Biomechanical Risk Factors Associated with Neuropathic Ulceration of the Hallux in People with Diabetes Mellitus

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In this study of people with diabetes mellitus and peripheral neuropathy, it was found that the feet of patients with a history of hallux ulceration were more pronated and less able to complete a single-leg heel rise compared with the feet of patients with a history of ulceration elsewhere on the foot. The range of active first metatarsophalangeal joint dorsiflexion was found to be significantly lower in the affected foot. Ankle dorsiflexion, subtalar joint range of motion, and angle of gait differed from normal values but were similar to those found in other studies involving diabetic subjects and were not important factors in the occurrence of hallux ulceration. These data indicate that a more pronated foot type is associated with hallux ulceration in diabetic feet. Further studies are required to evaluate the efficacy of footwear and orthoses in altering foot posture to manage hallux ulceration. (J Am Podiatr Med Assoc 96(3): 189-197, 2006)

Foot ulceration, the most common antecedent to amputation in people with diabetes mellitus, is experienced by 15% of diabetic patients at some time in their life.[1, 2] Although peripheral neuropathy is the leading risk factor for ulceration, other etiologic factors have been identified, including foot deformity, limited joint mobility, and peripheral vascular disease.[3, 4] From the many studies of risk factors, it is evident that the pathogenesis of diabetic foot ulceration is complex and depends on many variables.

The hallux, with its unique and important role in normal foot function, is the most common foot ulceration site, accounting for 20% to 30% of diabetic foot ulcers (W Tyrrell, O Gibby, unpublished data, 1998).[5] Of the foot ulcers seen in our diabetic foot clinic, 22% are on the hallux. Therefore, it is also a frequent site of amputation. Compared with amputations of the other toes, there is more subsequent forefoot deformity and pressure increases under the metatarsal heads, toes, and contralateral heel after hallux amputation.[6, 7] Hallux amputation, therefore, is frequently associated with subsequent ulceration and repeated amputation rates of up to 74%.[7-9]

Various studies have provided information regarding the biomechanical factors that may contribute to hallux ulceration. Some of these studies involved healthy, nondiabetic individuals, and others used diabetic subjects with no history of ulceration. Two such biomechanical studies[10, 11] found a relationship between reduced dorsiflexion at the first metatarsophalangeal joint and increased pressure at the hallux. Other characteristics linked to elevated plantar pressure at the hallux are neuropathy, increased length of the hallux, increased interphalangeal angle, elevated body weight, reduced soft-tissue thickness, and pes planus foot type.[10-13] Two other studies[14, 15] sought to identify biomechanical factors associated with ulcer location; one concluded that feet with hallux ulceration experience early and prolonged loading at this

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site, whereas the other showed that feet with hallux ulcers have a more everted resting calcaneal position than feet with ulcers under the second to fifth metatarsal heads. Case series[16, 17] of diabetic patients with hallux ulcers report a high prevalence of hallux limitus (or reduced dorsiflexion at the first metatarsophalangeal joint), among other characteristics. These studies, however, did not provide comparison groups, and it cannot be assumed that this characteristic is more common in people with hallux ulceration. One study[18] of neuropathic patients compared the range of first metatarsophalangeal joint dorsiflexion in feet with hallux ulcers and those with ulceration elsewhere and found that first metatarsophalangeal joint dorsiflexion was reduced in the former.

The present study attempted to provide further biomechanical information on hallux ulceration in people with diabetes mellitus. In particular, we compared the biomechanical characteristics of diabetic patients with a history of neuropathic hallux ulceration with those with ulceration elsewhere on the foot. This helps minimize the important confounding effects of diabetes mellitus and the presence of peripheral neuropathy and peripheral vascular disease. Furthermore, in a subgroup of patients with unilateral hallux ulceration, the affected and unaffected feet were also compared to reduce the impact of interindividual variations. The overall objectives were to assess the range of joint movement, foot posture, foot strength, and the angle and base of gait to determine what differences exist to explain the development of foot ulcers at the hallux.

Methods

Subjects

All of the diabetic patients who had previously attended the Diabetes Centre High Risk Foot Clinic, Sydney, Australia, for treatment of a neuropathic ulcer on the plantar aspect of the hallux and whose ulcer had healed were invited to participate in the study. The control group was composed of diabetic patients with a history of healed neuropathic ulceration at sites other than the hallux. The inclusion and exclusion criteria are given in Table 1. It was a requirement that the ulcer be healed before inclusion to ensure that active ulceration would not interfere with biomechanical measurements. All of the ulcers were judged to be primarily neuropathic because they were painless and were not associated with severe ischemia. Patients whose ulcers could be attributed to acute trauma, such as nail pathology, thermal injury, or chemical injury, were not included.

Table 1. Inclusion and Exclusion Criteria for the Study and Control Groups

Inclusion Criteria
Type 1 or type 2 diabetes mellitus
Healed neuropathic hallux ulceration in the study group and healed neuropathic foot ulceration not on the hallux in the control group
Mobile enough to perform activities of daily living
Exclusion Criteria
Ulcer caused by ischemia or acute trauma, such as thermal or chemical injury
Charcot's arthropathy in the studied limb
Hallux or forefoot amputation of the studied limb
Amputation of the contralateral limb
Ischemia (impalpable pulses or an ankle-brachial index <0.6)

Feet with Charcot's arthropathy were excluded because of their severe structural deformities, as were feet with amputation of the hallux or forefoot. Sensation was assessed using a biothesiometer and a vibratory perception threshold of 30 V or more, considered to be indicative of neuropathy. If subjects were unable to walk a sufficient distance to maintain their activities of daily living, they were not included because they would have difficulty undergoing the testing procedures. Approval was obtained from the Central Sydney Area Health Service Ethics Review Committee, and all of the participants provided written informed consent.

Measurement of Ankle Joint Dorsiflexion

Ankle dorsiflexion was assessed with the patient prone and the subtalar joint approximating its neutral position (Fig. 1). Bony and soft-tissue landmarks were used according to the method outlined by Rome.[19] The leg was bisected along the lateral aspect using the fibular head and lateral malleolus as points of reference. The neutral position of the ankle joint was defined as when the foot was angled 90° to the leg, with negative values indicating the inability of the foot to reach this position. This method is commonly applied in clinical practice and has demonstrated reliability in a similar patient population.[20] Normal values have been reported to be 8.25° ± 4.13°, 0° to 16.5°, and 18.1° in various studies.[21, 22]

Measurement of Subtalar Joint Frontal Plane Range of Motion

Subtalar joint range of motion was assessed with the patient in a prone position (Fig. 2). The angles be-

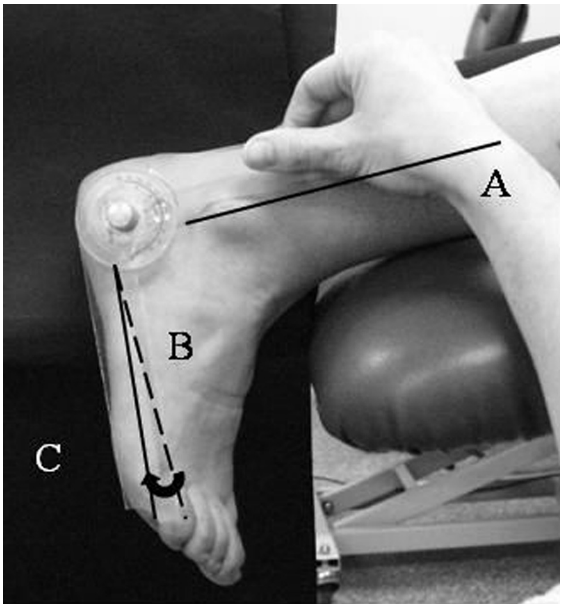

Figure 1. Measurement of ankle dorsiflexion. Line A indicates the bisection of the leg; line B, a line perpendicular to line A; and C, the plantar lateral aspect of the foot. The angle is denoted by an arrow.

tween the lines bisecting the posterior aspect of the leg and the calcaneus were measured with the foot in maximum inversion and eversion, and their sum was taken as the subtalar joint range of motion in the frontal plane. This method also has demonstrated reasonable reliability.[20] Normal range of motion determined using this method is traditionally considered to be 30°[23]; however, in a study of 121 healthy subjects, Astrom and Arvidson[24] found an average of 38°.

Measurement of First Metatarsophalangeal Joint Dorsiflexion

First metatarsophalangeal joint dorsiflexion was measured as described by Buell et al.[25] Using this method, the patient is examined in the supine position, with the subtalar joint approximating its neutral position. The angle between the longitudinal axis of the first metatarsal and the proximal phalanx was recorded three ways: 1) with the joint in its relaxed position, 2) with the patient actively dorsiflexing the hallux, and 3) with the examiner flexing the joint to its maximum range (passive) (Fig. 3). A large range of normal values is reported in the literature: 65° to 90° of dorsiflexion for healthy subjects[25, 26] and 68° to 82° for those with diabetes mellitus.[11, 27]

Measurement of the Angle and Base of Gait

Footprints were taken using the method described by Wilkinson and Menz (Fig. 4).[28] The patient's feet were dampened and coated with talcum powder immediately before walking on a strip of brown paper

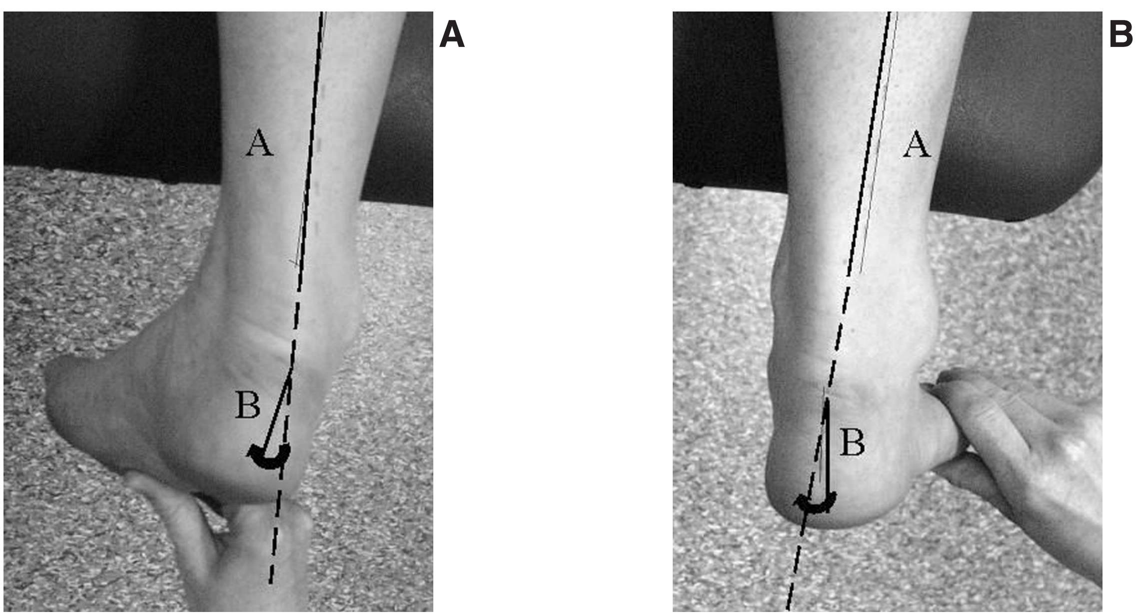

Figure 2. Measurement of subtalar joint range of motion: Line A indicates the bisection of the lower third of the leg; and line B, the bisection of the heel. The sum of the inversion (part A) and eversion (part B) values is equal to the total range. The angles are denoted by arrows.

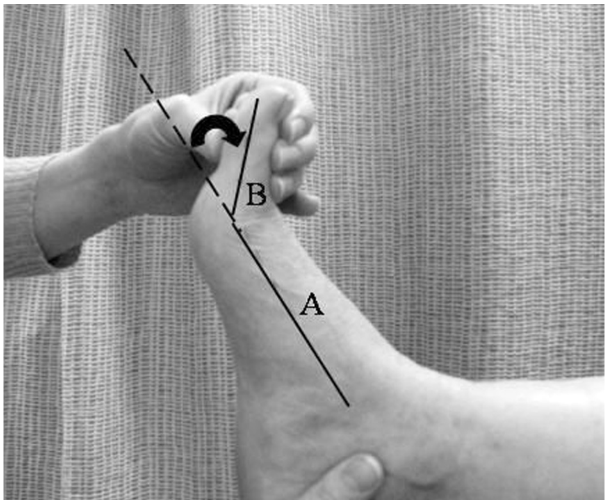

Figure 3. Measurement of passive first metatarsophalangeal joint range of dorsiflexion. Line A is the bisection of the first metatarsal; and line B, the bisection of the proximal phalanx. The angle is denoted by an arrow.

approximately 6 m long. The footprints were sprayed with artist's fixative and then laminated with adhesive plastic film. A podiatrist unaware of the ulcer location measured the angle and base of the midgait steps after receiving appropriate training. In most cases, where the quality of the footprints permitted, the measurements used in the analysis were an average of two steps.

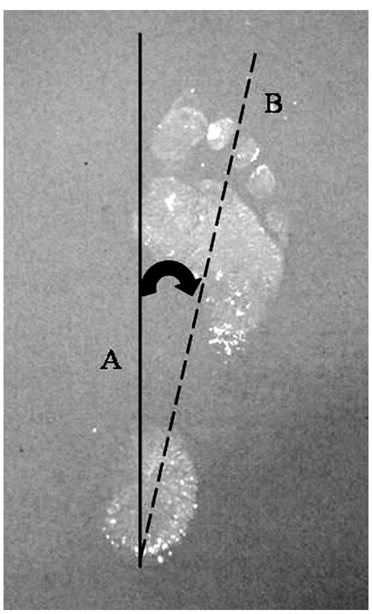

Figure 4. Measurement of the angle of gait using footprints. Line A is the line of progression of the foot; and line B, the bisection of the foot. The angle is denoted by an arrow.

Assessment of Foot Posture

Foot posture was evaluated using the Foot Posture Index, with the patient standing in a relaxed position. This is a new multidimensional and multiplanar tool used to quantify the degree of foot pronation or supination.[29] Essentially, eight commonly applied clinical indicators of foot posture are assessed, with each criterion rated by a whole number from –2 to +2, representing the extent to which the foot is either pronated or supinated. These results are then summed to give an overall score that becomes the composite Foot Posture Index. This technique has been shown to be reliable in defining foot posture type, but it is not very sensitive in detecting small changes.[30] A normal range is considered to be 2 to 7,[29] with a mean of 4.9 derived previously by Redmond et al[31] using a group of healthy subjects.

Evaluation of Muscle Strength

Manual muscle testing of the ankle dorsiflexor, plantar flexor, invertor, and evertor muscle groups was performed with the patient seated and the leg extended and supported. Strength was graded according to the Medical Research Council scale from 0 to 5, with 0 indicating an absence of movement and 5 indicating normal strength.

Muscle strength was also tested by asking each participant to stand and then rise to the ball of his or her foot. Patients performed the test on each foot with the other foot raised and then on both feet. Because our patients tend to be unstable, they were allowed to use a fixed object for balance. In this test, commonly referred to as the "single heel rise test," the function of the posterior tibial tendon is evaluated. If the posterior tibial tendon fails to invert the calcaneus, the gastrocnemius soleus complex cannot easily plantarflex the foot and lift the heel.[32, 33] The results of the patient's attempts were ranked as follows: 1 indicates heel inverted and patient able to rise fully onto the ball of the foot; 2, heel inverted and a small degree of heel lift attained; or 3, complete inability to lift the heel.

Statistical Methods

Statistical analysis was performed using the NCSS 2004 statistical software package (Jerry Hintze, Kaysville, Utah). Continuous data were assessed for normality and, if necessary, were normalized using log transformation. Continuous data are expressed as mean and SD or median and interquartile range. Biomechanical test results and footprint results were compared using analysis of variance and two-sample or paired *t*-tests, depending on the groups. Statistical significance was accepted at $P < .05$. Comparisons were made in feet with and without hallux ulcers. In addition, paired analysis was performed in the affected and unaffected feet in a subset of the hallux group whose ulcers were unilateral. When available, previously published reference values were used for comparison.

Results

Twenty-three people with a history of hallux ulceration were recruited to the study group and 14 individuals were enlisted in the control group. After the exclusion of individual feet that did not meet the inclusion criteria, 36 feet were included in the hallux ulcer study group and 24 feet were included in the control ulcer group. A subgroup of 16 patients with unilateral hallux ulceration was available for paired analysis. The clinical profiles and demographics of the participants are given in Table 2. The groups are well matched on age, duration of diabetes mellitus, and degree of neuropathy. Most of the subjects have type 2 diabetes mellitus, are obese, and have a moderately long duration of diabetes mellitus, with evidence of severe sensory loss. The preponderance of males is typical of the Diabetes Centre High Risk Foot Clinic patient population.

Hallux Ulcer Feet *versus* Control Ulcer Feet

Range of Joint Movement. Range of joint movement values for the 36 hallux ulcer feet and the 24 control ulcer feet are given in Table 3. Ankle dorsiflexion was similar between the groups, with many of the subjects unable to flex the foot to the neutral position, indicating severe ankle equinus. Ankle dorsiflexion was significantly less than the normal values previously reported but was consistent with other studies using diabetic subjects.[22, 27] The range of subtalar joint movement again was not different between hallux ulcer feet and control ulcer feet but was less than normal and similar to other reported values in patients with diabetes mellitus.[11] There was also no difference between hallux ulcer feet and control ulcer feet in first metatarsophalangeal joint dorsiflexion. In contrast, the degree of movement (66°) was within the reference range.

Table 3. Range of Motion at the Ankle, Subtalar, and First Metatarsophalangeal Joints of HUF and CUF

	HUF (n = 36)	CUF (n = 24)	*t*	*P* Value
Ankle dorsiflexion (°)	–2 ± 7	–3 ± 6	0.6	.6
Subtalar joint ROM (°)	19 ± 8	19 ± 5	0.3	.7
First MPJ dorsiflexion (°)				
Resting position	36 ± 13	36 ± 16	0.05	.96
Active range	62 ± 18	61 ± 26	0.06	.96
Passive range	66 ± 19	66 ± 27	0.1	.9
Angle of gait (°)	15 ± 7	13 ± 4	1.3	.2
Base of gait (cm)	10 ± 4	10 ± 2	0.4	.7

Abbreviations: HUF, hallux ulcer feet; CUF, control ulcer feet; ROM, range of motion; MPJ, metatarsophalangeal joint.
Note: Data are given as mean ± SD.

Angle and Base of Gait. The angle and base of gait were similar in hallux ulcer feet and control ulcer feet (Table 3); the angle of gait was considerably higher than reported normal values (8° and 8.8°)[28, 34] but similar to that found in people with diabetes mellitus (mean ± SD, 15.8° ± 7.8°).[12]

Table 2. Demographic and Clinical Characteristics of the Participants

Characteristic	Study Subjects: All (n = 23)	Study Subjects: Unilateral Cases Only (n = 16)	Control Subjects (n = 14)	Test Statistic	*P* Value
Age, mean ± SD (years)	60.5 ± 9.6	60.3 ± 9.6	58.2 ± 8.7	F = 0.3	.7
Male sex (No.)	18	13	13	$\chi^2_2 = 1.4$	.5
Diabetes duration, mean ± SD (years)	13.2 ± 7.4	16.4 ± 6.6	17.8 ± 7.3	F = 1.9	.3
Glycosylated hemoglobin, mean ± SD (%)	8.3 ± 1.7	9.1 ± 1.5	8.8 ± 2.2	F = 0.8	.4
Type 2 diabetes mellitus (No.)	21	15	12	$\chi^2_2 = 0.6$	.7
VPT, mean (IQR) (V)	50 (50–50)	50 (48–50)	50 (48–50)	$\chi^2_2 = 0.008$	.9
Height, mean ± SD (m)	1.77 ± 0.1	1.79 ± 0.09	1.76 ± 0.08	F = 0.3	.8
BMI, mean (IQR) (kg/m²)	32.2 (29.9–36.6)	31.4 (28.8–35.6)	33.6 (31.6–36.2)	$\chi^2_2 = 1.6$	.4

Abbreviations: VPT, vibratory perception threshold; IQR, interquartile range; BMI, body mass index.

Foot Posture Index. The Foot Posture Index showed a marked difference between the hallux ulcer feet and control ulcer feet, with the mean of the former group being fourfold greater, indicating that feet with hallux ulceration were more pronated than control feet (Table 4). When the individual criteria of the composite Foot Posture Index were compared in the two groups, all but one (forefoot abduction) reached statistical significance.

Muscle Strength. In functional strength testing, only 31% of the hallux ulcer feet and 66% of the control ulcer feet were able to perform the single heel rise test. This weakness of the hallux ulcer feet was not demonstrable by manual muscle testing, in which an average score of 4.5 was registered. When all of the subjects were considered together, those less able to perform the heel rise test had a higher Foot Posture Index (Fig. 5).

Affected *versus* Unaffected Feet in Patients with Previous Unilateral Hallux Ulceration

In comparing the affected and unaffected feet of the 16 subjects with unilateral hallux ulceration, the Foot Posture Index was again higher in the affected foot. This difference was less than that found comparing hallux ulcer feet and control ulcer feet, but it remained statistically significant (Fig. 6). In contrast to the comparison between hallux ulcer feet and control ulcer feet, there was a significant difference in the active range of movement at the first metatarsophalangeal joint comparing unilateral hallux ulcer feet and unilateral control ulcer feet (P = .03). Passive range of motion of this joint also approached statistical significance. The other parameters were similar in affected and unaffected feet (Table 5).

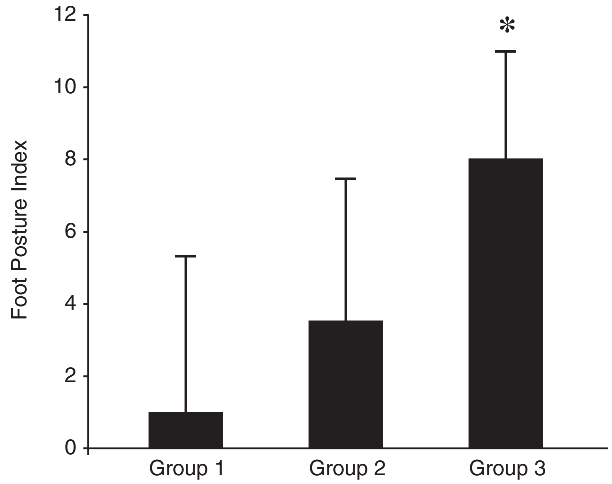

Figure 5. The Foot Posture Index grouped by ability to perform the single heel rise test. Group 1 was able to perform the test, group 2 was partially able to perform the test, and group 3 was unable to perform the test. The asterisk indicates a *post hoc* test different from group 1. Kruskal-Wallis analysis of variance $z = 19.0$; $P < .001$.

Discussion

The results of this study provide some new insights into the relationship between foot structure and hallux ulceration. The finding that hallux ulceration is associated with a more pronated foot type than ulceration elsewhere on the foot of diabetic patients has not been documented elsewhere, to our knowledge. Our conclusion was reached by studying diabetic patients with a similar degree of neuropathy and peripheral vascular disease, and the difference in foot posture is present even when interindividual varia-

Table 4. Composite and Individual Foot Posture Index Scores of HUF and CUF

	HUF (n = 36)	CUF (n = 24)	Test Statistic	P Value
Malleolar position	1 (0 to 2)	0 (0 to 0)	$z = 4.17$	.000031
Calcaneal frontal plane	1 (0 to 1)	0 (0 to 0)	$z = 3.76$	.00017
Talar head palpation	1 (1 to 2)	1 (0 to 1)	$z = 3.07$	.0021
Lateral border congruency	0 (0 to 1)	0 (0 to 0)	$z = 2.84$	.0045
Talonavicular bulge	1 (0 to 2)	0 (0 to 0)	$z = 2.79$	.0053
Helbing’s sign (Achilles tendon curvature)	0 (0 to 1.25)	0 (0 to 0)	$z = 2.26$	.024
Arch height	1 (0 to 2)	0 (–1 to 1)	$z = 2.17$	.030
Forefoot abduction/adduction	1 (0 to 1)	0 (0 to 1)	$z = 1.57$	.11
Composite Foot Posture Index, mean ± SD	6.4 ± 5.3	1.6 ± 3.5	$t = 3.7$	.0005

Abbreviations: HUF, hallux ulcer feet; CUF, control ulcer feet.
Note: Data are given as mean (range) except where indicated otherwise.

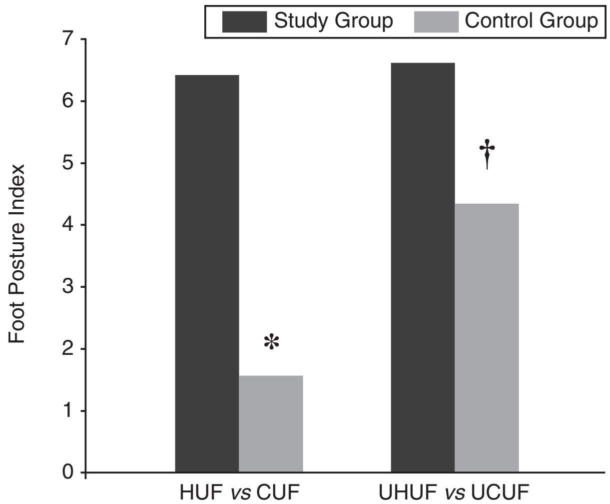

Figure 6. The Foot Posture Index in hallux ulcer feet (HUF) *versus* control ulcer feet (CUF) and in unilateral HUF (UHUF) *versus* unilateral CUF (UCUF). The asterisk indicates $t = 3.7$; $P = .0005$. The dagger indicates $t = 3.3$; $P = .005$.

tions are minimized by comparing affected and unaffected feet of the same individuals. In the absence of a universally accepted gold standard for the measurement of foot pronation, the Foot Posture Index was used in this study because it has the advantage of being composed of multiplanar criteria. We believe that this renders it more comprehensive than measures that depend on a single measurement, such as arch height or resting calcaneal position. Although it is not yet widely used clinically or in research, initial validation studies have demonstrated good correlation with Rose's Valgus Index.[31] Palpation of the talonavicular joint (one of the eight Foot Posture Index criteria) also correlates well with radiographic measurements of the talonavicular coverage angle, an index of pronation.[30] In fact, seven of eight individual Foot Posture Index criteria confirmed the relatively pronated state of the affected feet.

The use of closely matched diabetic controls in the present study leads us to believe that the demonstrated differences in foot type between subjects with and without hallux ulceration is more the result of intrinsic differences in foot structure than of the diabetic state. This is supported by the finding that differences between the two feet of the same individual regarding foot type are more subtle than those between individuals. It is interesting that the mean Foot Posture Index of 1.6 in patients with ulcers on another part of the foot is quite low compared with the mean of 4.9 reported in a group of 91 healthy individuals.[31] This suggests that these people with neuropathy were able to avoid hallux ulceration (but not ulceration elsewhere) because their feet were relatively supinated.

Apart from intrinsic differences in foot posture due to genetic and developmental factors, muscle imbalance and weakness can contribute to differences in foot posture. For example, tibialis posterior dysfunction is a common cause of adult-acquired flatfoot, and weak ankle plantar flexors have also been associated with excessive pronation.[35, 36] Note the strong relationship between the Foot Posture Index and the ability to perform the single heel rise test, a functional test of these muscles. Our findings are observational and do not allow a causal relationship to be established. It is equally possible that muscle weakness and pronation are independent phenomena and that each can, in its own right, increase the risk of hallux ulceration.

There was no reduction in first metatarsophalangeal joint dorsiflexion in the hallux ulcer feet when all of the individuals were considered. However, when the affected and unaffected feet of the same individuals were compared, there was a reduction in dorsiflexion of approximately 10% in the affected feet. Our search of the literature revealed only one controlled study comparing first metatarsophalangeal joint dorsiflexion in neuropathic subjects (approximately one-quarter with diabetes mellitus, most with leprosy) with hallux ulceration and those with ulceration elsewhere on the foot. This study[18] showed a 40% reduction in range of motion at the first metatarsophalangeal joint of patients with hallux ulcer. Thus our results support this finding, although the reduction is smaller and required the elimination of interin-

Table 5. Range of Motion, Angle of Gait, and Foot Posture Index in UHUF and UCUF

	UHUF (n = 16)	UCUF (n = 16)	*t*	*P* Value
Ankle dorsiflexion (°)	–2 ± 6	–3 ± 3	0.3	.7
Subtalar joint ROM (°)	18 ± 6	19 ± 6	0.4	.7
First MPJ dorsiflexion (°)				
Resting position	33 ± 12	34 ± 18	0.02	.9
Active range	57 ± 16	65 ± 18	2.5	.03
Passive range	63 ± 16	71 ± 18	2.1	.06
Angle of gait (°)	14 ± 5	13 ± 6	0.9	.4
Composite Foot Posture Index	6.6 ± 4.0	4.4 ± 3.6	3.3	.005

Abbreviations: UHUF, unilateral hallux ulcer feet; UCUF, unilateral control ulcer feet; ROM, range of motion; MPJ, metatarsophalangeal joint.

Note: Data are given as mean ± SD.

dividual differences for it to be revealed. In other studies[16, 17] in which reduced first metatarsophalangeal joint dorsiflexion in hallux ulceration was implicated, no controlled neuropathic subjects were examined. The present study is the first to specifically examine this phenomenon in diabetic subjects using relevant controls.

The mechanism by which reduced first metatarsophalangeal joint dorsiflexion contributes to hallux ulceration may be explained by the compensatory gait changes. Inadequate dorsiflexion prevents tightening of the plantar fascia, without which the foot is not stabilized appropriately for normal propulsion.[37] Potential compensations include abduction of the foot for toe-off, collapse of the medial longitudinal arch, and hyperextension of the interphalangeal joint, which could increase trauma to the plantar medial aspect.[38-40]

The same compensatory changes may also be true of functional restriction at the first metatarsophalangeal joint during gait, which can be the result of abnormal pronation. Indeed, Morag and Cavanagh[10] showed that reduced functional range of first metatarsophalangeal joint dorsiflexion can increase pressure at the hallux in healthy subjects.

Various surgical procedures, including Achilles tendon lengthening, interphalangeal joint arthroplasty, and metatarsophalangeal joint arthroplasty, have been shown to be useful in reducing pressure on the forefoot and in the healing of hallux ulcers.[41-44] The study by Armstrong et al[41] examined specifically the problem of hallux ulceration. They reported efficacy of the Keller procedure, which included removal of the first metatarsophalangeal joint. This is likely to be the result of overcoming the limited range of motion at the first metatarsophalangeal joint. Invariably, some patients with hallux ulcer will require surgical intervention to heal their hallux ulcers and to prevent recurrence. How these procedures alter the biomechanical abnormalities of feet with hallux ulceration is an important question that needs to be studied systematically.

Our results should be interpreted with consideration to some limitations of the study. The inclusion of only subjects with healed ulcers may have created a bias in selecting patients with less severe abnormalities. Nevertheless, our clinical experience is that failure to heal and amputation are often due to other factors, such as patient compliance and time to referral, rather than to intrinsic foot abnormalities alone. In any case, the exclusion of more severe cases would presumably only reduce the magnitude of the changes demonstrated. Most data were compiled by one of the authors (V.L.N.), who was aware of the clinical history of the patients. However, in a multidisciplinary foot clinic such as ours, it was not easy to nominate anyone completely unfamiliar with the patients. Despite our endeavor to provide more evidence-based information to support the clinical management of diabetic foot disease, many of the measurements used remain semiquantitative.

Conclusion

Despite the limitations of this study, we believe that our results contribute to the current understanding of foot ulcer pathogenesis, in particular, the role of foot posture. Further investigation of the positive findings using improved methods would strengthen the evidence for our conclusions. The results also highlight the need for objective evaluation regarding the efficacy of footwear and orthoses in reversing the specific biomechanical abnormalities demonstrated.

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References

1. Pecoraro RE, Reiber GE, Burgess EM: Pathways to diabetic limb amputation: basis for prevention. Diabetes Care **13:** 513, 1990.
2. Reiber GE: "Epidemiology of Foot Ulcers and Amputations in the Diabetic Foot," in *The Diabetic Foot*, 6th Ed, ed by JH Bowker and MA Pfeifer, p 13, CV Mosby, St Louis, 2001.
3. Lavery LA, Armstrong DG, Quebedeaux TL, et al: Practical criteria for screening patients at high risk for diabetic foot ulceration. Arch Intern Med **158:** 157, 1998.
4. Cavanagh PR, Ulbrecht JS, Caputo GM: Biomechanical aspects of diabetic foot disease: aetiology, treatment, and prevention. Diabet Med **13:** S17, 1996.
5. Armstrong DG, Lavery LA, Harkless LB: Validation of a diabetic wound classification system: the contribution of depth, infection, and ischaemia to risk of amputation. Diabetes Care **21:** 855, 1998.
6. Lavery LA, Lavery DC, Quebedeax-Farnham TL: Increased foot pressures after great toe amputation in diabetes. Diabetes Care **18:** 1460, 1995.
7. Quebedeaux TL, Lavery DC, Lavery LA: The development of foot deformities and ulcers after great toe amputation in diabetes. Diabetes Care **19:** 165, 1996.
8. Murdoch DP, Armstrong DG, Dacus JB, et al: The natural history of great toe amputations. J Foot Ankle Surg **36:** 204, 1997.
9. Greteman B, Dale S: Digital amputations in neuropathic feet. JAPMA **80:** 120, 1990.
10. Morag E, Cavanagh PR: Structural and functional pre-

dictors of regional peak pressures under the foot during walking. J Biomech **32:** 359, 1999.
11. Payne C, Turner D, Miller K: Determinants of plantar pressures in the diabetic foot. J Diabetes Complications **16:** 277, 2002.
12. Mueller MJ, Hastings M, Commean PK, et al: Forefoot structural predictors of plantar pressures during walking in people with diabetes and peripheral neuropathy. J Biomech **36:** 1009, 2003.
13. Ledoux WR, Hillstrom HJ: The distributed plantar vertical force of neutrally aligned and pes planus feet. Gait Posture **15:** 1, 2002.
14. Stacpoole-Shea S, Shea G, Lavery L: An examination of plantar pressure measurements to identify the location of diabetic foot ulceration. J Foot Ankle Surg **38:** 109, 1999.
15. Bevans JS: Biomechanics and plantar ulcers in diabetes. The Foot **2:** 166, 1992.
16. Boffeli TG, Bean JK, Natwick JR: Biomechanical abnormalities and ulcers of the great toe in patients with diabetes. J Foot Ankle Surg **41:** 359, 2002.
17. Dannels E: Neuropathic foot ulcer prevention in diabetic American Indians with hallux limitus. JAPMA **79:** 447, 1989.
18. Birke J, Cornwall MA, Jackson M: Relationship between hallux limitus and ulceration of the great toe. Sports Phys Ther J Orthop **10:** 172, 1988.
19. Rome K: Ankle joint dorsiflexion measurement studies: a review of the literature. JAPMA **86:** 205, 1996.
20. Diamond JE, Mueller MJ, Delitto A, et al: Reliability of a diabetic foot evaluation. Phys Ther **69:** 797, 1989.
21. Baggett BD, Young G: Ankle dorsiflexion: establishment of a normal range. JAPMA **83:** 542, 1993.
22. Moseley AM, Crosbie J, Adams R: Normative data for the passive ankle plantarflexion-dorsiflexion flexibility. Clin Biomech **16:** 514, 2001.
23. Root ML, Orien WP, Weed JH, et al: *Biomechanical Examination of the Foot*, Vol 1, Clinical Biomechanics Corp, Los Angeles, 1971.
24. Astrom M, Arvidson T: Alignment and joint motion in the normal foot. J Orthop Sports Phys Ther **22:** 216, 1995.
25. Buell T, Green DR, Risser J: Measurement of the first metatarsophalangeal joint range of motion. JAPMA **78:** 439, 1988.
26. Mann R: The function of toes in walking, jogging, and running. Clin Orthop Relat Res **142:** 24, 1979.
27. Bevans JS, Bowker P: Foot structure and function: aetiological risk factors for callus formation in diabetic and non-diabetic subjects. The Foot **9:** 120, 1999.
28. Wilkinson MJ, Menz HB: Measurement of gait parameters from footprints: a reliability study. The Foot **7:** 19, 1997.
29. Evans AM, Copper AW, Scharfbillig RW, et al: Reliability of the Foot Posture Index and traditional measures of foot position. JAPMA **93:** 203, 2003.
30. Scharfbillig R, Evans AM, Copper AW, et al: Criterion validation of four criteria of the Foot Posture Index. JAPMA **94:** 31, 2004.
31. Redmond A, Burns J, Ouvrier R, et al: An initial appraisal of the validity of a criterion based, observational clinical rating system for foot posture [abstract]. J Orthop Sports Physiother **31:** 160, 2001.
32. Johnson KA: Tibialis posterior tendon rupture. Clin Orthop Relat Res **177:** 140, 1983.
33. Johnson KA, Strom DE: Tibialis posterior tendon dysfunction. Clin Orthop Relat Res **239:** 196, 1989.
34. Messier SP, Davies AB, Moore DT, et al: Severe obesity: effects on foot mechanics during walking. Foot Ankle Int **15:** 29, 1994.
35. Kohls-Gatzoulis J, Dishan Singh JA: Tibialis posterior dysfunction as a cause of flatfeet in elderly patients. The Foot **14:** 207, 2004.
36. Snook AG: The relationship between excessive pronation as measured by navicular drop and isokinetic strength of the ankle musculature. Foot Ankle Int **22:** 234, 2001.
37. Hicks JH: The mechanics of the foot: part 2. The plantar aponeurosis and the arch. J Anat **88:** 25, 1954.
38. Payne CB, Dananberg HJ: Sagittal plane facilitation of the foot. Australas J Podiatr Med **31:** 7, 1997.
39. Dananberg HJ: Sagittal plane biomechanics. JAPMA **90:** 47, 2000.
40. Shrader JA, Lohmann Siegel K: Nonoperative management of functional hallux limitus in a patient with rheumatoid arthritis. Phys Ther **83:** 831, 2003.
41. Armstrong DG, Lavery LA, Vazquez JR, et al: Clinical efficacy of the first metatarsophalangeal joint arthroplasty as a curative procedure for hallux interphalangeal joint wounds in patients with diabetes. Diabetes Care **26:** 3248, 2003.
42. Rosenblum BI, Giurini JM, Habershaw GM: Preventing loss of the great toe with hallux interphalangeal joint arthroplasty. J Foot Ankle Surg **33:** 557, 1994.
43. Mueller MJ, Sinacore DR, Hastings MK, et al: Effect of Achilles tendon lengthening on neuropathic plantar ulcers: a randomized clinical trial. J Bone Joint Surg Am **85:** 1436, 2003.
44. Armstrong DG, Stacpoole-Shea S, Nguyen H, et al: Lengthening of the Achilles tendon in diabetic patients who are at high risk for ulceration of the foot. J Bone Joint Surg Am **81:** 535, 1999.