabetic patients, and high dynamic plantar pressure has been used as a practical criterion for screening patients at high risk of diabetic foot ulceration. [7] Difference in dynamic plantar pressure have also been reported in black and Hispanic diabetic patients from those in Caucasian.[8,9] However, neither static nor dynamic plantar pressure has been reported in the diabetic patients in Taiwan.

Although advanced neuropathy causes weakness of intrinsic foot muscles and foot deformity, its association with abnormal pressure distribution has not been proved in the Caucasian diabetic patients. High dynamic plantar pressure at metatarsal heads and low ratio of toe to metatarsal head loading were associated with neuropathy in the diabetic patients in referral practices that specialized in the treatment of lower limb complications,[3] but no association was reported between dynamic plantar pressure and advanced neuropathy among the unselected populations of diabetic patients in comparison.[10] The dynamic plantar pressure was reported to be higher at the third through fifth metatarsal heads and lower at the third through fifth toes in the diabetic patients with advanced neuropathy than those without advanced neuropathy, but the differences were not statistically significant.[11,12] However, it is possible that either static or dynamic plantar pressure may be associated with advanced neuropathy in the diabetic patients. The purpose of the study was therefore to reveal any difference in the static and dynamic plantar pressure between the diabetic patients with and without advanced neuropathy. The relation between the static and dynamic plantar pressure would also be delineated.

MATERIALS AND METHODS

Sixteen diabetic patients with neuropathy but no history of foot ulceration (Group N) and 16 diabetic patients with no neuropathy (Group D) were recruited from a screening clinic of diabetic complications in a university hospital. Neuropathy was determined by inability to perceive the 5.07 Semmes-Weinstein monofilament at one or more sites in each foot. There were nine women in Group D, and eight women in Group N. The age was from 33 to 78 years old (63 ± 11 years, mean ± standard deviation) in Group D, and from 44 to 80 years old (63 ± 11 years) in Group N; the body height from 1.50 to 1.76 m (1.59 ± 0.07 m) in Group D, and from 1.44 to 173 m (1.58 ± 0.08 m) in Group N; the body weight from 48 kg to 81 kg (62 ± 8 kg) in Group D, and from 49 kg to 96 kg (62 ± 12 kg) in Group N.

The patients were informed and gave their consents to the plantar pressure measurement. Their in-shoe plantar pressures in standing and walking were measured using Parotec-System (Paromed Medizintechnik GmbH, Markt Neubeuern, Germany), consisting 4 pairs of measuring soles with size 35-36, 37-38, 39-40, and 41-42. Each sole was a 2.5-mm-thick sheet containing 24 conductive transducers embedded in hydrocells with a resolution of 2.5 kPa and a range of 600 kPa. The sites of the discrete sensors were determined by the previous study based on the load distribution tests of 350 subjects: [13] six sensors in heel, six in midfoot, four in posterior part of metatarsal heads, four in anterior part of metatarsal heads, and four in toes (Fig. 1). The measuring area of the 4 sensors in toes are identical, which range from 1.7 to 2.9 cm^2; the surface area of the other sensors are identical, from 2.8 to 3.8 cm^2, depending on the insole size. The sensors are calibrated once in the factory and the calibration data are stored in the software for pressure analysis.

Each patient wore standard shoes with flat rubber sole and canvas cover, and was measured with the most suitable measuring soles for four sessions. In each session, static plantar pressure in standing was measured at 10 Hz for five seconds. Dynamic plantar pressure in walking was measured at 100 Hz for mean peak pressure of five steps at each side while the patient walked at self-chosen speed along a 12 m walkway. The measurements of four sessions were averaged.

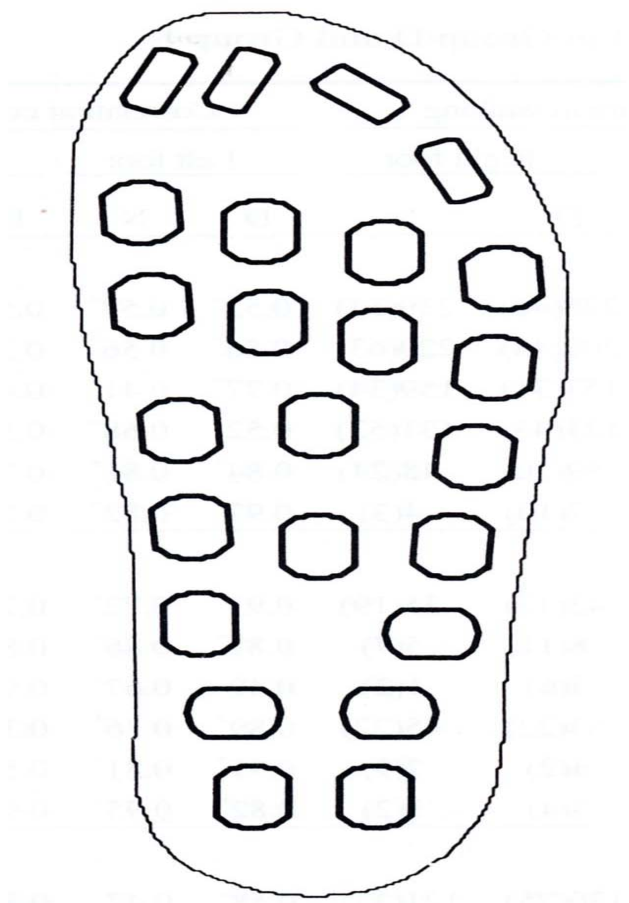

Fig. 1 The positions of the twenty-four discrete sensors in a measuring insole

Both static and dynamic measurements were compared at each sensor between Group D and Group N using Student t test. Pearson's correlation coefficients were calculated for static and dynamic measurements between Group D and Group N. The α value was set at 0.05.

RESULTS

Static plantar pressure was higher ($p < 0.05$) at the posterior part of bilateral central lateral metatarsal heads in Group N than in Group D, but lower ($p < 0.05$) at the left anterior medial heel, lateral toes, and central lateral toes in Group N than in Group D (Table 1).

The cadence (0.56 ± 0.05 s vs. 0.57 ± 0.05 s), step length (0.61 ± 0.04 m vs. 0.57 ± 0.09 m), and speed (1.12 ± 0.13 m/s vs1.03 ± 0.19 m/s) in walking were not significantly different between Group D and Group N. The dynamic plantar pressure was higher ($p < 0.05$) at the posterior part of left central lateral metatarsal heads in Group N than in Group D, but lower ($p < 0.05$) at the left posterior central midfoot, lateral toes, and central lateral toes in Group N than in Group D (Table 1).

Static plantar pressure was significantly correlated ($p < 0.05$) to dynamic plantar pressure at all except two sensors in bilateral midfoot, at all except four sensors in bilateral heel, at all except four sensors in bilateral toes, and at all except five sensors in anterior and posterior parts of bilateral metatarsal heads, respectively (Table 1).

DISCUSSION

The small number of patients limited the statistical power of our results. Many statistically significant differences in static and dynamic pressure between Group D and Group N were detected at one side only. If our number of patients increased, most of the statistically significant differences should be detected at bilateral sides. Both static and dynamic pressures were significantly higher at the posterior part of central lateral metatarsal heads, and lower at lateral and central lateral toes in advanced diabetic neuropathy. Static pressure was significantly lower at anterior medial heel, while dynamic pressure was significantly lower at posterior central midfoot in advanced diabetic neuropathy.

Static measurement of plantar pressure in standing can reveal the structural variation of foot. [5] Dynamic measurement was only moderately correlated to static measurement in the study, because dynamic plantar pressure was a more complex biomechanical phenomenon than static plantar pressure. It was influenced by structural factors, as well as functional factors, such as walking speed, step length, gait pattern, and so on.

Because neuropathy involves the distal intrinsic flexor muscles earlier than the proximal extrinsic flexor muscles of the foot, muscle imbalance with ineffectiveness of the intrinsic flexors results in high foot arch[1,14] and hyperextension of metatarsophalangeal joints.[1,3,11,12] High arch was related to decreased pressure at the midfoot in walking. [15] Hyperextension of metatarsophalangeal joints not only reduces pressure at the third through fifth toes in both standing and walking, but also displaces metatarsal fat pad anterior, and results in the metatarsal heads exposed.[1,3,11,12] The lack of soft-tissue cushioning under the osseous prominence increases pressure at the third and fourth metatarsal heads in standing. The intrinsic muscles atrophy, along with sensory impairment, results

Table 1. Static and dynamic plantar pressure and their correlation in Group D and Group N

	Static pressure in standing				Dynamic pressure in walking				Correlation coefficient			
	Left foot		Right foot		Left foot		Right foot		Left foot		Right foot	
	D	N	D	N	D	N	D	N	D	N	D	N
Heel:												
Posterior lateral	37(19)	47(22)	55(26)	54(29)	227(53)	239(51)	225(40)	239(53)	0.55^{+}	0.57^{+}	0.50^{+}	0.39
Posterior medial	52(17)	62(24)	56(21)	66(22)	224(47)	225(45)	209(44)	220(63)	0.56^{+}	0.56^{+}	0.37	0.13
Middle lateral	37(14)	44(14)	46(17)	48(17)	155(41)	164(29)	153(31)	159(34)	0.77^{+}	0.41	0.42	0.70^{+}
Middle medial	46(12)	52(22)	40(13)	52(20)	135(38)	137(42)	121(43)	131(52)	0.52^{+}	0.68^{+}	0.51^{+}	0.57^{+}
Anterior lateral	20(12)	16(8)	24(13)	21(12)	55(23)	43(15)	59(20)	48(24)	0.84^{+}	0.81^{+}	0.76^{+}	0.81^{+}
Anterior medial	6(7)	2(3)*	2(4)	3(3)	13(18)	5(8)	7(10)	4(3)	0.97^{+}	0.82^{+}	0.76^{+}	0.57^{+}
Midfoot:												
Posterior lateral	17(15)	11(6)	17(9)	16(10)	44(31)	28(11)	43(17)	35(19)	0.93^{+}	0.72^{+}	0.77^{+}	0.82^{+}
Posterior central	8(6)	5(4)	4(5)	3(6)	14(9)	8(5)*	8(11)	5(7)	0.87^{+}	0.88^{+}	0.82^{+}	0.89^{+}
Posterior medial	1(2)	0(1)	1(3)	0(1)	7(18)	2(2)	3(6)	1(2)	0.49	0.67^{+}	0.93^{+}	0.54^{+}
Anterior lateral	17(12)	18(9)	13(5)	14(8)	54(23)	48(22)	53(22)	45(22)	0.89^{+}	0.76^{+}	0.33	0.83^{+}
Anterior central	2(3)	3(3)	1(1)	2(4)	5(4)	10(14)	4(2)	7(9)	0.91^{+}	0.81^{+}	0.57^{+}	0.84^{+}
Anterior medial	2(3)	1(2)	1(2)	1(1)	3(4)	4(6)	3(4)	1(2)	0.82^{+}	0.95^{+}	0.93^{+}	0.72^{+}
Metatarsal heads, posterior part:												
Lateral	35(14)	39(12)	33(17)	41(15)	114(42)	124(37)	130(75)	121(37)	0.58^{+}	0.47	0.82^{+}	0.58^{+}
Central lateral	28(12)	36(11)*	26(10)	35(12)*	99(34)	132(51)*	104(47)	115(35)	0.67^{+}	0.50^{+}	0.71^{+}	0.78^{+}
Central medial	23(9)	26(11)	26(8)	24(14)	92(34)	121(53)	106(32)	111(47)	0.57^{+}	0.60^{+}	0.49	0.54^{+}
Medial	31(17)	30(15)	33(15)	26(18)	149(69)	145(53)	143(42)	135(45)	0.43	0.78^{+}	0.32	0.40
Metatarsal heads, anterior part:												
Lateral	25(9)	28(16)	26(11)	33(13)	102(33)	94(50)	111(40)	109(42)	0.44	0.82^{+}	0.51^{+}	0.62^{+}
Central lateral	42(15)	41(17)	41(11)	49(12)	234(70)	202(75)	218(40)	221(53)	0.25	0.56^{+}	0.29	0.19
Central medial	39(19)	35(20)	36(14)	33(18)	239(65)	225(78)	235(53)	228(63)	0.52^{+}	0.62^{+}	0.69^{+}	0.55^{+}
Medial	31(24)	23(18)	26(16)	20(13)	215(77)	169(79)	179(78)	145(46)	0.71^{+}	0.79^{+}	0.63^{+}	0.45
Toes:												
Lateral	11(9)	5(2)*	8(7)	6(3)	63(37)	21(13)*	52(33)	32(22)	0.71^{+}	0.43	0.64^{+}	0.71^{+}
Central lateral	12(4)	8(6)*	11(5)	14(9)	110(40)	59(45)*	101(43)	77(41)	0.15	0.74^{+}	0.53^{+}	0.76^{+}
Central medial	18(13)	17(12)	13(8)	19(13)	134(75)	88(57)	100(55)	94(54)	0.81^{+}	0.83^{+}	0.57^{+}	0.70^{+}
Medial	29(16)	26(18)	31(23)	27(25)	210(108)	153(90)	251(152)	175(78)	0.68^{+}	0.85^{+}	0.48	0.47

Data are means (SD) in kPa.
* $p < 0.05$ between Group D and Group N.
$^{+}$ $p < 0.05$ for the correlation coefficient.

in extensor substitution and flexor stabilization in walking. These alterations lead to increased supinatory moments in the feet with an increased pressure under the fourth and fifth metatarsal heads.[12]

Stess et al reported higher dynamic barefoot pressure measured by EMED-SF system under the fourth and fifth metatarsal heads,[12] and Perry et al also reported higher dynamic in-shoe pressure at the third through fifth metatarsal heads, and lower pressure at the third through fifth toes and medial midfoot using Pedar system in diabetic patients with advanced neuropathy than diabetic patients without neuropathy.[11] However, the differences were not statistically significant in both studies.[11,12]

The dynamic plantar pressure in this study was smaller than those reported by Perry et al[11] and by Stess et al.[12] The discrepancy may be due to the differences in the sensor size, dynamic range, sampling rate, spatial resolution, frequency response, linearity, hysteresis, and temperature sensitivity among the pressure measuring devices.[16] The positions of the twenty-four discrete sensors in this study were selected at the sites where the maximal loads most frequently occurred. The measuring area of a sensor was from 1.7 to 3.8 cm^2, depending on the insole size. If a pressure is acting on an area smaller than the measuring area of the sensor, the pressure is beyond the resolution of the sensor and would be under-estimated. The greatest underestimate of plantar pressures due to measuring area occurs at the toes.[17] At the meta-tarsal heads, the underestimate is less than 5% for an in-shoe sensor with measuring area of 1 cm^2, although this depends on the sharpness of the "true" pressure.[18]

Besides resolution, there are other important factors for a useful pressure measurement system, such as reli-ability and validity.[19,20] The resolution of a measurement will be acceptable if the measurement can provide accu-rate, extra information which is relevant to the clinical picture, helpful to the diagnosis and treatment, and which can not be obtained in a simpler way.

We have proved that abnormal pressure distribution in advanced diabetic neuropathy can be revealed more clearly with both static and dynamic measurement. Although Duckworth et al reported that dynamic plantar pressure tended to show multiple areas of high pressure better than static plantar pressure, they also stressed that both measurements were needed to reveal all the spots at risk of ulceration.[6] Physiatrists are encouraged to meas-ure both static and dynamic pressure in the diabetic patients with advanced neuropathy to evaluate their structural and functional impairments.

CONCLUSION

In a limited number of patients referred from diabe-tologists, we proved that advanced neuropathy tends to increase the plantar pressure at lateral metatarsal heads and to decrease the plantar pressure at lateral toes during both standing and walking, and to decrease the plantar pressure at anterior heel during standing and at posterior midfoot during walking. Further researches of more patients are required to reveal other possible abnormal distribution of plantar pressure related to advanced neuropathy. Static and dynamic plantar pressures were only moderately correlated, and both measurements are needed to detect all the spots at risk for ulceration.

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罹患嚴重神經病變之糖尿病患者之靜態與動態足底壓力

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本研究之目的在探討罹患嚴重神經病變之糖尿病患者的靜態與動態足底壓力。總共收集了十六位罹患嚴重神經病變之糖尿病患者(神經病變組)，與十六位無嚴重神經病變之糖尿病患者(對照組)。神經病變組在兩腳均無法感受到 5.07 單一細絲纖維的碰觸感。靜態足底壓力是在站立時測量，動態足底壓力是在行走時測量。結果顯示神經病變組在兩側蹠骨頭後半之中外部的靜態足底壓力，與在左側蹠骨頭後半之中外部之動態足底壓力，均顯著大於對照組($p<0.05$)；在左腳趾頭之外與中外部之靜態與動態足底壓力均顯著小於對照組($p<0.05$)；在左足跟之前內部之靜態足底壓力，與在左足弓之後中部之動態足底壓力，也都顯著小於對照組($p<0.05$)。結論爲嚴重神經病變使糖尿病患者在站立與走路時位於外側蹠骨頭的壓力增加，位於外側趾頭的壓力則減少；在站立時位於足跟前段的壓力減少，而在走路時壓力減少則位於足弓後段。（中華復健醫誌 2002; 30(2): 65 - 71）

關鍵詞：靜態(static)，動態(dynamic)，足底壓力(plantar pressure)，糖尿病(diabetes mellitus)，嚴重神經病變(advanced neuropathy)

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