

See editorial on pages 496–498 in this issue.

Development of grading scales of pedal sensory loss using Mokken scale analysis on the Rotterdam Diabetic Foot Study Test Battery data

Willem D. Rinkel MD^{1,2,3}  | M. Hosein Aziz MD¹ | Johan W. Van Neck PhD¹ |
 Manuel Castro Cabezas MD, PhD⁴ | L. Andries van der Ark PhD⁵ |
 J. Henk Coert MD, PhD^{2,3}

¹Department of Plastic, Reconstructive, and Hand Surgery, Erasmus University Medical Center, Rotterdam, The Netherlands

²Department of Plastic, Reconstructive, and Hand Surgery, Franciscus Gasthuis & Vlietland, Rotterdam, The Netherlands

³Department of Plastic, Reconstructive and Hand Surgery, University Medical Center Utrecht, Utrecht, The Netherlands

⁴Department of Internal Medicine/Centre for Diabetes, Endocrinology and Vascular Medicine, Franciscus Gasthuis & Vlietland, Rotterdam, The Netherlands

⁵Faculty of Social and Behavioural Sciences, Research Institute of Child Development and Education, University of Amsterdam, Amsterdam, The Netherlands

Correspondence

Willem D. Rinkel, Department of Plastic, Reconstructive, and Hand Surgery, University Medical Center Utrecht, Utrecht, The Netherlands.

Email: w.d.rinkel@umcutrecht.nl

Abstract

Introduction: Loss of sensation due to diabetes-related neuropathy often leads to diabetic foot ulceration. Several test instruments are used to assess sensation, such as static and moving 2-point discrimination (S2PD, M2PD), monofilaments, and tuning forks.

Methods: Mokken scale analysis was applied to the Rotterdam Diabetic Foot Study data to select hierarchies of tests to construct measurement scales.

Results: We developed 39-item and 31-item scales to measure loss of sensation for research purposes and a 13-item scale for clinical practice. All instruments were strongly scalable and reliable. The 39 items can be classified into 5 hierarchically ordered core clusters: S2PD, M2PD, vibration sense, monofilaments, and prior ulcer or amputation.

Discussion: Guided by the presented scales, clinicians may better classify the grade of sensory loss in diabetic patients' feet. Thus, a more personalized approach concerning individual recommendations, intervention strategies, and patient information may be applied.

KEYWORDS

diabetic sensorimotor polyneuropathy, early detection, grading loss of sensation, medical decisionmaking, neuropathy, psychometrics, risk stratification, scale development

Abbreviations: ApoB, apolipoprotein B; DSP, diabetic sensorimotor polyneuropathy; HbA1c, glycated hemoglobin; HDL, high-density lipoprotein; IIO, invariant item ordering; IQR, interquartile range; IRT, item-response theory; LDL, low-density lipoprotein; M2PD, 2-point moving discrimination; MAP, mean arterial pressure; MDRD, Modification of Diet in Renal Disease; MNSI, Michigan Neuropathy Screening Instrument; MSA, Mokken scale analysis; nIRT, nonparametric item-response theory; PIM, person-item map; RDF, Rotterdam Diabetic Foot (study); S1PD, 1-point static discrimination; S2PD, 2-point static discrimination; SWM, Semmes-Weinstein monofilament; TG, triglycerides.

Parts of this work were presented at the annual meeting of the American Society for Peripheral Nerve on January 2016, Scottsdale, AZ, and at the Dutch Society for Plastic and Reconstructive Surgery on May 2016, Eindhoven, The Netherlands.

Supporting information citations in text: S1, S2, and S3.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2019 The Authors. *Muscle & Nerve* published by Wiley Periodicals, Inc.

1 | INTRODUCTION

Diabetic sensorimotor polyneuropathy (DSP) occurs in about 50% of diabetic patients, leading to decreased quality of life and increased mortality.¹⁻³ Sensory loss due to DSP is one of the most important risk factors for diabetic foot ulceration and amputation.⁴ DSP is frequently accompanied by positive sensory phenomena. Yet, it is the simultaneous process of decreased sensation that places the feet of diabetic patients at risk.⁵ Because not every patient with positive sensory symptoms has sensory loss, it is useful to focus on objective measures such as foot sensation to assess large-fiber nerve function.⁶

Loss of sensation can be assessed with several instruments.^{7,8} Current guidelines recommend an annual screening with a 10-g Semmes-Weinstein monofilament (SWM) or a tuning fork.⁹⁻¹¹ These instruments test different somatosensory corpuscles and nerve fibers, functions of which are progressively lost during the natural course of DSP.¹²⁻¹⁴ However, a cutaneous threshold of ≥ 10 g is an indicator of large-fiber demyelination, which becomes informative in a late stage of neuropathy and reflects a high risk for foot ulceration and lower extremity amputation.¹⁵ Other measurements, such as 2-point discrimination, have proven to be early indicators of nerve pathology and may be able to detect earlier alterations in foot sensation.^{6,16,17}

Few available studies have described the sequence in which sensory tests become abnormal in the natural course of diabetes-related neuropathy.^{6,18,19} To more precisely categorize patients with diabetes according to their degree of sensory loss, we applied the Mokken scale analysis (MSA), which is related to nonparametric forms of item-response theory (IRT), to the tests used in the Rotterdam Diabetic Foot (RDF) Study.⁶ MSA is a scaling method increasingly used in health sciences.²⁰⁻²³ IRT assumes that a latent (not directly observable) trait, denoted as θ (theta), drives the patients' scores on the items. Typically, θ is used as a proxy for the construct being measured (ie, foot sensation, hence foot sensation determines the item scores). Because θ is latent, a patient's score on θ must be estimated from the observable item scores.^{6,24} MSA is a flexible scaling method, in contrast to other IRT models such as Rasch analysis, so it fits data relatively well and includes a fair amount of items that can be used for ordinal measurement. In the present analysis, we used questionnaire data and the results of sensory tests of the feet as items (RDF Study Test Battery).

We investigated whether the tests of the RDF Study Test Battery were unidimensional, scalable, and reliable in assessing sensation in the feet. Information on the degree of sensory loss may help clinicians to assess the risk of lower extremity complications, resulting in more personalized recommendations regarding intervention strategies and patient information.

2 | METHODS

2.1 | Study design and subjects

Between January 2014 and June 2015, patients were evaluated in the outpatient Diabetes Clinic of the Franciscus Gasthuis in Rotterdam,

The Netherlands, as part of the RDF Study—a prospective cohort study that investigates the deterioration of sensation in diabetic patients' feet over time. The RDF Study design and methods are described in more detail in previous studies.^{6,25} Inclusion criteria included patients diagnosed with diabetes mellitus (treated by oral blood glucose-lowering drugs and/or insulin), who were ≥ 18 years old, spoke Dutch or English, and had no significant cognitive impairment. Exclusion criteria were assessed at the interview and with a screening questionnaire and included a positive history of active radicular syndrome or a neurological disease that interfered with sensation in the feet. Demographic data were obtained from the patients' files. All subjects provided written informed consent. The institutional review board and the medical ethics committee of Erasmus MC University Center, Rotterdam, The Netherlands, approved the study (MEC-2009-148).

2.2 | Comparison with healthy controls without known neuropathy

A total of 196 healthy volunteers were tested with the same measurement instruments and the same protocol as the RDF Study population as part of a separate study to obtain normative test values.²⁶ Volunteers were recruited from hospital and university personnel and relatives and friends of patients visiting the outpatient clinic. Patients were included in the study if they were ≥ 18 years of age, had no significant cognitive impairment, spoke Dutch or English, and provided signed informed consent. Exclusion criteria were a positive history of active radicular syndrome, a neurological disease that interfered with sensation in the feet, diabetes mellitus, thyroid malfunction, alcohol abuse, human immunodeficiency virus, or chemotherapy—all these were established at the interview using a screening questionnaire. Data sets were combined to compare patients with healthy controls.

2.3 | Measurement instrument

2.3.1 | Rotterdam Diabetic Foot Study Test Battery

Patients and volunteers were screened using monofilaments, static and moving 2-point discrimination tests, a tuning fork, cold sensation tests, the Michigan Neuropathy Screening Instrument (MNSI), and the Romberg test. Information on prior ulceration and amputation, as indicators of severe sensory loss, was retrieved from the patient's file and interview. Cutaneous threshold (1-point static discrimination, S1PD) was tested on 5 locations of each foot using SWMs (Baseline; Tactile Fabrication Enterprises, White Plains, NY, USA) ranging from 0.008 to 300 g. The test locations were chosen in concordance with the nerve distribution in the foot (see Figure S1 online). Areas with excessive callus formation were avoided. Innervation density (determined by static and moving 2-point discrimination tests: S2PD and M2PD) was assessed on the same test locations using a Disk-Criminator (US Neurologicals LLC, Poughkeepsie, NY, USA). M2PD was not assessed at the fifth toe because the area is too small to conduct the test. A Rydel-Seiffer tuning fork (Martin, Tuttlingen, Germany) tested the vibration threshold on the

medial malleolus and dorsal interphalangeal joint of the hallux. Both feet were examined. Neuropathy symptoms were assessed using the MNSI questionnaire, which was administered before the physical examination.

Using the Tinel sign, we scored localized nerve compression as positive when tingling and electrical shocks were elicited after tapping the tibial nerve at the left and right tarsal tunnel. To test cold perception, a cold piece of metal was bilaterally applied to the skin of the foot arc. Proprioception was tested using the Romberg test.

2.4 | Data analysis

A cross-sectional analysis of the RDF Study baseline data was carried out for the MSA. Results from the RDF Study Test Battery (both tests of sensation and questionnaire data) were dichotomized because MSA requires that all items have the same number of categories. Individual sensory test items were comprised of both a sensory test and the test location (eg, S1PD at the hallux is labeled as S1PD I, and S2PD at the medial heel as S2PD II). Based on previously published normative values, the threshold for S2PD and M2PD was set at 8 mm and at 10 g for S1PD.²⁶ Vibration threshold was compared with age-related reference values.²⁷ Positive symptoms (eg, tingling and burning sensations) and negative symptoms (eg, numbness) were retrieved from the MNSI questionnaire, resulting in two items. When scoring at or below the threshold (ie, “could feel the stimulus”), 0 was noted. A score of 1 was noted when a patient scored above the threshold, meaning aberrant (ie, “could not feel the stimulus”). In total, 42 individual RDF Study Test Battery items were identified per subject. Second and third annual follow-up data are presented and compared with baseline data as a measure of the statistical significance of the change scores.

2.5 | Mokken scale analysis

Refer to the supporting information available online for Mokken scale analysis.^{28–38}

2.6 | Person-item map

The ordering of the items along the latent trait (θ) was graphically displayed using a person-item map (PIM). The PIM shows the relationship between the estimated item location parameters and the estimated latent trait (ie, foot sensation), together with a histogram of the estimated latent trait values.³⁹ The map provides useful graphical information on the ordering of items and the relationship between items and persons.

2.7 | Statistics

MSA was conducted using the R package Mokken (R Foundation for Statistical Computing).^{40,41} The PIM was constructed using the R package eRm.⁵⁰ Other statistical analyses were carried out using IBM SPSS Statistics version 22.0 (IBM, Armonk, New York, USA). Missing item data were replaced by imputed data using the procedure of expectation maximization, using 25 iterations. The Shapiro–Wilk test was used to assess normality. Because the majority of the variables

significantly deviated from a normal distribution, we continued our analyses with nonparametric tests. Correlations between grading scale scores and demographic characteristics of the control population were investigated using Spearman coefficients. Using the Mann–Whitney U test, we compared differences between total item scores of RDF Study participants and controls without neuropathy as well as differences in grading scale scores between genders. Differences in grading scale scores of subjects with a second and third follow-up were assessed using the Friedman test. Spearman coefficients were used to determine the direction and magnitude of the correlations or differences between these change scores (as a measure of responsiveness), with the null hypothesis that no differences exist in foot sensation during follow-up. $P < .05$ (two-sided) was considered statistically significant.

3 | RESULTS

3.1 | General characteristics

A total of 416 diabetic patients with varying degrees of symptoms and loss of sensation were included in the RDF Study. Table S1 (online) shows the general characteristics of the patients. Fifty-two patients had a prior ulcer, and thirteen patients had a history of lower extremity amputation.

3.2 | Mokken scale analysis

Under the monotone homogeneity model, the automated item-selection procedure selected 39 of the original 42 items (Table S2 online). The items “Tinel sign left” and “Right” and “MNSI-positive symptoms” were not selected, so the 40-point scale ranges from 0 (no aberrant tests) to 39 (all tests aberrant). Scalability coefficient (H_i) values ranged from 0.354 to 0.713 (Table S2 online, third column), with a coefficient of scalability of $H = 0.538$, which indicates a strong scale—except for the item “Amputation left,” for which $H_i > 0.8$. The Molenaar-Sijtsma statistic, $\rho = 0.964$, suggested that the 39-item scale (RDF-39) is highly reliable. Of the 39 items, no items showed a violation of monotonicity. The most frequent aberrant items (eg, on S2PD and M2PD) represent early stages of sensory loss (Table S2 online, second column). Sensory functions were lost symmetrically, with items representing more distal test sites (eg, vibration sense at the interphalangeal joint) becoming aberrant before the proximal ones (eg, vibration sense at the medial malleolus).

Under the double monotonicity model, the manifest invariant item-ordering procedure selected 8 items violating IIO. The remaining scale consisted of 31 items (RDF-31) and had an H^T coefficient of 0.581. H_i values ranged from 0.431 to 0.836 and featured an $H = 0.550$, which indicates a strong scale. The reliability statistic (ρ) was 0.958.

3.3 | Person-item map

A PIM showed that the 39 items of the RDF-39 could be classified into five core clusters (Figure S2 online). The S2PD cluster contained

the items that were first becoming aberrant during the natural history of sensory loss, followed by a cluster of all M2PD items, vibration sense items, S1PD items, and items on prior ulceration/lower extremity amputation.

3.4 | Clinically applicable screening scale

Table S2 (online, sixth column) shows the item selection that we used to construct a clinically applicable screening scale, based on the 31-item scale. This 13-item scale (RDF-13) examines both extremities; items feature scalability coefficients ranging from 0.404 to 0.736 with $H = 0.551$, which indicates a strong scale. The reliability coefficient suggests that the scale is also reliable. Strong positive correlations have been found between the 39-item scale and the 31-item scale, $r_s = 0.993$, $P < .001$, and 31-item scale and 13-item scale, $r_s = 0.966$, $P < .001$. The item-response functions for the 13-item scale were plotted (Figure 1), showing their different discriminatory values along the sum score. As the latent trait increases (indicative of more severe sensory loss), so does the chance of obtaining an aberrant item test result. A clinically applicable scoring sheet for the respective scales is shown in Table S3 (online).

3.5 | Comparison to healthy controls

A total of 196 healthy volunteers, with a median age of 50.5 (interquartile range [IQR], 36.5–65.7) years, served as the control group—66 men (median age, 50.6 years; IQR, 37.7–64.1 years) and 130 women (median age, 50.0 years; IQR, 33.3–66.9 years).²⁶ The median height for this group was 172.0 (IQR, 166.3–178.8) cm and the median weight

72.0 (IQR, 63.0–82.0) kg. Diabetic subjects were significantly older and heavier than controls ($P < .0005$; Table S1 online).

Figure 2 shows the 39-item sum-score distribution of diabetic RDF Study participants compared with the controls. Median total RDF-39 scores differed significantly between individuals in the control group (5.5; IQR, 3.0–10.8) and RDF Study subjects with diabetes (17; IQR, 9.0–22.0) ($P < .0001$).

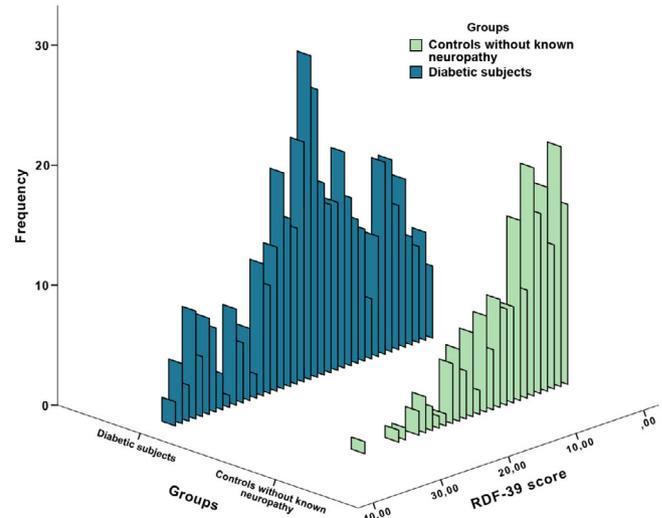


FIGURE 2 Sum-score distribution of the 39-item scale in diabetic patients and controls without known neuropathy [Color figure can be viewed at wileyonlinelibrary.com]

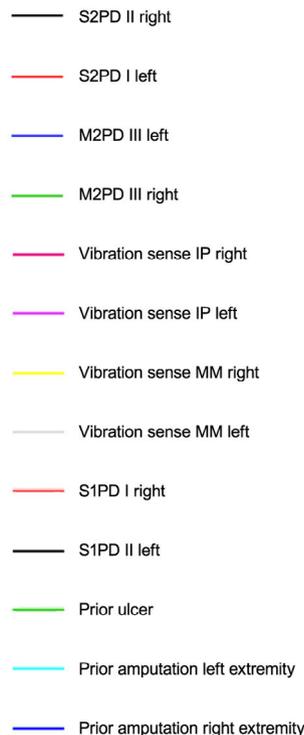
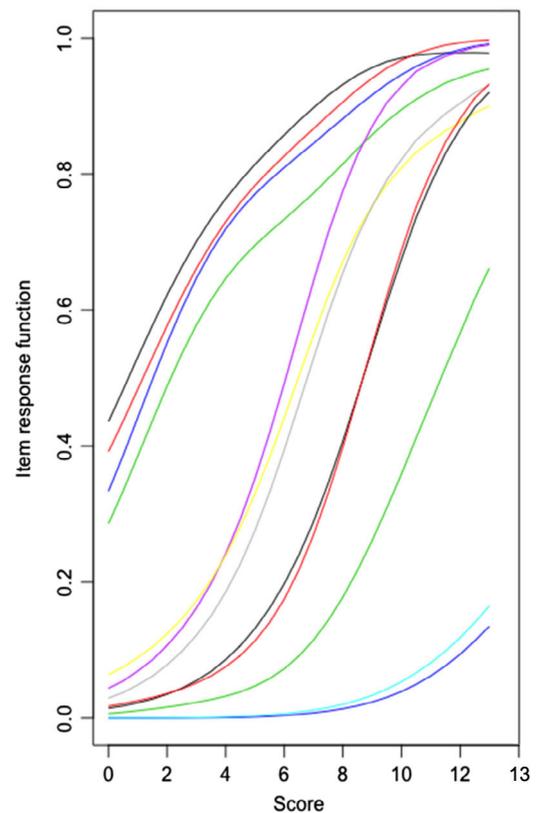


FIGURE 1 Item-characteristic curve of the 13-item scale. The ICC curves of items "Vibration sense IP left" and "Right" are plotted on top of each other. I, plantar hallux; II, medial heel; IP, interphalangeal joint; MM, medial malleolus [Color figure can be viewed at wileyonlinelibrary.com]



Because diabetes-related lower extremity complications (ie, neuropathy symptoms, sensory loss, ulceration, and amputations) are the main drivers of RDF-39 scores in diabetic subjects, correlations between RDF-39 scores and demographic variables, such as age, height, and weight, were only explored in the control population. Significant positive correlations were found between RDF-39 scores and age ($r_s = 0.405$, $P < .0005$) and RDF-39 scores and weight ($r_s = 0.212$, $P = .003$). A nonsignificant positive trend was observed between RDF-39 scores and height, $r_s = 0.135$, $p = 0.059$. Nonsignificant differences in median RDF-39 scores (IQR) were found between males (6.0; IQR, 3.0-12.5) and females (5.0; IQR, 2.8-10.0) ($P = .563$).

3.6 | Responsiveness of RDF-39

We conducted a Friedman test to determine whether there were differences in within-subjects' RDF-39 scores, which were collected during follow-up of the RDF study ($n = 135$). RDF-39 scores at baseline (median, 17; IQR, 17-22), at the 1-year follow-up (median, 16; IQR, 16-24), and at 2-year follow-up (median, 18; IQR, 18-22) did not differ significantly ($\chi^2(2) = 1.536$, $P = .464$). There was a strong positive correlation between baseline and first follow-up RDF-39 scores ($r_s = 0.698$, $P < .0005$) and between first and second follow-up scores ($r_s = 0.697$, $P < .0005$).

4 | DISCUSSION

This quantitative assessment of the categorical loss of pedal sensation of patients with diabetes has shown that the ability to sense S2PD, M2PD, vibration, and S1PD disappears in this order. This study has emphasized the added value of testing static and moving 2-point discrimination and highlights the importance of test locations in the screening of diabetic patients. Furthermore, the instruments (RDF-39, -31, and -13) captured the functional loss that is dictated by the pathophysiology of neuropathy.^{16,18,19}

At present, no data are available on how a tuning fork, monofilament testing, and test locations compare or how these should be interpreted.¹¹ By taking the site of screening into account, we observed that the first dorsal web and the lateral foot are the last of all sensibility tests and locations to become the least sensitive to the 10-g monofilament. This may have predictive value for future lower extremity complications because it suggests substantial deafferentation. Originally, the monofilament was studied as a prognostic indicator of ulceration and amputation.^{42,43} Nowadays, the validity of the monofilament examination to identify the presence of DSP is generally accepted.^{44,45} Because the onset of sensory loss is insidious, its diagnosis may be difficult. Several scoring systems for signs and symptoms of DSP have been developed, but they can be complex and time-consuming.⁴⁶ Electrodiagnostic techniques do not assess all nerve fibers undergoing changes in diabetes and may be technically challenging on the plantar surface of the foot.^{47,48} It has been recommended that the diagnosis of DSP requires a test battery, with high sensitivity, that can detect early or mild forms in low-risk populations.⁴⁹ Furthermore, it is important for population studies to possess screening tools that are reproducible, sensitive, and fast to carry out. The simple-to-

use instruments used in the presented scales fulfill these criteria and are already being applied in clinical practice. These scales can quickly and reliably estimate skin sensation and may be easily implemented by nurses, nurse practitioners, and physicians treating diabetic patients.

MSA is also a flexible scaling method. More restrictive scaling methods, such as Rasch analysis, typically fit the data worse (ie, the data are not well-described by the Rasch model) and include relatively few items in the scale. However, the scales allow interval measurement.⁶ We believe ordinal measurement is sufficient for our study because the 40 ordinal levels of pedal sensory function produced by the 39-item scale are very informative. Most of the included items are indicators of large-fiber function; however, some items assessed small-fiber function (items "cold perception left" and "right"). We included these items to investigate how they become aberrant in the natural course of sensory loss, as compared with large-fiber function. Our data show that the ability to detect a cold stimulus decreases at a late stage of sensory loss, just before abnormal monofilament tests on the first dorsal web and lateral foot. However, the exact temporal sequence in which the different nerve fibers lose their functions is not fully understood.^{19,50} MSA may aid in this debate in future studies.

The results of our study confirm that a patient most often first loses sensation in the distal extremity, with vibration sense lost at the interphalangeal joint of the hallux before the medial malleolus. The scales also show that a patient loses sensation in both legs symmetrically, which is in line with the definition of DSP being a distal, symmetrical neuropathy.⁴⁹ The item on numbness of the feet is positioned after the items on S2PD, M2PD, and vibration sense, which is of interest and suggests that patients seem unaware of the loss of these sensory modalities. At the same time, axonal density decreases, indicating that the feet are likely already at risk.⁵¹ The 39-item and 31-item scales (RDF-39 and -31) were developed for research purposes, yet they can also be used for patient-level measurements. The short 13-item (RDF-13) scale may help with individualized medical decision-making and may serve as a complement to the current prediction models for lower extremity complications.⁵²⁻⁵⁵

An automated item-selecting procedure ruled out the items "Tinel left" and "Right" and "MNSI-positive symptoms," meaning that they did not pass the marginal test for fitting the monotone homogeneity model. These items do not hold a robust position in the natural course of the disease, as clinicians will recognize from daily practice—patients who have had an ulcer and patients without aberrant large-fiber function (eg, intact S2PD) may still complain of painful neuropathic symptoms. As these results suggest, subjective positive symptoms do not necessarily correlate with the degree of sensory loss, which is in contrast to negative symptoms experienced, such as "numbness," which does have a robust position on the scale.

In our study, 44.9% (95% CI, 40.1%-49.7%) of diabetic patients exhibited signs of tibial nerve compression, as indicated by a positive Tinel sign at the tarsal tunnel.²⁵ However, we also found that this sign had an uncertain place in the natural course of sensory loss; the Tinel sign items were not selected by the models and therefore were not included in the scales. This exclusion may be explained by the pathophysiology behind this diagnostic tool—demyelination and axonal sprouting elicit a positive sign, but a negative sign is reported when

those phenomena have not yet occurred or when the nerve has been irreversibly damaged.⁵⁶ Therefore, sensitivity/specificity calculations are not appropriate because they only can be interpreted when the degree of nerve damage is known.^{57,58}

The population of the RDF Study has a wide variation sensory loss, with and without symptoms of DSP, resulting in a low risk of spectrum bias. Therefore, we believe that the external validity of our findings is likely to be high. By comparing the distribution of the sum score of diabetic subjects to that of healthy volunteers without known neuropathy, we confirmed our hypothesis that the instruments correctly categorize patients' sensation in the feet. However, due to prior dichotomization of items, with the threshold set at 8 mm for items on static and moving 2-point discrimination, we noted some aberrancy in the first 18 items (S2PD and M2PD) assessed in the healthy controls. Decline in foot sensation due to age was confirmed in our analysis, with age being the most important determinant.⁵⁹ Only nonsignificant differences were observed between genders, which is in line with previous reports.^{7,26,60} The observed association between weight and foot sensation is presumably confounded by (components of) the metabolic syndrome, as it relates to polyneuropathy, and should be investigated in future studies.⁶¹ The most important risk factors for DSP relate to the duration of diabetes, control of glucose levels, and the existence of cardiovascular risk factors.^{62,63} We retained the null hypothesis that no differences existed in foot sensation in this time-frame. A follow-up of this cohort will reveal which time-frame is applicable on the progressive steps on the scale, as well as the associated risk for (re-)ulceration or amputation, per sum score.¹⁵

In conclusion, MSA has revealed new dimensions in the use of current screening instruments in this diverse diabetic population. Based on the presented scales, clinicians may better categorize patients' loss of sensation in their feet. Therefore, an individualized approach with recommendations regarding intervention strategies and patient information may be feasible.⁶⁴⁻⁶⁷

ACKNOWLEDGMENTS

The authors thank Erwin Birnie PhD, Katharina B. E. Jorgensen, and N. Ahmad Aziz MD, PhD, for critical review of the manuscript and for their useful comments.

CONFLICT OF INTEREST

The authors declare no potential conflicts of interest.

AUTHOR CONTRIBUTIONS

W.D.R. collected data, designed the study, performed the data analysis, and wrote the manuscript. M.H.A. collected data, performed the data analysis, and wrote the manuscript. M.C.C. contributed to the discussion and reviewed/edited the manuscript. J.W.v.N. edited the manuscript. L.A.v.d.A. contributed to the data analysis, discussion, and edited the manuscript. J.H.C. designed the study, contributed to the data analysis, and edited the manuscript.

ETHICAL PUBLICATION STATEMENT

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

ORCID

Willem D. Rinkel  <https://orcid.org/0000-0001-8137-3076>

REFERENCES

- Callaghan BC, Cheng HT, Stables CL, Smith AL, Feldman EL. Diabetic neuropathy: clinical manifestations and current treatments. *Lancet Neurol*. 2012;11:521-534.
- Mayfield JA, Reiber GE, Maynard C, Czerniecki J, Sangeorzan B. The epidemiology of lower-extremity disease in veterans with diabetes. *Diabetes Care*. 2004;27(suppl 2):B39-B44.
- Brennan MB, Hess TM, Bartle B, et al. Diabetic foot ulcer severity predicts mortality among veterans with type 2 diabetes. *J Diabetes Complic*. 2017;31:556-561.
- Feng Y, Schlosser FJ, Sumpio BE. The Semmes-Weinstein monofilament examination is a significant predictor of the risk of foot ulceration and amputation in patients with diabetes mellitus. *J Vasc Surg*. 2011;53:220-226. e221-225.
- Dyck PJ, Herrmann DN, Staff NP, Dyck PJB. Assessing decreased sensation and increased sensory phenomena in diabetic polyneuropathies. *Diabetes*. 2013;62:3677-3686.
- Rinkel WD, Rizopoulos D, Aziz MH, Van Neck JW, Cabezas MC, Coert JH. Grading the loss of sensation in diabetic patients: a psychometric evaluation of the Rotterdam Diabetic Foot Study Test Battery. *Muscle Nerve*. 2018;58:559-565.
- van Nes SI, Faber CG, Hamers RM, et al. Revising two-point discrimination assessment in normal aging and in patients with polyneuropathies. *J Neurol Neurosurg Psychiatry*. 2008;79:832-834.
- Singh N, Armstrong DG, Lipsky BA. Preventing foot ulcers in patients with diabetes. *JAMA*. 2005;293:217-228.
- Schaper NC, Van Netten JJ, Apelqvist J, Lipsky BA, Bakker K. International Working Group on the Diabetic Foot. Prevention and management of foot problems in diabetes: a summary guidance for daily practice 2015, based on the IWGDF guidance documents. *Diabetes Metab Res Rev*. 2016;32(suppl 1):7-15.
- American Diabetes Association. Standards of medical care in diabetes—2014. *Diabetes Care*. 2014;37(suppl 1):S14-S80.
- Boulton AJ, Armstrong DG, Albert SF, et al. Comprehensive foot examination and risk assessment: a report of the task force of the Foot Care Interest Group of the American Diabetes Association, with endorsement by the American Association of Clinical Endocrinologists. *Diabetes Care*. 2008;31:1679-1685.
- Shun CT, Chang YC, Wu HP, et al. Skin denervation in type 2 diabetes: correlations with diabetic duration and functional impairments. *Brain*. 2004;127:1593-1605.
- Pare M, Albrecht PJ, Noto CJ, et al. Differential hypertrophy and atrophy among all types of cutaneous innervation in the glabrous skin of the monkey hand during aging and naturally occurring type 2 diabetes. *J Comp Neurol*. 2007;501:543-567.
- Vinik A, Ullal J, Parson HK, Casellini CM. Diabetic neuropathies: clinical manifestations and current treatment options. *Nat Clin Pract Endocrinol Metab*. 2006;2:269-281.
- Crawford F, Cezard G, Chappell FM, et al. A systematic review and individual patient data meta-analysis of prognostic factors for foot ulceration in people with diabetes: the international research

- collaboration for the Prediction of Diabetic Foot Ulcerations (PODUS). *Health Technol Assess*. 2015;19:1-210.
16. Dellon AL. Clinical grading of peripheral nerve problems. *Neurosurg Clin N Am*. 2001;12:229-240.
 17. Rinkel WD, Castro Cabezas M, Setyo JH, Van Neck JW, Coert JH. Traditional methods versus quantitative sensory testing of the feet at risk: results from the Rotterdam Diabetic Foot Study. *Plast Reconstr Surg*. 2017;139:752e-763e.
 18. Dyck PJ. Detection, characterization, and staging of polyneuropathy: assessed in diabetics. *Muscle Nerve*. 1988;11:21-32.
 19. Dyck PJ, O'Brien PC, Litchy WJ, Harper CM, Klein CJ, Dyck PJB. Monotonicity of nerve tests in diabetes: subclinical nerve dysfunction precedes diagnosis of polyneuropathy. *Diabetes Care*. 2005;28:2192-2200.
 20. Roorda LD, Roebroek ME, van Tilburg T, et al. Measuring activity limitations in climbing stairs: development of a hierarchical scale for patients with lower-extremity disorders living at home. *Arch Phys Med Rehabil*. 2004;85:967-971.
 21. Shenkin SD, Watson R, Laidlaw K, Starr JM, Deary IJ. The attitudes to ageing questionnaire: Mokken scaling analysis. *PLoS One*. 2014;9:e99100.
 22. Meijer JW, van Sonderen E, Blaauwweikel EE, et al. Diabetic neuropathy examination: a hierarchical scoring system to diagnose distal polyneuropathy in diabetes. *Diabetes Care*. 2000;23:750-753.
 23. Watson R, van der Ark LA, Lin LC, Fieo R, Deary IJ, Meijer RR. Item response theory: how Mokken scaling can be used in clinical practice. *J Clin Nurs*. 2012;21:2736-2746.
 24. Narayanaswami P, Burns TM. Clinical outcome assessments: the "Rasch-Ionale" for improved accuracy. *Muscle Nerve*. 2018;58:327-329.
 25. Rinkel WD, Castro Cabezas M, van Neck JW, Birnie E, Hovius SER, Coert JH. Validity of Tinel sign and prevalence of tibial nerve entrapment at the tarsal tunnel in both diabetic and non-diabetic subjects: a cross-sectional study. *Plast Reconstr Surg*. 2018;142:1258-1266.
 26. Rinkel WD, Aziz MH, Van Deelen MJM, et al. Normative data for cutaneous threshold and spatial discrimination in the feet. *Muscle Nerve*. 2017;56:399-407.
 27. Martina IS, van Koningsveld R, Schmitz PI, van der Meche FG, van Doorn PA. Measuring vibration threshold with a graduated tuning fork in normal aging and in patients with polyneuropathy. European Inflammatory Neuropathy Cause and Treatment (INCAT) group. *J Neurol Neurosurg Psychiatry*. 1998;65:743-747.
 28. Sijtsma K. Nonparametric item response theory models. In: Kempf-Leonard K, ed. *Encyclopedia of Social Measurement*. New York: Elsevier; 2005.
 29. Sijtsma K, van der Ark LA. A tutorial on how to do a Mokken scale analysis on your test and questionnaire data. *Br J Math Stat Psychol*. 2017;70(1):137-158.
 30. Draak THP, Vanhoutte EK, van Nes SI, et al. Comparing the NIS vs. MRC and INCAT sensory scale through Rasch analyses. *J Peripher Nerv Syst*. 2015;20(3):277-288.
 31. Vanhoutte EK, Faber CG, van Nes SI, et al. Modifying the medical research council grading system through Rasch analyses. *Brain*. 2012; 135(Pt 5):1639-1649.
 32. Vanhoutte EK, Hermans MC, Faber CG, et al. Rasch-ionale for neurologists. *J Peripher Nerv Syst*. 2015;20(3):260-268.
 33. Sijtsma K, Molenaar IW. *Introduction to Nonparametric Item Response Theory*. Thousand Oaks, CA, USA: Sage; 2002.
 34. van der Ark LA, Croon MA, Sijtsma K. Mokken scale analysis for dichotomous items using marginal models. *Psychometrika*. 2008;73(2): 183-208.
 35. van der Ark LA. Mokken scale analysis in R. *J Stat Softw*. 2007;20(11): 1-19.
 36. Nunnally JC, Bernstein I. *Psychometric Theory*. New York, NY: McGraw-Hill; 1994.
 37. Sijtsma K, Meijer RR, van der Ark LA. Mokken scale analysis as time goes by: an update for scaling practitioners. *Pers Individ Dif*. 2010;50: 31-37.
 38. Ligtoet R, van der Ark LA, Te Marvelde JM, Sijtsma K. Investigating an invariant item ordering for polytomously scored items. *Educ Psychol Meas*. 2010;70(4):578-595.
 39. Mair P, Hatzinger R. Extended Rasch modeling: the eRm package for the application of IRT models in R. *J Stat Softw*. 2007;20:1-20.
 40. van der Ark LA. Mokken scale analysis in R. *J Stat Softw*. 2007;20: 1-19.
 41. van der Ark LA. New developments in Mokken scale analysis in R. *J Stat Softw*. 2012;48:1-27.
 42. Olmos PR, Cataland S, O'Dorisio TM, Casey CA, Smead WL, Simon SR. The Semmes-Weinstein monofilament as a potential predictor of foot ulceration in patients with noninsulin-dependent diabetes. *Am J Med Sci*. 1995;309:76-82.
 43. Smieja M, Hunt DL, Edelman D, Etchells E, Cornuz J, Simel DL. Clinical examination for the detection of protective sensation in the feet of diabetic patients. International Cooperative Group for Clinical Examination Research. *J Gen Intern Med*. 1999;14: 418-424.
 44. Canadian Diabetes Association Clinical Practice Guidelines Expert Committee, Bril V, Perkins B, Toth C. Neuropathy. *Can J Diabetes*. 2013;37(suppl 1):S142-S144.
 45. Olaley D, Perkins BA, Bril V. Evaluation of three screening tests and a risk assessment model for diagnosing peripheral neuropathy in the diabetes clinic. *Diabetes Res Clin Pract*. 2001;54:115-128.
 46. Hanewinkel R, Ikram MA, van Doorn PA. Assessment scales for the diagnosis of polyneuropathy. *Journal of the peripheral nervous system*. *J Peripher Nerv Syst*. 2016;21:61-73.
 47. Schmid AB, Bland JD, Bhat MA, Bennett DL. The relationship of nerve fibre pathology to sensory function in entrapment neuropathy. *Brain*. 2014;137:3186-3199.
 48. Vinik AI, Mehrabyan A. Diabetic neuropathies. *Med Clin N Am*. 2004; 88:947-999.
 49. Hanewinkel R, Drenthen J, van Oijen M, Hofman A, van Doorn PA, Ikram MA. Prevalence of polyneuropathy in the general middle-aged and elderly population. *Neurology*. 2016;87:1892-1898.
 50. Ziegler D, Papanas N, Zhivov A, et al. Early detection of nerve fiber loss by corneal confocal microscopy and skin biopsy in recently diagnosed type 2 diabetes. *Diabetes*. 2014;63:2454-2463.
 51. Peltier AC, Myers MI, Artibee KJ, et al. *J Peripher Nerv Syst*. 2013;18: 162-167.
 52. Monteiro-Soares M, Boyko EJ, Ribeiro J, Ribeiro I, Dinis-Ribeiro M. Predictive factors for diabetic foot ulceration: a systematic review. *Diabetes Metab Res Rev*. 2012;28:574-600.
 53. Monteiro-Soares M, Dinis-Ribeiro M. A new diabetic foot risk assessment tool: DIAFORA. *Diabetes Metab Res Rev*. 2016;32: 429-435.
 54. Boyko EJ, Ahroni JH, Cohen V, Nelson KM, Heagerty PJ. Prediction of diabetic foot ulcer occurrence using commonly available clinical information: the Seattle Diabetic Foot Study. *Diabetes Care*. 2006;29: 1202-1207.
 55. Boyko EJ, Seelig AD, Ahroni JH. Limb- and person-level risk factors for lower-limb amputation in the prospective Seattle Diabetic Foot Study. *Diabetes Care*. 2018;41:891-898.
 56. Vinik A, Mehrabyan A, Colen L, Boulton A. Focal entrapment neuropathies in diabetes. *Diabetes Care*. 2004;27:1783-1788.
 57. Dellon AL. Tinel or not Tinel. *J Hand Surg Br*. 1984;9:216.
 58. Patel AT, Gaines K, Malamut R, et al. Usefulness of electrodiagnostic techniques in the evaluation of suspected tarsal tunnel syndrome: an evidence-based review. *Muscle Nerve*. 2005;32:236-240.
 59. Lin YH, Hsieh SC, Chao CC, Chang YC, Hsieh ST. Influence of aging on thermal and vibratory thresholds of quantitative sensory testing. *J Peripher Nerv Syst*. 2005;10:269-281.

60. Shimokata H, Kuzuya F. Two-point discrimination test of the skin as an index of sensory aging. *Gerontology*. 1995;41:267-272.
61. Hanewinkel R, Drenthen J, Ligthart S, et al. Metabolic syndrome is related to polyneuropathy and impaired peripheral nerve function: a prospective population-based cohort study. *J Neurol Neurosurg Psychiatry*. 2016;87:1336-1342.
62. Tesfaye S, Chaturvedi N, Eaton SE, et al. Vascular risk factors and diabetic neuropathy. *N Engl J Med*. 2005;352:341-350.
63. Dyck PJ, Davies JL, Wilson DM, Service FJ, Melton LJ 3rd, O'Brien PC. Risk factors for severity of diabetic polyneuropathy: intensive longitudinal assessment of the Rochester Diabetic Neuropathy Study cohort. *Diabetes Care*. 1999;22:1479-1486.
64. Liao C, Zhang W, Yang M, Ma Q, Li G, Zhong W. Surgical decompression of painful diabetic peripheral neuropathy: the role of pain distribution. *PLoS One*. 2014;9:e109827.
65. Baltodano PA, Basdag B, Bailey CR, et al. The positive effect of neurolysis on diabetic patients with compressed nerves of the lower extremities: a systematic review and meta-analysis. *Plast Reconstr Surg Glob Open*. 2013;1:e24.
66. Chin YF, Liang J, Wang WS, Hsu BR, Huang TT. The role of foot self-care behavior on developing foot ulcers in diabetic patients with peripheral neuropathy: a prospective study. *Int J Nurs Stud*. 2014;51:1568-1574.
67. Gibson TB, Driver VR, Wrobel JS, et al. Podiatrist care and outcomes for patients with diabetes and foot ulcer. *Int Wound J*. 2014;11:641-648.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Rinkel WD, Aziz MH, Van Neck JW, Cabezas MC, van der Ark LA, Coert JH. Development of grading scales of pedal sensory loss using Mokken scale analysis on the Rotterdam Diabetic Foot Study Test Battery data. *Muscle Nerve*. 2019;60:520-527. <https://doi.org/10.1002/mus.26628>