

# Walking Strategy in Diabetic Patients With Peripheral Neuropathy

CLAUDIA GIACOMOZZI<sup>1</sup>  
ANTONELLA CASELLI, MD<sup>2</sup>  
VELIO MACELLARI<sup>1</sup>

LAURA GIURATO, MD<sup>2</sup>  
LINA LARDIERI, MD<sup>2</sup>  
LUIGI UCCIOLI, MD<sup>2</sup>

**OBJECTIVE** — Diabetic neuropathic patients show a peculiar loading pattern of the foot, which led us to hypothesize that a substantial modification exists in their deambulatory strategy. The aim of the present study was to support this hypothesis by quantifying the changes of the loading patterns and by monitoring the excursion of center of pressure (COP) during gait.

**RESEARCH DESIGN AND METHODS** — A total of 21 healthy volunteers (C) and 61 diabetic patients were evaluated: 27 diabetic subjects without neuropathy (D), 19 with neuropathy (DN), and 15 with previous neuropathic ulcer (DPU). A piezo-dynamometric platform was used to record the foot-to-floor interaction by measuring loading time and the instantaneous COP position during the stance phase of gait.

**RESULTS** — Loading time was significantly longer in neuropathic patients than in control subjects (DPU:  $816.8 \pm 150$  ms; DN:  $828.6 \pm 152$  ms; D:  $766.5 \pm 89.9$  ms; C:  $723.7 \pm 65.7$  ms;  $P < 0.05$ ). COP excursion along the medio-lateral axis of the foot clearly decreased from C to DPU groups (C:  $6.41 \pm 0.1$  cm; D:  $4.88 \pm 0.2$  cm; DN:  $4.57 \pm 0.1$  cm; DPU:  $3.36 \pm 0.1$  cm;  $P < 0.05$ ) as well as COP excursion along the longitudinal axis for the DPU group only (C:  $26.6 \pm 1$  cm; D:  $26.9 \pm 1$  cm; DN:  $27.2 \pm 1$  cm; DPU:  $24.2 \pm 1$  cm;  $P < 0.05$ ). COP integrals were significantly reduced for all pathological classes (DPU:  $14.2 \pm 8$  cm<sup>2</sup>; DN:  $25.8 \pm 6$  cm<sup>2</sup>; D:  $27.7 \pm 3$  cm<sup>2</sup>; C:  $38.6 \pm 6$  cm<sup>2</sup>;  $P < 0.05$ ).

**CONCLUSIONS** — The accurate quantification of loading patterns and of COP excursions and integrals highlights changes of foot-to-floor interaction in diabetic neuropathic patients. The decreased medio-lateral and longitudinal COP excursions and corresponding changes of loading times and patterns support our hypothesis that a change in the walking strategy of diabetic patients with peripheral neuropathy does occur.

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**A**bnormal plantar pressures are considered the main cause of neuropathic foot ulceration (1–5). However, high pressures are only the last ring of a chain to which several factors contribute, including peripheral neuropathy and limited joint mobility. It is worth emphasizing that those factors may influence not only the foot loading, but, more

widely, the whole performance of the lower limb during gait.

A few authors have suggested that patients with peripheral neuropathy develop a change in their walking strategy, shifting from an ankle to a hip strategy (6,7). In a recent article, our group also hypothesized this kind of change by analyzing the foot loading pattern (8). The

aim of the present work was to further support this hypothesis by using a different parameter, namely the evolution of the center of pressure (COP) that is the point of application of the ground reaction force (GRF). COP records the succession of instantaneous positions during the entire period of contact between foot and floor and is plotted as a sequence of points on the ground plane. It takes into account the displacement of load throughout the foot during the stance phase of a walking cycle and contains useful information regarding the anatomical structures acting in and on the foot during walking. More specifically, spatial evolution of COP along the longitudinal axis of the foot mainly depends on the articular mobility of tibio-talar and metatarso-phalangeal joints in the sagittal plane. The former joint allows the foot to roll over the ground during the initial contact phase; the latter manages the push-off phase. COP excursions along the medio-lateral axis of the foot mainly depend on the inversion-eversion movements made to better control landing, energy storage, and propulsion. Such movements are performed by subtalar and minor foot joints in the frontal and transversal planes. Several articles (9–15) deal with the importance of COP pattern alterations during gait, and some of them report the definition of COP indexes for measuring abnormal COP displacements.

In this study, we standardize COP spatial and temporal evolution and compare data from diabetic patients and healthy volunteers, highlighting the differences in spatial and temporal evolutions of the foot loading curve and identifying specific foot subareas abnormally loaded in diabetic patients.

## RESEARCH DESIGN AND METHODS

### Population

A total of 61 subjects from our outpatient clinic were recruited for the study: 27 diabetic subjects without neuropathy (D) and 34 diabetic subjects with neuropathy, 19 of whom had previous neuropathic ulceration (DN) and 15 of whom did not

From the <sup>1</sup>Biomedical Engineering Laboratory, Istituto Superiore di Sanità, Rome, Italy; and the <sup>2</sup>Department of Internal Medicine, “Tor Vergata” University of Rome, Rome, Italy.

Address correspondence and reprint requests to Claudia Giacomozzi, Biomedical Engineer, Biomedical Engineering Laboratory, Istituto Superiore di Sanità, Viale Regina Elena 299, 00161 Rome, Italy. E-mail: c\_giacomozzi@yahoo.com.

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**Abbreviations:** C, healthy volunteers; COP, center of pressure; D, diabetic subjects without neuropathy; DN, diabetic patients with neuropathy but without previous neuropathic ulceration; DPU, diabetic patients with neuropathy and with previous neuropathic ulceration; GRF, ground reaction force; NDS, neuropathy disability score; 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—Baseline patient characteristics

Characteristic	C	D	DN	DPU
n	21	27	19	15
M/F	13/8	19/8	10/9	10/5
Age (years)	30–61	34–65	40–65	40–65
BMI (kg/m <sup>2</sup> )	25.0 ± 3.1	25.3 ± 3.4	27.0 ± 4.9	27.5 ± 4.1
Type 1/type 2 diabetes	—	8/19	9/10	3/12
Diabetes duration (years)	—	15.1 ± 9.3	19.4 ± 9.3	16.9 ± 8.6
HbA <sub>1c</sub> (%)	—	7.5 ± 1.5	7.8 ± 1.8	7.3 ± 2.4
VPT toe (V)	5.3 ± 2.1	14.7 ± 5.7	31.5 ± 7.6*	39.9 ± 13.3*†
NDS	0	3.8 (0–5)	6.95 (6–8)*	7.9 (7–9)*†
Retinopathy (a/b/p)	—	24/0/3	9/5/5	5/3/7
Nephropathy (a/m/M)	—	26/1/0	16/2/1	15/0/0

Data are means ± SD, range, or median (range). \*P < 0.05 vs. D; †P < 0.05 vs. DN. a/b/p, absent/background/proliferative; a/m/M, absent/microalbuminuria/macroalbuminuria.

have previous neuropathic ulceration (DPU). There were 21 age-matched healthy volunteers (C) recruited to serve as the control group.

The study was approved by the local ethics committee, and all subjects gave their written informed consent before the screening, in accordance with the principles of the Helsinki Declaration.

The inclusion criterion for diabetic patients was the diagnosis of type 1 or type 2 diabetes under stable metabolic control. The exclusion criteria for all subjects were as follows: >65 years of age, significant neurological diseases (except for those related to diabetic neuropathy), muscular/orthopedic problems, inability to ambulate independently without pain, use of a walking aid, and evidence of peripheral vascular disease (ankle brachial pressure index <0.85 or symptoms of intermittent claudication). The neuropathic patients were excluded if they had active foot ulcers, previous minor or major amputations, or Charcot's joints.

The clinical history evaluation included sex, age, height, and weight to calculate BMI, history of smoking, and, for diabetic patients, duration of the disease, metabolic control (HbA<sub>1c</sub>), and presence of other chronic complications (retinopathy and nephropathy).

The presence of diabetic peripheral neuropathy was defined for a neuropathy disability score (NDS) >6/10 and a vibration perception threshold (VPT) at the big toe of ≥25 V for one foot and >20 V for the other foot. VPT was measured by means of a neurothesiometer (Horwell, Nottingham, U.K.). The mean value was calculated over three readings.

The NDS is the product of scoring ankle reflexes (0 = normal; 1 = present on reinforcement; 2 = absent) plus vibration, pin-prick, and temperature sensation (cold tuning fork) at the big toe (0 = normal; 1 = abnormal). The maximum NDS (left and right legs combined) was 10, and scores of 3–5, 6–8, and 9–10 were defined as evidence of mild, moderate, and severe signs of neuropathy, respectively.

The DPU group included patients with a previous neuropathic ulcer healed for at least 3 months. All the previous ulcerations were localized at the metatarsal

heads. If present, callosities were removed before measurements

**Recording system**

The device used to evaluate the biomechanical parameters analyzed in this study has already been validated and widely described (8,16). Briefly, a piezodynamometric platform was obtained by rigidly fixing a dedicated pressure platform onto a commercial force platform (Bertec) to allow the resultant GRF to be transmitted unaltered from one platform to the other. The pressure platform was made of a matrix of resistive sensors

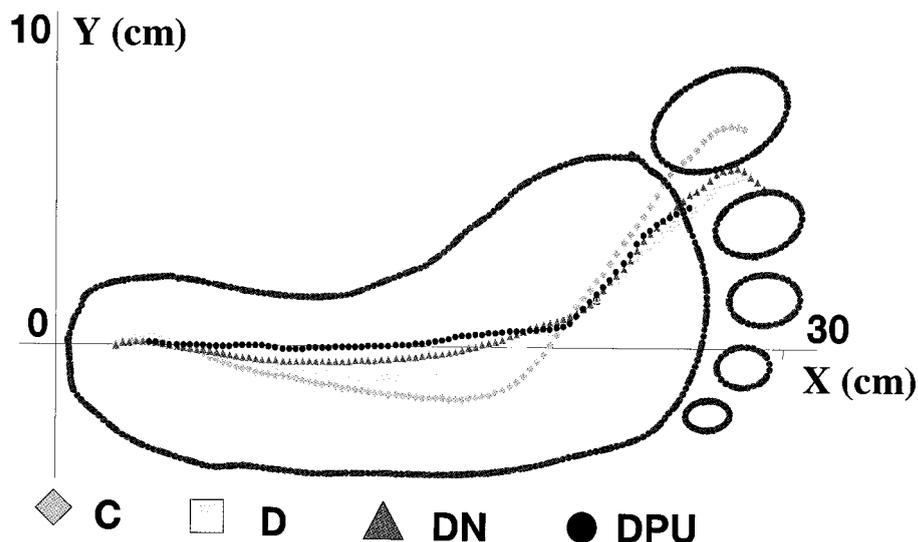
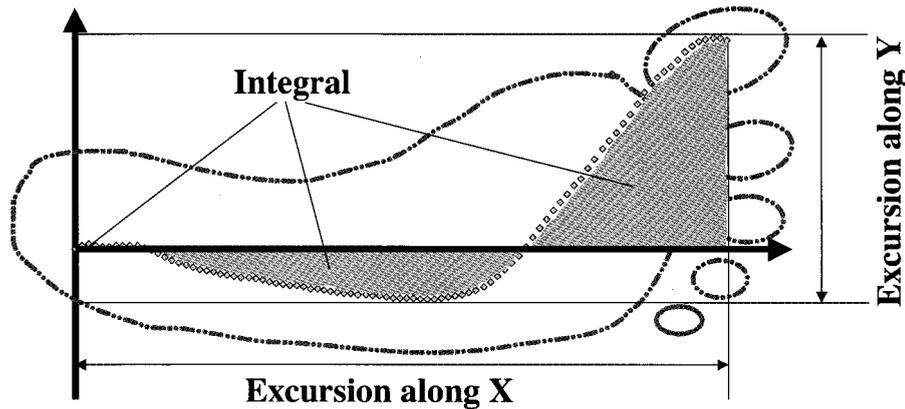


Figure 1—COP trajectories. For each group, the curve represents the average COP spatial evolution during the whole stance phase of gait. The distance between two successive markers of the same curve takes into account the velocity of transferring load from one point to the other: the smaller is the distance, the lower is the velocity, and the longer is the time of loading of the same area.



**Figure 2**—Definitions of COP parameters quantified in the present study: excursion along the longitudinal axis (x), excursion along the medio-lateral axis (y), and integral, computed as the sum of all the areas delimited by the COP curve and the longitudinal axis.

spaced 5 mm in both directions, pressure resolution was 150 Pa, and acquisition rate could be set up to 100 Hz. The force platform had a resolution of 2 N for force components and 0.3 Nm for moment components.

The resulting compound instrument simultaneously measures, for each sample, the GRF resultant (vertical and tangential components, free moment, and COP location) and pressure distribution throughout the foot-to-floor contact area. It allows, for small areas of any desired shape and dimension, the measurement of the vertical local GRF components and the computation of the local tangential forces (anterior-posterior and medio-lateral GRF component). This peculiarity has been widely exploited in our previous study (8) aimed at the evaluation of the alterations of the tangential stress under specified subareas—namely the heel, metatarsals, and hallux. The main advantage of using this compound instrument rather than a pressure platform or a force platform alone is the enhanced accuracy while measuring COP. In fact, as described in the study by Giacomozzi and Macellari (16), a coefficient has been calculated to correct the absolute force value delivered by the pressure platform on the basis of the corresponding value delivered by the force platform. Once the pressure platform is calibrated, it estimates COP more accurately than the force platform, in which the error depends on the position of the foot. COP is here computed according to its definition, i.e., as the mean value of the sensors coordinates, weighted by the local pressure level.

### Experimental setup and measurement protocol

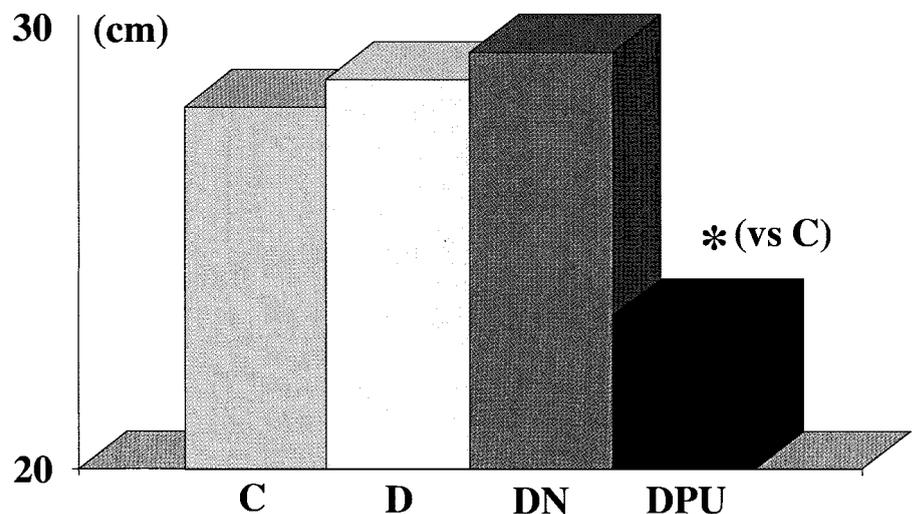
The platform was inserted at a level in the middle of a wooden walkway that was long enough to guarantee that the acquisition was made “at regimen” (8,17,18). The patient was trained to walk barefoot on the walkway at his or her preferred speed in a natural way and to center the active surface with one foot only without looking down at the platform. At the end of the training phase, six footprints were acquired for each foot, and the biome-

chanical data were stored together with the other relevant anthropometric and general data on the patient.

For each foot of each patient, three specific subareas were accurately selected: the hallux, the metatarsals, and the heel (8). All the kinematic and dynamic parameters of interest were calculated accordingly.

With regard to COP, the correct averaging and comparison of its trajectories claimed for standardization of stance phase duration, ab-adduction angle, and foot size. To overcome these problems, the footprints were realigned and normalized with respect to the foot length and width, and the temporal curves were resampled with respect to 256 samples and linearly interpolated. The spatial realignment was basically in the rotation and translation of the reference system solid with the footprint so that it coincided with the reference system of the platform. To define the former reference system, the bisecting line, which represents the anterior-posterior axis of the foot, was previously identified on the footprint. According to the guidelines delivered in the CAMARC (Computer Aided Movement Analysis in a Rehabilitation Context) II European Project (19), this line was defined as the line that splits the angle be-

	C (cm)	D (cm)	DN (cm)	DPU (cm)
mean value	26.6	27.7	25.8	14.2
SD	1.1	0.8	1.3	1.0



**Figure 3**—Maximum COP excursions along the longitudinal axis (x) of the foot.

	C (cm)	D (cm)	DN (cm)	DPU (cm)
mean value	6.4	4.9	4.6	3.4
SD	0.1	0.2	0.1	0.1

the right and left foot that are comparable with intersubject variability. Even though diabetic neuropathy is a symmetric pathology, it does not overcome the preexisting asymmetries in the biomechanics of gait.

**Statistical analysis**

The following data were analyzed for each foot of each patient: total foot COP trajectories and loading times of the total foot and of the three selected subareas (heel, metatarsals, and hallux). Mean values and SDs were evaluated over six trials for each foot. Each patient's feet were studied separately. Two contributions were obtained from each patient, with the exception of those in the DPU class, in whom only the previously ulcerated foot was included in the study.

One-way ANOVA was performed on the raw data of each class to obtain comparisons between multiple groups. The Bonferroni test was used for equal variance for post hoc multiple comparison of the means.

**RESULTS**— This section contains the main results of the spatial and temporal quantification of COP pattern, which well describes how the foot interacts with the floor. COP is an effective means to char-

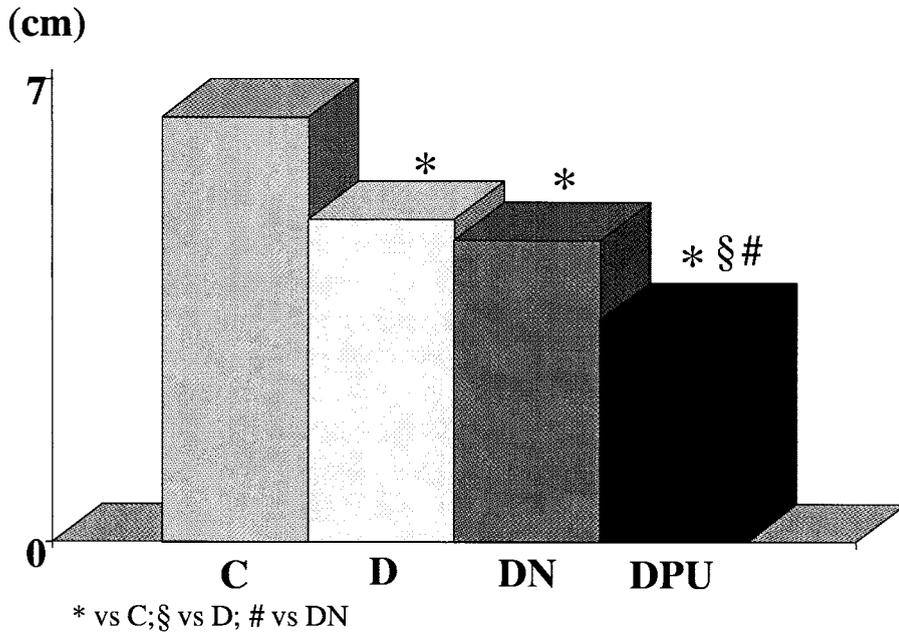


Figure 4—Maximum COP excursions along the medio-lateral axis (y) of the foot.

tween the inner and external tangents to the footprint into equal parts. The medio-lateral axis of the foot-based reference system was then defined as the line perpendicular to the bisecting line and passing through the most distal point of the calcaneus.

Finally, to allow comparisons among COP trajectories of different patients, the curve length and width were resized to a standard footprint 30-cm long and 12-cm wide. The standard footprint was used only to maintain the original measurement units for COP excursions (cm), instead of delivering them as percentages of the corresponding foot dimension. The left foot COP curves were rotated 180° around the longitudinal axis for comparison with the right foot curves. Possible physiological differences, dominance, and working habits do lead the right and left foot to develop different ways of interacting with the ground. Macellari et al. (20) reported that the Student's *t* test, applied to the main gait parameters of a wide sample of healthy subjects, highlights statistically significant differences between

	C (cm <sup>2</sup> )	D (cm <sup>2</sup> )	DN (cm <sup>2</sup> )	DPU (cm <sup>2</sup> )
mean value	38.6	27.7	25.8	14.2
SD	6	3	6	8

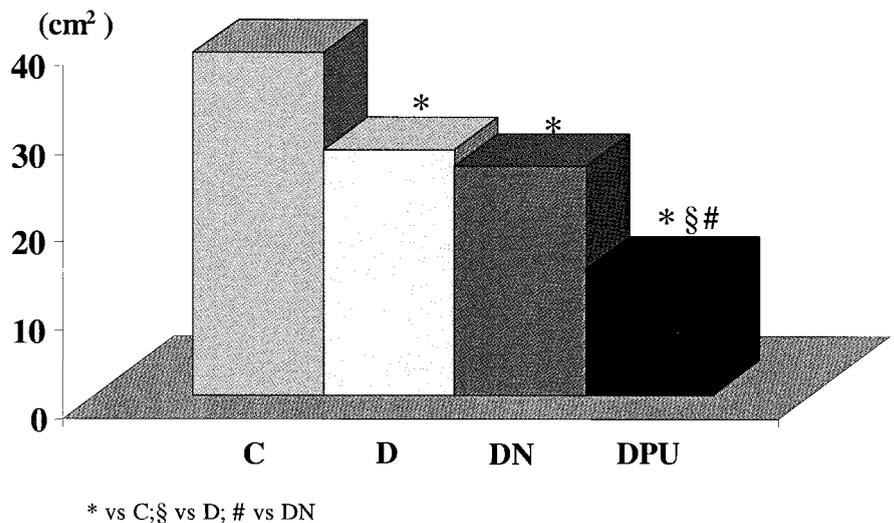
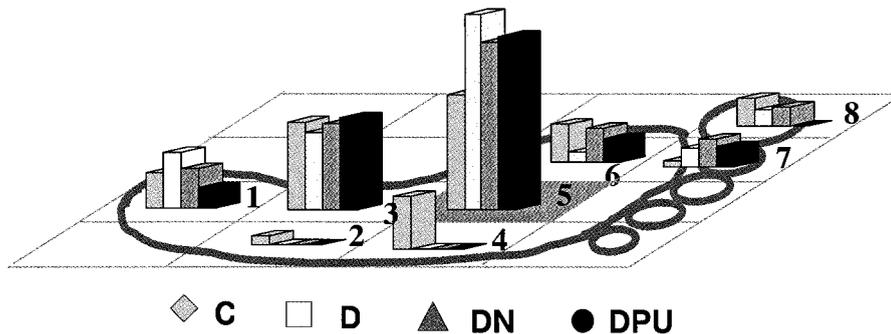


Figure 5—COP curve integrals along the longitudinal axis (x) of the foot.

	1	2	3	4	5	6	7	8
C	9.4	2.4	23.6	14.2	31.1	10.2	1.6	7.5
D	14.8	-	20.7	-	52.3	2.7	5.1	4.3
DN	10.5	-	23.0	-	44.9	9.0	7.4	5.1
DPU	6.2	-	27.9	-	52.7	7.1	6.2	-



**Figure 6**—Histograms of time percentage with respect to the whole stance period, during which COP instantaneous position remained in each specific subarea. Gray area corresponds to central metatarsals.

acterize both static and dynamic loading. This study focuses on the analysis of gait.

Demographic data are provided in Table 1. There were no significant differences among groups for age, BMI, metabolic control, or diabetes duration. VPT and NDS were significantly increased in the DN group with respect to the D and C groups and in the DPU group with respect to the DN, D, and C groups.

**COP pattern**

Figure 1 shows the average COP curve pattern from a qualitative point of view; it is worth noting its trend to reduce its excursion, both medio-laterally and longitudinally, in diabetic patients and further in diabetic patients with peripheral neuropathy.

To obtain quantitative information, we computed the excursion along the longitudinal x-axis, the excursion along the medio-lateral y-axis, and the integral under the curve (Fig. 2).

Mean values of the maximum excursions along the longitudinal axis are reported in Fig. 3. The differences with respect to control subjects are statistically

significant ( $P < 0.05$ ) for DPU patients only.

Differences in the excursions along the medio-lateral axis (Fig. 4) are clearly evident for all diabetic classes and are even more evident for DPU patients. Finally, similar results are found for the integral of the COP curve related to the loading of the total foot (Fig. 5).

COP excursions along the longitudinal and the medio-lateral axes of the footprint only account for eventual COP pattern alterations in the space domain because of shifts of load under parts of the foot that are different from usual. No information on abnormal loading time could be extrapolated from such parameters. Thus, a further analysis of the COP pattern was performed, taking into account the temporal evolution of the curve throughout the whole period of stance. This COP pattern study in the time domain highlighted further critical modifications in the gait of diabetic patients, especially those without neuropathy. The most interesting results are summarized in Fig. 6; the histograms show the time interval during which COP falls into the

corresponding area. Special attention should be paid to the histogram related to the metatarsal area (gray area), which clearly shows that, in diabetic patients, COP remains for a long time on the central metatarsals, whereas it is definitely absent in correspondence with the fifth metatarsal. In DPU patients, the load is absent in the hallux area. In general, diabetic patients tend to shift the load medially, even in the absence of neuropathy.

**Loading times**

As reported in Table 2, loading time was significantly longer in the DN and DPU groups than in the C group for total foot, heel, and metatarsals. Furthermore, at the heel region, it was significantly longer in the DPU group than in the D group. At the big toe level, however, the loading time for the DPU group was significantly shorter than that in the DN and D groups.

**CONCLUSIONS**— The accurate quantification of spatial and temporal evolution of COP pattern has been proved to be effective in describing how the foot manages the floor during gait.

Looking at the COP curves reported in Fig. 1, healthy subjects show a COP progression that starts from the heel, passes through the metatarsals, reaches the anterior and medial part of the foot, and ends on the hallux. This pattern is consistent with the COP pattern described by Hong et al. (11) for healthy barefoot gait. Our data show that diabetic patients with severe neuropathy approach the floor with the most anterior part of the heel and perform their push-off phase at the metatarsals level, as proven by the reduction of the COP progression along the longitudinal axis. The resulting gait, similar to a flat-footed gait, is then characterized by a minimum heel strike and a minimum push-off phase. Furthermore, neuropathic gait is characterized by a significant reduction of the COP trajectory along the medio-lateral

**Table 2—Loading time**

Patient group	Total foot	Heel	Metatarsals	Big toe
C	723.7 ± 65.7	427.1 ± 65.3 (59.0)	638.2 ± 62.2 (88.2)	446.4 ± 33.4 (61.6)
D	766.5 ± 89.9	468.6 ± 91.3 (61.1)	691.0 ± 75.8 (90.1)	498.8 ± 43.2 (65.1)
DN	828.6 ± 152.2*	528.1 ± 133.9 (63.7)*	759.8 ± 143.7 (91.7)*	520.6 ± 86.4 (62.8)
DPU	816.8 ± 150.6*	547.7 ± 142.0 (67.1)*†	760.5 ± 144.2 (93.0)*	377.0 ± 98.5 (46.2)†‡

Data are means ± SD (in milliseconds) (% stance phase). \* $P < 0.05$  vs. C; † $P < 0.05$  vs. D; ‡ $P < 0.05$  vs. DN.

axis and a concurrent shift of the loading pattern from the lateral toward the medial part of the foot. According to Scherer and Sobiesk (14), this might be read as a clear sign of instability of the whole ankle articular complex. These authors use a COP index, calculated as the ratio between the COP areas that are, respectively, lateral and medial to the midline of the foot. On the basis of the resulting reduced values of such an index, the authors demonstrate that there is a premature load shift toward the medial part of the foot. Therefore, they suggest that the feeling of instability at the ankle level causes a greater stiffness mainly in the frontal plane aimed at preventing ankle lateral sprains.

On the basis of our findings, we hypothesize that reduced muscular strength at the ankle joint should be included among the main causes that lead to critical changes in neuropathic walking strategy (6). Such a hypothesis is well supported by the accurate analysis of Hunt et al. (7) that points out the role that specific muscle compartments of the leg have in managing the floor. Briefly, they infer on possible links between muscle deficit and abnormal foot function; more specifically, they state that between heel contact and 10% of stance, dorsal flexors act eccentrically and evertors act concentrically. Because neuropathic patients show muscle weakness of these muscle groups, especially of the tibialis anterior (21), there is a general lack of foot control in the heel strike phase, which entails a flat-footed approach. In addition, a poor foot eversion explains the limited lateral shift of the load. This lack of lateral shift is also well justified during foot flat phase, heel rise, and push off, when the increased unbalance between plantar and dorsal flexors and between invertors and evertors greatly impairs the rise of the forefoot both in the sagittal and frontal plane. However, in diabetic patients without neuropathy, some stiffness of the ankle joint may be responsible for the reduced excursion of COP (22).

As for the loading time, we observed a significant increase of the absolute values in patients with peripheral neuropathy, as reported in previous studies (23,24). More specifically, the major increases were recorded at the heel and at the metatarsal area, whereas loading time was significantly reduced at the hallux area. These results indicate that the increase in contact time is not homogeneously sub-

divided among the main subareas of the foot, as shown in Fig. 6. It is thus reasonable to infer that a larger contact time could result not only from the loss of proprioception (25,26), which should entail a general increase in contact time of the whole plantar surface with the ground, but also from hypothesized compartmental muscle weakness. Neuropathy affects ankle dorsal flexors more than other muscle compartments (21,26) and consequently alters foot-to-floor interaction.

### Summary

The study of foot-to-floor interaction during gait in terms of COP evolution allowed us to further highlight the modifications in the walking strategy of diabetic patients with and without peripheral neuropathy.

The main effects of the changes in the biomechanics of the neuropathic gait can be summarized as follows:

- With regard to the COP spatial evolution, in neuropathic patients, COP curve has a significantly reduced excursion both longitudinally and medio-laterally; a sensible reduction along the medio-lateral axis is also evident in diabetic subjects without neuropathy. A similar trend is found for COP integrals.
- Patients with peripheral neuropathy demonstrate a significant increase in loading time, mainly at the heel and at the metatarsal area, and they demonstrate a reduction at the hallux.
- The above findings support the hypothesis of a substantial change in the functionality of the whole ankle complex, in which articular and muscular impairments entail the development of a functional flat foot and the acquisition of a hip-based walking strategy. The loss of function of the hallux is responsible for the further increase of loading at the metatarsal heads level and therefore further contributes to the increased risk of ulceration at that level.

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