A Pilot Study of a Plantar Sensory Evaluation System for Early Screening of Diabetic Neuropathy in a Weight-bearing Position

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Abstract—**The purpose of this study is to develop smart equipment to quantify plantar tactile sensibility for the early diagnosis and tracking of peripheral neuropathy caused by diabetes mellitus. In this paper, we offer a new testing system that is composed of a plantar tactile stimulation platform with a small moving contactor to stretch the skin tangentially, a response switch for each tactile stimulus, a motor control box, and a personal computer (PC) for psychophysical data processing. This quantitative sensory testing system has detailed measurements available and is easy to use compared with the conventional testing devices, such as von Frey monofilaments, pin-prick testing devices, and current perception threshold testers. When using our testing system in a weight-bearing position, we observed that the plantar tactile thresholds for the tangential stretching stimulus on the plantar surface of the foot ranged from approximately 10 µm to 30 µm for healthy subjects. However, the threshold for a subject with diabetes was nearly three times higher than that for healthy subjects. The significant difference between these values suggests that the plantar sensory evaluation system using the lateral skin stretch stimulation can be used for early diagnosis, for the accurate staging of diabetic neuropathy, and for evaluating its progression noninvasively in a clinic and at home.**

I. INTRODUCTION

Globally pronounced changes in lifestyle and the social environment over the last century have resulted in a dramatic increase in the incidence of diabetes mellitus. The International Diabetes Federation (IDF) diabetes atlas reported that the number of people with diabetes will rise from the current estimate of 382 million to 592 million in 2035 [1]. Currently, diabetes is one of the main threats and a global burden to human health in this century [2].

There are two main types of diabetes mellitus. Type 1 is insulin-dependent diabetes mellitus (IDDM) and is usually diagnosed in children and young adults. Type 2 is non-insulin-dependent diabetes mellitus (NIDDM), is the most common form of diabetes, and is associated with a sedentary lifestyle and obesity. Complications from any type of diabetes may include neuropathy (nerve damage), retinopathy (eye damage), and nephropathy (kidney damage). Additionally, people with diabetes have a reduced quality of life because of these complications [3]. The early signs of diabetes and its complications are difficult to detect. In addition to physical problems, management and treatment of this disease cause substantial economic consequences for the patients, their families, and the community. The challenge facing the global diabetes community is how to best implement screening, educational, and treatment programs in every region of the world [10].

A prototype plantar sensory evaluation system has been developed to provide an effective and convenient testing method for early detection and to reduce the progression of diabetic neuropathy and other complications. In this study, we focused on reducing the tactile sensation at the peripheral regions such as limbs (the foot and hand), which is a common symptom in patients with diabetic neuropathy and appears at a relatively early stage of the disease [11]. The tactile stimulation of our testing method was adopted for lateral skin stretches, which is more sensitive than normal (vertical) skin forces [4]. The system features a plantar tactile stimulation platform with a small moving contactor to stretch the skin tangentially, a response switch for each tactile stimulus, a motor control box, and a personal computer (PC) for psychophysical data processing. By using this system in a weight-bearing position, we determined the detection thresholds of the lateral skin stretches on the plantar surface, the dependency of the stimulation velocity and the stimulation site, and a difference in the threshold between healthy subjects and a patient with a diagnosis of early neuropathy. This system may have a potential use in early and noninvasive diagnosis and the staging degrees of severity of diabetic neuropathy and measuring its progression at home and in the clinic for point-of-care testing.

II. PLANTAR SENSORY EVALUATION SYSTEM

A. System Design

Conventional testing devices and systems of peripheral neuropathy have several problems, including the accuracy and durability of a quantitative estimation, user operation, the time of testing, and the cost of the devices or systems. The Semmes-Weinstein monofilament (von Frey hair) [5] and a pin-prick stimulator (needle) are inexpensive and easy to use for rough sensory testing, but several attempts are required to obtain accurate measurements. However, the Neurometer (electrical stimulator) [6] is a device for quantitatively assessing neuropathy by measuring the current perception threshold. However, this device is expensive and is difficult to use in clinical practice. For these reasons, a new and efficient system to diagnosis and quantify the tactile deficiency caused by peripheral neuropathy is needed for urgent action on diabetes prevention.

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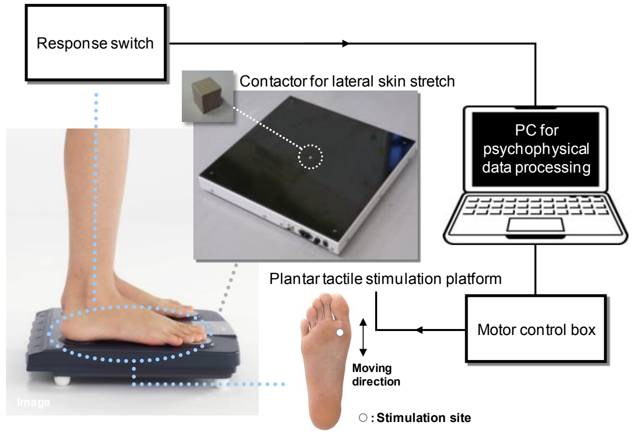

Figure 1. Schematic diagram of the plantar sensory evaluation system using a lateral skin stretch.

The tactile sense of healthy subjects is significantly more sensitive to tangential forces than normal forces [4]. Therefore, we originally adopted the lateral skin stretch stimulus on the plantar area to sensitively quantify the tactile deficiency caused by diabetic neuropathy.

The prototype system was composed of a plantar tactile stimulation platform with a moving contactor to stretch the skin tangentially, a response switch for each tactile stimulus, a motor control box, and a personal computer (PC) for psychophysical data processing as shown in Fig. 1. In addition, the system has been designed for laboratory testing and uses a relatively wide foot platform to adapt to the various measurement postures of the human subjects. The final design of the system for home and clinical use will feature portability (i.e., as a bathroom scale), the direct integration of all accessories and a small PC for system control and data analysis into the foot platform.

B. *System Fabrication*

The plantar tactile stimulation platform was installed with a contactor (a 10-mm cubic tip) mounted on a precision linear stage (Oriental motor ESR4, ± 5 μm accuracy, Japan) and a stepping motor, and it had outer dimensions of 50 cm x 50 cm x 7.5 cm thick and a weight of 17 kg. The contactor moved at a maximum of 5 mm back and forth on the plantar skin. The velocity of the contactor was controllable through the motor control box (Oriental motor ESMC, Japan), which was located between the stimulation platform and the PC (Dell Vostro420, USA) for the subject's response data acquisition and the proper and accurate control of the contactor. The psychophysical data processing system was developed by combining the PC with the response switch and the software program for sensory evaluation based on the method of limits [7] in the psychophysical methodology.

III. MATERIALS AND METHODS

A. *Subjects*

Four healthy subjects (2 women and 2 men), ranging in age from 20 to 40 years (mean age 37 years), and one healthy elderly subject (female, age 65 years) were recruited to determine the standard tendency of the detection thresholds

Figure 2. Five testing sites on the plantar aspect of the foot (bottom view).

(i.e., absolute thresholds) of tactile sense on the plantar surface. The protocol was approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology in Japan, and all subjects provided informed consent. To ensure that the subjects received the same information regarding the experimental procedures, written instructions were reviewed by each subject. One patient (female, age 77 years) at an early stage of diabetes was recruited from Tokuyukai Rehabilitation Clinic in Japan. The patient was interviewed and assessed by the Semmes-Weinstein monofilament examination and a blood test for hemoglobin A1c (HbA1c) to diagnose the stage of diabetes.

B. *Apparatus*

All lateral skin stretch stimulations on the subject's planter surface were delivered by the contactor of the plantar sensory evaluation system as shown in Fig. 1. The contactor was made of PEEK (Poly-Ether-Ether-Ketone) plastics with heat and chemical resistance and good mechanical strength. The speeds for the lateral stretch movements were 0.2, 1.0, and 4.0 mm/s. The skin's temperature and the hardness of the planter surface were measured using an infrared laser thermometer (Fluke 568, USA) and a durometer (Ozaki TDM-N1, Japan), respectively. A pressure distribution pattern of the plantar in a standing position was scanned by a pressure sensitive foot analysis platform (Medicapteurs PEL38, France).

C. *Stimuli*

Subjects in the standing position received lateral skin stretches on the planter surface in a distal and proximal direction according to a psychophysical measurement protocol (i.e., the method of limits). Stretch displacements were automatically generated by a PC with the algorithm of the measurement protocol. The speed of the contactor was constant (e.g., 1.0 mm/s) during the same testing session. The experimenter could monitor the progress of each stimulus condition on the PC screen.

D. *Procedure*

Prior to the main experiments to measure the tactile threshold, the skin's temperature and the hardness of the measurement sites and the foot plantar pressure distribution were established for all subjects. Subsequently, the subjects with the response switch in hand stood barefoot on the plantar tactile stimulation platform. The stimulations were applied to five different sites (the first toe, the fifth toe, the plantar aspect

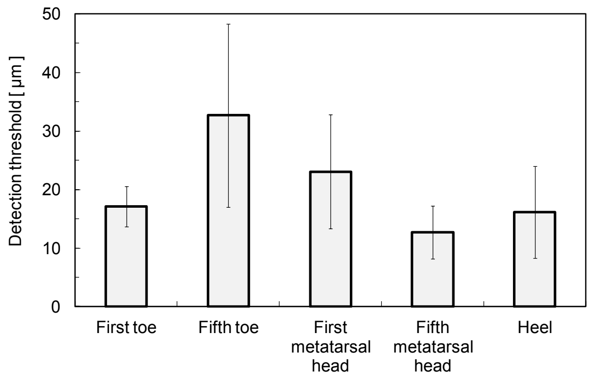

Figure 3. Detection threshold comparison for different stimulation sites of healthy subjects. The lateral skin stretch speed of the contactor at each stimulation site on the plantar surface was 1.0 mm/s.

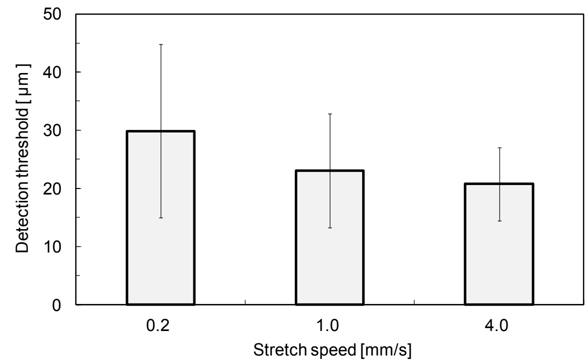

Figure 5. Detection threshold comparison for different lateral skin stretch speeds applied to the first metatarsal head of the healthy subjects.

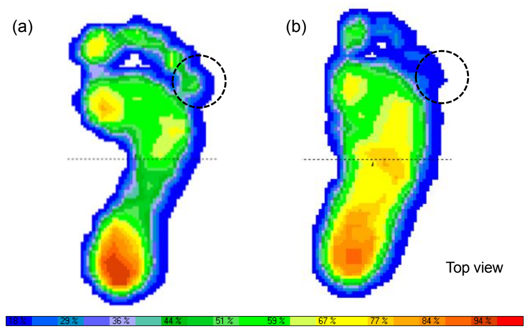

Figure 4. Examples of the plantar pressure patterns of (a) a subject with a normally arched foot and (b) a subject with a flat (low arch) foot. The dotted circle indicates the area of the fifth toe. The values increase towards the initial peak pressures under the foot during the standing posture (=100%).

of the first metatarsal head, the plantar aspect of the fifth metatarsal head, and the heel) of the right foot as shown in Fig. 2. The subjects were not informed regarding the number of stimuli, and no indication was provided concerning their performance until all of the tests were completed. The absolute thresholds were measured by the method of limits in psychophysics. Stimuli were presented in a descending and ascending series and began with a stimulus that was either well above or well below the anticipated threshold. In the descending series, the trial stops when the subject reported that the stimulus was no longer perceived. In the ascending series, the trial stops when the subject first indicated the presence of the stimulus. The absolute threshold is defined as the mean of the transition points in each of the series presented. In the experiments, each descending and ascending series were performed four times (for a total of eight series), and the step width of the descending and ascending series was set to 5 µm. The subjects reported their feedback using the response switch connected to the PC to state whether they could perceive a presented stimulus at a measurement site of the foot plantar skin. The testing time was usually less than five minutes per person.

IV. Results

A. *Skin temperature and hardness*

The mean skin temperature at the plantar surface for all healthy subjects was approximately 32 °C. The skin hardness of the younger subjects in their 20s was lower than that of the older subjects in their 40s.

B. *Detection threshold comparison among stimlus sites*

We compared the detection thresholds of the lateral skin stretch with the stimulus sites on the plantar surface as shown in Fig. 3. The stretch speed of the contactor was fixed at 1.0 mm/s. We observed that the detection threshold for the tangential stretching stimulus on the plantar surface of the foot ranged from approximately 10 µm to 30 µm for healthy subjects. However, the mean detection threshold at the fifth toe was 32.7 ± 15.7 µm and was significantly higher than that at the other plantar sites ($p < 0.001$). The detection threshold at the fifth toe was greater than 2.5 times the plantar aspect of the fifth metatarsal head.

C. *Plantar pressure distribution*

Two typical patterns of plantar pressure distribution for the subjects are shown in Fig. 4. One pattern was a normally arched foot (Fig. 4a), and the other pattern was a flat foot, which had a low medial arch on weight bearing (Fig. 4b). A major difference was observed on the pressure scale of the fifth toe. The subjects with a normal foot were provided a higher contact pressure and a slightly wider area in comparison with the subjects with a flat foot.

D. *Detection threshold with stimulus speed*

The detection threshold of the lateral skin stretch at the plantar aspect of the first metatarsal head decreased as the stretch stimulus speed increased, as shown in Fig. 5. The detection threshold (29.8 µm) for a stimulus speed of 0.2 mm/s was significantly higher than both stimulus speeds of 1.0 mm/s ($p < 0.05$) and 4.0 mm/s ($p < 0.001$). A similar trend was observed for all the other sites (the first toe, the fifth toe, the plantar aspect of the fifth metatarsal head, and the heel) of the foot.

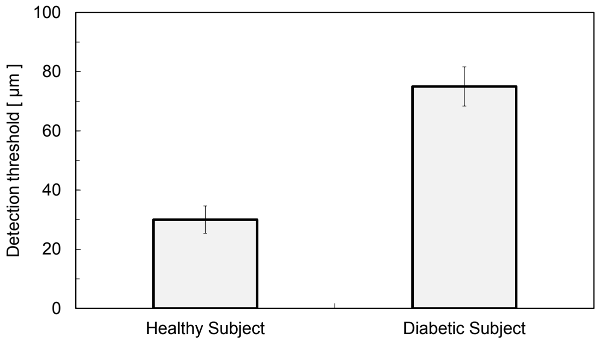

Figure 6. Comparison of the detection threshold of lateral skin stretch at the first metatarsal head between elderly subjects with or without diabetes. The stretch speed of the stimuli was 1.0 mm/s.

E. Comparison of healthy and early diabetic subjects

The detection threshold of one diabetic subject at an early stage of diagnosis was 75.0 ± 6.6 μm, as shown in Fig. 6. The measurement site and the stimulus speed were the plantar aspect of the first metatarsal head and 1.0 mm/s, respectively. The detection threshold of the patient was much higher than that of a healthy elderly subject (30.0 ± 4.6 μm).

V. Discussion

The present study demonstrates that the detection threshold (μm-order resolution) of the lateral skin stretch at the plantar aspect was more sensitive in comparison with the two-point discrimination threshold (mm-order resolution) [8]. Additionally, we explained the dependency of the detection threshold on the speed and site of the plantar surface, which was associated with sensory information processing as well as the palm surface [9]. The detection threshold increased as the speed of the lateral stretch decreased and increased at the fifth toe on the plantar aspect. The bluntness and threshold variation at the fifth toe may be caused by the instability (i.e., low contact force) of the toe contact condition of the subjects with a flat foot, as shown in Fig. 4b. Thus, the fifth toe is not a very suitable testing area for our plantar sensory evaluation system. A supplementary improvement in clinical use is that the testing time of our method was much less than that with conventional methods, such as the Semmes-Weinstein monofilament test and the Neurometer test, which required approximately 10-30 minutes.

The detection threshold of the early diabetic subject was significantly higher than that for the health subjects. The significant difference between both values suggests that the plantar sensory evaluation system using the lateral skin stretch stimulation has a potential use in early diagnosis, in accurate staging of diabetic neuropathy, and in evaluating its progression noninvasively in a clinic and at home. However, the possibility of a new quantitative sensory testing method for neuropathy is limited because the experimental data were based on a few healthy and diabetic subjects in this pilot study. We need to increase the sample size of healthy subjects and diabetic subjects to obtain and confirm the cut-off points for an adequate quantitative assessment (i.e., a gold standard) of diabetic neuropathy.

VI. Conclusion

A plantar sensory evaluation system using a lateral skin stretch stimulation was developed and tested on healthy and diabetic subjects. The testing stimulation for the system was carefully determined by considering the psychophysical and brain research findings in human haptic perception. Hence, the prototype system to quantify the tactile threshold of the foot had a significantly higher sensitivity (μm-order resolution) and was less time consuming compared with the traditional sensory testing devices for the diagnosis of peripheral neuropathy and the staging degree of the tactile deficit. From the results, we recognized that the plantar tactile perception elicited by lateral skin stretch was dependent upon the speed and site on the plantar aspect of the foot. Furthermore, the stretch detection threshold of the early diabetic subject was much higher than that for the healthy subjects. In conclusion, our pilot study may provide evidence for a new accurate quantitative assessment using noninvasive tactile testing in a weight-bearing position for an early diagnosis of diabetes mellitus, for the prevention of its complications and for an improved quality of life. Further study is required along with data from subjects with or without various degrees of diabetes for practical applications in healthcare.

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