Muscle Weakness and Foot Deformities in Diabetes

Relationship to neuropathy and foot ulceration in Caucasian diabetic men

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OBJECTIVE — To examine the relationships among muscle weakness, foot deformities, and peroneal and tibial nerve conduction velocity in diabetic and nondiabetic men.

RESEARCH DESIGN AND METHODS — A neuropathic and foot evaluation was undertaken in 10 nondiabetic control subjects (group C) and in 36 consecutive diabetic patients attending Diabetes Centre clinics, including 10 diabetic control subjects (group D), 15 diabetic neuropathic patients (group DN), and 11 diabetic patients with a history of ulceration (group DU). Neuropathy was defined as a peroneal motor nerve conduction <40 m/s. Muscle weakness was assessed in seven intrinsic and seven extrinsic muscles of the foot using a semiquantitative score (max score per muscle = 3). Foot deformities were assessed using a foot deformity score (max score = 3). A higher score indicated increased muscle weakness or more severe foot deformities. Muscle weakness and foot deformities were assessed without prior knowledge of patient and neuropathy status.

RESULTS — Peroneal and tibial nerve conduction velocity were associated with weakness in muscles innervated by, respectively, the peroneal and tibial nerve ($r = -0.70$ and $r = -0.51$, $P < 0.01$) and foot deformities ($r = -0.60$ and $r = -0.59$, $P < 0.001$). The DN and DU groups had more weakness in intrinsic and extrinsic muscles compared with the C and D groups. Muscles innervated by the tibial nerve had a greater proportional muscle weakness than those innervated by the peroneal nerve in the DN and DU groups. The DN and DU patients had more foot deformities (median food deformity score [interquartile range]) (3 [2–3] and 2 [2–3]) compared with D and C patients (0 [0–0.75] and 0 [0–0]).

CONCLUSIONS — Important relationships have been shown between motor nerve conduction deficit and muscle weakness; however, it is still not clear whether abnormal nerve function, leading to a decrease in muscle strength, could be responsible for the development of foot deformities.

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Lower extremity problems represent the most common source of complications and hospitalization in the diabetic population. The prevalence of past or present foot ulceration has been estimated at 5.1% of all diabetic people in a U.K. population-based study (1) and 5.3% of type 2 diabetic patients in a community-based study (2). Furthermore, people with diabetes are 15 times more likely to undergo a lower extremity amputation than their nondiabetic counterparts (3). One reason why foot ulcers pose such an enormous problem is the large number of factors that contribute to their development and perpetuation (4–6). Distal symmetrical polyneuropathy, a common sequela of diabetes, has been implicated as the primary cause of plantar ulceration and affects both sensory and motor sections of the peripheral nervous system (5,7). Although sensory and autonomic neuropathies have been well studied through standardized cutaneous perception threshold and autonomic function tests, very few studies have been carried out regarding motor neuropathy (8–12).

Motor neuropathy is commonly believed to lead to weakness in the intrinsic muscles of the foot, thus upsetting the delicate balance between flexors and extensors of the toes. Atrophy of the small muscles responsible for metatarsophalangeal plantar flexion is thought to lead to the development of hammer toes, claw toes, prominent metatarsal heads, and pes cavus. Unfortunately, structural deformities are common sites of abnormally high pressure, and repetitive pressure at these sites could result in tissue breakdown. Likewise, callosities may develop at these high-pressure sites, and in the absence of protective sensation continued activity can cause the callosities to thicken, hemorrhage underneath, and eventually ulcerate (13). Thus, foot deformities can cause alteration in pressure distribution predisposing the skin to traumatic ulceration. This is confirmed by evidence (14–16) that ulcers develop at sites of maximum pressure.

Likewise, significant relationships have been described (17–19) between foot deformities, such as forefoot to rear foot position, and characteristic patterns of plantar pressure distribution, callus formation, and ulceration. Foot deformities such as toe deformities and prominent metatarsal heads have been reported (5) to be among the most important causal factors leading to the majority of diabetic foot ulcers. These results support the hypotheses (18) that insensitivity, coupled with increased repetitive pres-

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Abbreviations: ABPI, ankle-brachial pressure index; MNCV, motor nerve conduction velocity; MS, muscle weakness score; PPT, pressure perception threshold; 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—*Semiquantitative grading system for the assessment of muscle weakness: the muscle weakness test*

Extrinsic muscles	Innervation	Intrinsic muscles	Innervation
Tibialis anterior	Peroneal	Extensor digitorum brevis	Peroneal
Tibialis posterior	Tibial	Flexor digitorum brevis	Tibial
Peroneal longus	Peroneal	Extensor hallucis brevis	Peroneal
Extensor digitorum longus	Peroneal	Flexor hallucis brevis	Tibial
Flexor digitorum longus	Tibial	Interossei	Tibial
Extensor hallucis longus	Peroneal	Lumbricales	Tibial
Flexor hallucis longus	Tibial	Abductor hallucis	Tibial

Muscle weakness was scored 0 for normal strength, 1 for mild, 2 for severe weakness, and 3 for complete loss of strength.

sure, is an important contributing factor to the development of ulcers.

Although the relationship between foot deformities and foot ulceration is well described, the etiology of foot deformities is less clear. Recent studies (20–24) have shown evidence of muscle weakness and atrophy in the lower limb and foot of diabetic patients with peripheral neuropathy. However, the relationship with foot deformities has only been addressed by one group (24) who reported no relation between toe deformity and muscle atrophy.

Thus, while it is commonly accepted that specific foot deformities in diabetes are the result of a muscle imbalance between the intrinsic and extrinsic musculature, this relationship has not received much scientific attention to date. Moreover, the specific relationships among the motor nerve conduction deficit, muscle weakness, and foot deformities have not been clarified.

Therefore the aims of this study were: *1*) to examine the relationships among peroneal and tibial motor nerve conduction velocity (MNCV), muscle weakness, and the presence of foot deformities in diabetic men and *2*) to examine muscle weakness, foot deformities, and sensory neuropathy in four groups of diabetic men with and without motor neuropathy or foot ulceration.

RESEARCH DESIGN AND METHODS

— Four groups of male Caucasian individuals were studied: Group C consisted of 10 nondiabetic control subjects, group D comprised 10 diabetic subjects without motor peripheral neuropathy, group DN consisted of 15 diabetic subjects with motor peripheral neuropathy but without past foot ulceration, and group DU comprised 11 diabetic subjects with past (healed) neuropathic foot ulceration. The diabetic patients were consecutive patients attending a general diabetes clinic at the Manchester Diabetes Centre who fulfilled the study criteria and agreed to take part. The control subjects were relatives or friends of the patients and staff of the Diabetes Centre.

The study was approved by the local ethics committee. All patients received full information about the study and gave informed consent before any testing was carried out. For the purposes of classification of subject groups, motor peripheral neuropathy was defined as a peroneal MNCV <40 m/s. All subjects were free of peripheral vascular disease (assessed by presence of foot pulses and ankle-brachial pressure index [ABPI]). Systolic blood pressure was determined in the dorsalis pedis artery and the brachial artery. The pressure at the ankle divided by the pressure at the arm gave the value for the ABPI. Any patients with ABPI values <0.85 or with less than one pulse per foot were excluded from the study. Patients with a history of Charcot joints, congenital deformities, acute or chronic musculoskeletal disease, any lower-limb amputation, or any other secondary polyneuropathies were excluded from the study. Patients presenting with foot pain, which could affect the muscle strength assessments, were also excluded from the study.

All subjects were assessed by clinical examination for muscle weakness, foot deformities, and signs of sensory neuropathy by one investigator (C.V.), with sensory neuropathy always tested after the muscle and foot deformity examination. Motor nerve conduction velocities were determined by a different investigator (A.L.C.), so that both investigators were blinded to each other's results.

Muscle weakness was determined according to methods described by Kendall, McCreary, and Provance (25). Assessments were carried out on the dominant lower limb, situated horizontally in a controllable heated leg trough. It has been shown that the weight of the body is an important factor affecting stability, so the horizontal position was used and the examiner stabilized the proximal part of the foot. Muscle strength (i.e., weakness) was assessed as the ability of the muscle to produce active movement against the examiner's resistance (25,26). Any skeletal abnormalities or asymmetry with atrophy or hypertrophy were recorded using a standard form. Several muscles were selected for assessment in accordance with their classification into extrinsic and intrinsic and their innervation from the peroneal and tibial nerves (Table 1). Muscle strength (i.e., weakness) was scored using a semiquantitative grading system that was based on the scoring system as used in the Michigan Diabetic Neuropathy Score (27). Muscle weakness was scored as 0 for normal muscle strength, 1 for mild, 2 for severe weakness, and 3 for complete loss of strength. A muscle weakness score (MS) was, therefore, obtained for each set of muscles examined. Higher values for this score represented increased muscle weakness.

The presence of hammer toes, claw toes, prominent metatarsal heads, and high medial arch were assessed using a foot deformity score designed for this study (a point was given for each deformity present to whatever degree), with a maximum score of 3 (subject could only score for one of the toe deformities). A grading system was not used in this context because of the subjectivity of the observation. Hammer toes were defined as "a hyperextended metatarsophalangeal joint with a flexion deformity of the proximal interphalangeal joint and hyperex-

Table 2—*Subject characteristics*

	Groups				Significant differences ($P < 0.001$)
	C	D	DN	DU	
n	10	10	15	11	—
Age (years)	48.2 ± 6.2	54.9 ± 13.2	59.7 ± 9.5	54.0 ± 8.0	C:DN ($P < 0.05$)
Duration diabetes (years)	NA	16.8 ± 10.9	19.3 ± 13.1	14.0 ± 6.9	NS
ABPI	1.10 ± 0.15	1.03 ± 0.14	1.11 ± 0.18	1.24 ± 0.24	NS
TPT (°C)	0.6 ± 0.2	1.8 ± 2.3	8.4 ± 3.4	9.2 ± 3.4	C:DN, C:DU, D:DN, and D:DU
VPT (V)	4.1 ± 3.6	10.5 ± 5.1	26.7 ± 9.9	33.2 ± 7.7	C:DN, C:DU, D:DN, and D:DU
Dorsal PPT	4 (4–4)	4 (4–4)	4 (4–5)	5 (4–6.5)	C:DU, D:DU, and DN:DU
Plantar PPT	4 (4–4)	4 (4–4)	5 (5–6)	7 (6–7)	C:DN, C:DU, D:DN, D:DU, and DN:DU
Peroneal MNCV (m/s)	49.5 ± 2.7 (44.3–53.2)	42.9 ± 2.3 (40–46.4)	32.0 ± 5.4 (22–38.6)	34.1 ± 6.4 (24.7–42.8)	C:D, C:DN, C:DU, D:DN, and D:DU
Tibial MNCV (m/s)	45.9 ± 4.8 (37.5–51.7)	37.2 ± 4.4 (32.5–47)	28.9 ± 6.5 (22–38.6)	26.9 ± 5.9 (22–36.5)	C:D, C:DN, C:DU, D:DN, and D:DU

Data are means ± SD, means ± SD (range), and median (interquartile range). Statistical analysis was conducted by ANOVA with Tukey's range test. TPT, temperature perception threshold.

tension of the distal interphalangeal joint," claw toes as "hyperextension of the metatarsophalangeal joints and flexion of the proximal and distal interphalangeal joints," prominent metatarsal heads as "any palpable plantar prominences of the metatarsal site of the foot," and high medial arch as "an abnormally high medial longitudinal arch, which extends between the first metatarsal head and the calcaneus and the apex of the arch between the Chopart and Lisfranc joint" (28–30).

Quantitative sensory testing included assessment of pressure, vibration, and warm temperature perception. Cutaneous pressure perception threshold (PPT) was determined using Semmes Weinstein Monofilaments (Gillis W. Long, Hansens's Disease Center, Carville, LA) at the dorsum and at three plantar sites (first and fifth metatarsal heads and heel) of the foot. Three filaments (1, 10, and 75 g) were used for assessment. If the patient could feel the 1-g filament, then PPT = 4. If only the 10- or 75-g filament was felt, then PPT = 5 or 6, and if none of the filaments was perceived, then PPT = 7.

Vibration perception threshold (VPT) was measured on the tip of dominant hallux using a neurothesiometer (Horwell Scientific Laboratory Supplies, Wilford, Nottingham, U.K.). The mean of three readings was taken as the VPT (11).

Warm thermal perception threshold was measured using a thermoesthesiometer, Model AZVU (Medical Instruments Department, VU Hospital, Amsterdam, the Netherlands) at the foot dorsum using a two-alternative forced-choice procedure (31).

Motor nerve conduction was measured using the MS92a EMG machine (Medelec Limited, Old Woking, Surrey, U.K.) using surface stimulation and recording techniques. The dominant limb was placed in the leg trough and warmed using a controllable heating pad. The procedure commenced only when skin temperature was ≥30°C. The recording electrode was then placed on the extensor digitorum brevis muscle for the peroneal nerve and on the abductor hallucis for tibial nerve recording. If no muscle action potentials were obtained and edema was not present, a value of 22 m/s was given for the MNCV, i.e., the lower limit (because no values have been recorded below this value in our laboratory).

Statistical analysis

Group means were compared using one-way ANOVA with Tukey's range test and the Kruskal-Wallis and Wilcoxon tests for nonparametric data, and the association between MNCV and muscle strength or foot deformity score was examined using Pearson's correlation coefficient.

RESULTS — All subjects were well matched for diabetes duration. All diabetic subjects were matched for age, but control subjects were a little younger than the DN group (Table 2).

The first aim of this study was to examine the relationships among the peroneal and tibial motor nerve conduction deficits, muscle weakness, and foot deformities. The results from all diabetic patients involved in the study were combined for the correlation analysis. Analysis indicated a strong inverse relation between both peroneal and tibial MNCVs with the MS for their specifically innervated muscles and for both MNCVs and the foot deformity score (Table 3).

The second aim of this study was to examine muscle weakness, foot deformities, and sensory neuropathy in the four groups of subjects. Warm temperature perception threshold (which assessed C fiber function) was significantly impaired in group DN compared with groups C and D (Table 2). A similar pattern arose for the measures of Aβ-fiber function (VPT and PPT). In all tests for sensory neuropathy, there was a trend for the most severe impairment of nerve function to be in the DU group (Table 2), with a

Table 3 —*Correlation coefficients for MNCV with muscle weakness and foot deformity scores*

	R	R^2	*P*
Peroneal			
MNCV vs. PMS	−0.702	0.49	<0.001
MNCV vs. FDS	−0.600	0.36	<0.001
Tibial			
MNCV vs. TMS	−0.513	0.26	<0.01
MNCV vs. FDS	−0.593	0.35	<0.001

FDS, foot deformity score; PMS, peroneal muscle weakness score; TMS, tibial muscle weakness score.

significant difference between the DN and DU groups for pressure perception. The peroneal MNCV was used as a selection criterion; consequently, these data are included purely to demonstrate the MNCV distribution across the groups.

The mean extrinsic and intrinsic MSs can be seen in Table 4. In both sets of muscles, there was more muscle weakness in groups DN and DU compared with and groups C and D ($P < 0.001$ for trend, Kruskal-Wallis). The intrinsic MS was higher than the extrinsic MS ($P < 0.0001$, paired Wilcoxon test), indicating that the intrinsic muscles were more severely affected.

For both muscles innervated by the peroneal and tibial nerve, there was more muscle weakness in groups DN and DU compared with groups C and D ($P < 0.001$ for trend, Kruskal-Wallis).

The MS was also calculated as the proportion of the maximum obtainable score to allow a comparison between scores since the maximum value varied between the different MSs (Table 4). The muscles innervated by the tibial nerve had a greater proportional decrease in muscle strength as compared with the peroneal innervated muscles ($P < 0.0001$, paired Wilcoxon test). However, there was no difference between neuropathic patients with and without past foot ulceration.

The mean foot deformity score (Table 4) was higher in the DN and DU groups compared with the C or D groups ($P < 0.001$ for trend, Kruskal-Wallis). Again, there was no difference between the DN and DU groups.

CONCLUSIONS — From this study, muscle weakness and foot deformities were found to be equally severe in diabetic subjects with past foot ulceration compared with diabetic patients without ulceration but with motor neuropathy alone. Several studies have reported (4,5,32) that foot deformities are important contributory risk factors and predictive of foot ulceration, possibly by predisposing the skin to high pressure at the site of the foot deformity. This suggests that the neuropathic patients without past ulceration in this study are indeed at high risk of ulceration in the future. However, the etiology of foot ulceration is extremely complex, also involving contributions from trauma, peripheral vascular disease, impaired wound healing, and psychological factors (4,6,33,34), and does not always include foot deformities (5). The fact that sensory testing of pressure perception was worse in the group with past ulceration may suggest that sensory neuropathy contributes more to the etiology of diabetic foot ulceration than foot deformity.

The findings from this study highlight the increased risk for foot ulceration with diagnosis of sensory and motor neuropathy, which currently can only be prevented by good glycemic control because no pharmaceutical treatment is available yet that prevents or slows down the development of peripheral motor neuropathy.

The most important findings from this study are the clear relationships among the motor nerve conduction deficit, muscle weakness, and foot deformities relating to individual nerves and the muscles they innervate. The decrease in MNCV in diabetes reflects either demyelination or functional changes to the axon membrane. These changes in peripheral nerve function can lead to either a decrease in mass or resting tone of the muscles innervated by the nerve. It was not possible to measure muscle mass or tone in intact human feet, and the clinical method of assessing muscle weakness used in this study was a surrogate measure for more invasive techniques.

Although a decrease or loss of sensation is well described in the literature, changes in muscle strength due to diabetic peripheral neuropathy are rarely reported. However, it is interesting that >40% of diabetic patients have been reported (35) to have abnormal scores for muscle strength. In addition, the muscle strength and reflex components of the Michigan Diabetic Neuropathy score have been reported (36) to be predictive of foot ulceration. Muscle atrophy in diabetic neuropathic subjects has been demonstrated using magnetic resonance imaging and shown to be related to motor weakness at the ankle, with most pronounced atrophy at more distal muscles, indicating a length-dependent process (21). Further evidence for muscle atrophy in the foot in subjects with diabetic neuropathy was recently shown, again by using magnetic resonance imaging technology (22–24). Evidence for the cause of muscle atrophy in diabetic neuropathic patients comes from macroelectromyographic studies, showing increased amplitude of macromotor unit potential

Table 4—*MS and foot deformity score*

	Groups				
	C	D	DN	DU	*P*
EMS (max = 21)	0 (0–0)	0 (0–0)	10 (7–11)	8 (5.5–12.5)	<0.001
IMS (max = 21)	0 (0)	1.5 (0–9)	17 (16–19)	17 (16.5–18.5)	<0.001
PMS (max = 18)	0 (0–0)	0 (0–0)	8 (6.5–10)	8 (6–9)	<0.001
TMS (max = 24)	0 (0–0)	1.5 (0–9)	18 (17–20)	18 (16.5–20.5)	<0.001
Proportional EMS	0 (0–0)	0 (0–0)	0.48 (0.33–0.52)	0.38 (0.26–0.6)	—
Proportional IMS	0 (0)	0.07 (0–0.43)	0.81 (0.76–0.9)	0.81 (0.79–0.88)	—
Proportional PMS	0 (0–0)	0 (0–0)	0.44 (0.36–0.56)	0.44 (0.33–0.5)	—
Proportional TMS	0 (0–0)	0.06 (0–0.38)	0.75 (0.71–0.83)	0.75 (0.69–0.85)	—
FDS (max = 3)	0 (0–0)	0 (0–0.75)	3 (2–3)	2 (2–3)	<0.001

Data are median (interquartile range). Statistical analysis was conducted by Kruskal-Wallis test for trend. The proportional score is the total score divided by maximum obtainable score. EMS, extrinsic MS; FDS, foot deformity score; IMS, intrinsic MS; PMS, peroneal MS; TMS, tibial MS.

and fiber density of the anterior tibial muscle in diabetic neuropathic patients without muscle weakness and a further increase in patients with weakness. This indicates that the loss of muscle strength in diabetic patients is due to incomplete reinnervation following axonal loss (37).

Data from our study indicate proportionally weaker tibial compared with the peroneal innervated muscles, which is not supportive of previous findings (21) of more atrophy in peroneal compared with tibial innervated muscles. Weaker peroneal innervated muscles suggest a length-dependent process because the peroneal nerve originates more proximal than the tibial nerve (21). The contradictory findings from our study may be explained by the greater number of tibial compared with peroneal innervated muscles tested and the inclusion of intrinsic muscles in our study. The finding of more severe muscle weakness in intrinsic muscles in our study supports this explanation.

Although the relationships between motor nerve conduction deficit, muscle weakness, and foot deformities are indicative of a causal relationship, it is not clear how muscle weakness leads to the development of foot deformities. Toe deformities have been suggested to be related to muscle weakness in the toe flexors; however, the most significant stabilizing force on the plantar aspect of the metatarsophalangeal joint is the plantar aponeurosis, together with the plantar plate and capsule (29,38). In a foot with an inefficient plantar aponeurosis and plantar plate, the toe flexors and extensors probably have a more significant effect on the toe position. In this study, 26.9% (18 of 67) of the scored foot deformities were related to the toe, whereas 40% were prominent metatarsal heads. Because prominent metatarsal heads are usually related to toe abnormalities, one could argue that similar processes are responsible for the development of both deformities. It is not clear from this study whether muscle weakness is a cause of foot deformities or whether muscle weakness may have developed after the foot deformities. It is probably almost impossible to separate weakness-caused deformity or deformity-caused weakness, and, with the design of the current study, this issue can't be addressed appropriately. Recent evidence against a causal relationship was reported by Bus et al. (24), as they did not find a relation between toe deformity and muscle atrophy. It is likely that inefficient plantar structures, the plantar aponeurosis, joint capsules, and intrinsic muscles all contribute to an extended proximal phalanx in particular and foot deformities in general.

To summarize, important relationships have been shown between motor nerve conduction deficit and muscle weakness. Although a relationship between motor nerve conduction deficit and foot deformities was observed, it is not clear whether abnormal nerve function, leading to muscle weakness, could be responsible for the development of foot deformities.

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