Processing of foot pressure images and display of an advanced clinical parameter PR in Diabetic Neuropathy

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Abstract-In diabetic foot, sensation loss predisposes to skin ulceration which may result in amputation, the most feared complication. Therefore, understanding and detection of factors responsible for plantar ulceration and their measurement reproducibly is necessary to save the foot at risk. As peak foot pressure were not sufficiently sensitive, Power Ratio(PR), a new diagnostic parameter, by analysis of foot pressure distribution in standing and walking images of foot has been developed. PR is related to different levels of sensation loss in the diabetic foot. Algorithm is developed (in MATLAB) to automatically separate (crop) bitmap files of different foot sizes. Algorithm is also developed (in Visual C ++) to calculate PR of cropped images and display simultaneously PR of all foot sole areas. This display of PR simultaneously in all foot areas helps clinician to effectively discriminate between normal, early and advanced stages of diabetic neuropathic subjects and also in detecting foot sole areas at risk.

I. INTRODUCTION

The diabetic foot ulcer is a serious medical problem with far-reaching consequences. Foot ulcers need to be managed carefully. Notwithstanding the best care, many patients have foot complications that necessitate hospitalization and treatment. There is a constant need to understand the mechanisms of diabetic foot ulcers in order to manage and prevent ulceration. Diabetic feet develop calluses, which in turn lead to ulcers. Higher foot pressures are associated with callus development. The method of measuring foot pressures is of prime importance in this area of endeavor. Diabetes is a disorder caused by decreased production of insulin, or by decreased ability to use insulin. Insulin is a hormone produced by the pancreas that is necessary for the cells to be able to use blood sugar. The diabetes population is ever increasing and studies both in advanced and developing nations indicate high prevalence of diabetes.

The complications of diabetes that are most relevant to lower-extremity are distal peripheral neuropathy and, to a lesser extent, peripheral vascular disease. The most feared lower-extremity problem among patients with diabetes is amputation, and the sequence of events leading to amputation is initiated by skin ulceration. This occurs most frequently because of loss of sensation.

II. DATA ACQUISITION AND QUANTIFICATION OF NEUROPATHY

The data acquisition for foot pressure involves the use of an optical pedobarograph developed earlier (Patil et al., 1996; Bhatia, 1996) in the Biomedical Engineering laboratory, IIT, Madras as shown in Fig.1. This being connected to an IBM PC–AT, grabs the image and load data as the subject stands or walks over a glass platform mounted on the wooden box standing on load cells.

The image acquisition involves three stages. The first, where the applied pressure on the glass–plastic interface is converted to a high-resolution intensity image (obtained by scattering of light at the glass and plastic sheet interface as explained in Betts et al., 1980 d), the intensity being proportional to the applied pressure. The second, where the light image is converted to an analog electrical signal. The third, where the analog electrical signal is digitized and stored.

Each footprint is divided into ten anatomically significant areas as per the detailed method indicated in Cavanagh et al. (1987), Patil et al. (1996).The material required for quantification of sensation levels of different areas of the foot is Semmes–Weinstein colored nylon monofilaments (Weinstein, 1993). Foot areas of diabetic subjects are scanned in ten specified areas using Semmes–Weinstein nylon monofilaments to determine quantitatively the degree of neuropathy as per the following classification (Elftman, 1991; Bell–Krotoski et al., 1993; Malaviya et al., 1994):

(a) Normal: Sensation level of 3 gm force exerted by the nylon monofilament.
(b) Diminished light touch: Sensation level of 4.5 gm force exerted by the nylon monofilament.
(c) Diminished protective sensation: Sensation level of 7.5 gm force exerted by the nylon monofilament.
(d) Loss of protective sensation: Sensation level of 10 gm force exerted by the nylon monofilament.

From the above classification it is clear that higher the force used for sensation level, more is the sensation loss and neuropathy. When the foot sole sensation loss is determined,
The sensation levels in adjacent areas or other areas (1 to 10) were found to be between 3 gm, 4.5 gm, 7.5 gm, 10 gm (depending upon the progress of neuropathy) or it can be 10 gm in all the areas or > 10 gm in advanced levels of neuropathy.

Fig.1 Schematic diagram of optical pedobarograph

III. FREQUENCY DOMAIN ANALYSIS

The pressure distributions under the feet of normal subjects are found to be smooth and spread over larger areas of the foot (Patil et al., 1996). It is observed that corresponding variation under the diabetic feet is not uniformly distributed and there is an increase in pressure gradient when neuropathy level (quantified by sensation levels) increases. The situation is worse in the presence of a scar or ulcer at a particular area of the diabetic neuropathic feet. Abrupt changes in (the foot pressures represented by) light intensity variations of an image reflect in higher spatial frequency variations (Gonzalez and Wintz, 1987) of the light image. Therefore, an attempt is made to analyze the foot pressure images in the frequency domain with a new pressure parameter and relate it to degree of neuropathy (characterized by different levels of sensation loss). This study could possibly help to detect diabetic feet at risk at an early stage.

The standing and walking foot intensity images obtained from optical pedobarograph are converted to the bit map (BMP) files for image processing. The size of the individual footprint varies and these footprint images are divided into ten standard regions using the program developed in MATLAB. Each plantar foot area is obtained manually using the Graphic Workshop software package. Thus, number of samples $M$ and $N$ depend on the size of the particular area of the foot and corresponding image size is represented as $(M \times N)$ pixels. The Fourier spectrum $F(u,v)$ of an image $f(x,y)$ corresponding to a foot area is obtained using (1). The spatial frequencies ($u$ and $v$) are denoted by cycles per distance (Kandarakis et al., 1999) and for this analysis since the image size (distances) is given in terms of pixels, the spatial frequencies are represented by cycles per pixel.

$$F(u,v) = \frac{1}{MN} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) e^{-j2\pi \frac{ux}{M} \frac{vy}{N}}$$  \hspace{1cm} (1)

for, $u = 0, 1, 2 \ldots M-1$ and $v = 0, 1, 2 \ldots N-1$.

Spatial frequencies and their distributions of these images are analyzed by performing the 2-D Discrete Fourier Transform (DFT) using MATLAB version 5.1. Using the periodicity property of discrete Fourier transform (Gonzalez and Wintz, 1987), the Fourier spectrum is shifted to the center of frequency plane. The DC component, $F(0,0)$ is deleted since it gives only the average value of the image intensity. The power spectrum is obtained by squaring the magnitudes of Fourier spectrum (Gonzalez and Wintz, 1987) of light intensity variations of foot images and the total power, $TP$ (Volts$^2$) in an image is obtained using (2).

$$TP = \left\{ \sum_{u=-M/2}^{M/2} \sum_{v=-N/2}^{N/2} \right\} \left| F(u,v) \right|^2 - \left| F(0,0) \right|^2$$  \hspace{1cm} (2)

Since for a foot area image, $M$ and $N$ are different (depend on the size of the particular area), the cut-off frequency, $D_0$ (cycles per pixel), which separates the lower, and higher spatial frequency components, is defined by (3).

$$D_0 = \begin{cases} \frac{M}{4} & \text{if } N \geq M \\ \frac{N}{4} & \text{if } N < M \end{cases}$$  \hspace{1cm} (3)

Where $D(u,v)$ is the distance from point $(u,v)$ to the origin of the frequency plane,

$$D(u,v) = \sqrt{u^2 + v^2}.$$  \hspace{1cm} (4)

The low frequency power, $LFP$ (Volts$^2$) and high frequency power, $HFP$ (Volts$^2$) are calculated using (5) and (6), respectively. A new parameter, power ratio, $PR$ of the power spectrum is defined as ratio of the high frequency power to the total power in an image and obtained using (7). Multiplication by 100 is to express the PR value as a whole number.

$$LFP = \left\{ \sum_{D(u,v) = 0} \left| F(u,v) \right|^2 \right\} - \left| F(0,0) \right|^2$$  \hspace{1cm} (5)
It is observed that the spatial intensity variation distribution for a diabetic foot has abrupt jumps (Fig.3) compared to that of a normal foot (Fig.2). The power spectrum of foot pressure image intensity for a diabetic foot shows higher proportion of higher spatial frequency power component out of the total power spectrum compared to the corresponding variations for a normal foot (6), giving rise to higher value of PR in that area of the foot for the diabetic subject.

\[ HFP = TP - LFP \]

(6)

\[ PR = \left( \frac{HFP}{TP} \right) \times 100 \]

(7)

The parameter, PR is evaluated for normal and diabetic feet with different levels of sensation loss in the specified ten areas of the foot, for standing as well as walking foot pressure images.

IV. COMPARISON OF PR BETWEEN NORMAL AND DIABETIC SUBJECTS

Comparisons of PR values are made between normal and diabetic subjects in different levels of loss of sensation. Fig.2 and Fig.3 show the spatial variation of intensity distribution in area 2 (lateral heel) of left foot for a normal and diabetic subject with early stage diabetic neuropathy (sensation level 4.5 gm), respectively.

V. METHODOLOGY USED FOR CALCULATION AND DISPLAY OF POWER RATIO

It has been emphasized that function is the key, which must be understood and fully appreciated whenever we examine a patient with a foot problem, and that the primary function of the foot is locomotion (Brachman, 1971). Therefore in the examination of the foot by pressure measurement, dynamic (during walking) measurements have a rightfully prominent place. When the function of the foot is disturbed by disease or trauma, it can be expected to reflect in abnormal plantar pressure patterns during gait (Lord et al., 1986). This information is useful for a description of the kinematics of the foot alone, for prosthesis and orthosis designers, orthopedic surgeons, researchers in biomechanics and rehabilitation engineers (Ranu, 1986).

For the first time an analysis and display of walking and standing foot pressure patterns, in all foot sole areas of normal and diabetic patients, using Visual C++ is presented here. Statistical study is performed to find the correlation between the values of PR calculated by previous method (using MATLAB) and new method (Using Visual C++).

The foot pressure images, of standing (for example normal subject shown in Fig.2) and diabetic subject shown in Fig.3 obtained from optical pedobarograph, are converted to bitmap (BMP) files for image processing and calculating the new foot pressure distribution parameter PR.

Cropping of the foot images done earlier manually in different foot sole areas was found cumbersome and also time consuming using GWS (Graphic Work Shop) tool. This was restricting the ability of diabetic clinicians to rely on the expertise of a technically qualified person for use of the new foot pressure parameter PR for diagnosis in diabetic foot clinics. Therefore, a new method of cropping of the standing foot pressure image is carried out using MATLAB.

In this novel method, automatic cropping of all foot sole areas (1 to 10) and sub an area (top and bottom in selected bigger areas of the foot) was done. It is necessary to provide only the foot pressure images of the right and the left foot grabbed from pedobarograph.

In this program before cropping of each foot sole area, the left and right foot images are to be separated using Graphic Work Shop (GWS) software and should be named as “Lonly.bmp” (Left foot only) and “Ronly.bmp” (Right foot only). The size of the foot has to be ascertained and the foot has to be classified as large, medium or small depending upon dimensions such as width and length of the foot. The large size foot has a width and length = 50*164 pixels,
The medium foot has a size range of 45*142 to 46*158 pixels, and the small foot has a size range of 39*134 to 39*143 pixels. Software is developed using Visual C ++ to calculate the power ratio (PR) in all 16 foot sole areas (for each foot of 10 normal and 9 diabetic subjects) and display the output in the form of the pseudo color foot images as per predefined color-coding according to the value of the PR. Calculation of PR is made in all 16 areas of the standing foot images (obtained by auto crop program developed and stored in Resource folder of the program). “Database.bmp” file (which holds the details of the Patients name, Age, Sex, Clinical details) is also needed to be made available to the Res (Recourse) folder of the program. Maximum values of intensities of all these images will be read in sequence by the program for discrimination among normal and diabetic subjects. Then the height and width of all the images are also read and stored as m and n. Total Power (TP) of each image is calculated using (2). Subsequently using equation (3), $D_o$ is calculated and then the Low Frequency Power (LFP), using (5) is also calculated. Now, using (6), High Frequency Power (HFP) is calculated. Subsequently the Power Ratio (PR) for each of the foot sole areas is calculated using (7) and displayed in the form of pseudo color image for quick diagnosis of the diabetic foot.

The foot pressure parameter (PR) variation in each foot sole area is displayed in the BGR form.

VI. RESULTS

Statistical analysis is done by, finding correlation coefficients – ‘r’ between PR values results obtained by previous software (MATLAB) and the newly developed software (Using Visual C++). Fig.4 compares the PR values obtained by both the methods (using MATLAB and Visual C++) in area 8 of a standing normal subject. Table 1 represents coefficient of correlation between PR values obtained by previous method (using MATLAB) and newly developed method (using Visual C++) in foot sole area 8. It is clear from the table 1 that they have moderate to good correlations (‘r’ ranging from 0.64 to 0.93), obtained from the data of 11 normal subjects in all 10 areas of the foot.

![Diagram](image)

It is clear from table 1 that they have moderate to good correlations (‘r’ ranging from 0.84 to 0.93), obtained for 10 diabetic subjects in specified areas of the foot.

REFERENCES

[3] Cavanagh, P.R., M.M.Rodgers and A.Limboshi “Pressure distribution under symptom-free during barefoot standing” Foot and Ankle, 7, pp 262-276