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Static and dynamic measurement and computer simulation of diabetic mellitus foot biomechanics

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Abstract

The objective of this study was to evaluate static and dynamic results on the foot pressure measurement and computer simulation for diabetes mellitus patients. The finite element analysis was used to compare with pressure foot measurement. The foot and ankle model consisted of 28 bony segments is created from DICOM CT slice from specific patient with diabetes mellitus diagnosis. All material properties are considered as homogeneous, isotropic and linearly elastic. Foot pressure measurement for both static and dynamic condition gave topographic distribution of high pressure points which is in correlation with clinical tests results. The result for maximum pressure measurement of the left foot 124.74 kPa is in good comparison with finite element results for 121 kPa. It looks that numerical simulation in combination with foot pressure measurement device can be efficient and inexpensive screening tool, which could go in direction for prevention of the diabetic foot complications, associated with high mortality and morbidity that has significant economic impact on healthcare system.

Keywords: Foot pressure measurement; Diabetes mellitus patient, Finite element analysis.

1. Introduction

Diabetes mellitus is chronic disease with insidious beginning, without specific symptoms, which leads to late diagnosis, most often when complications have already taken place. There were 366 million patients with diabetes in year 2011, worldwide, of which 4.6 million died. There were 630000 patients with diabetes mellitus in year 2010, which constitutes 8.6% of Serbian population. It is estimated that 10.2% of Serbian population will be diabetic in the year 2030 **(**Diabetes –The Policy Puzzle, www.batut.org.rs**).**

During its course diabetes mellitus leads to chronic microvascular and macrovascular complications. Bad glycoregulation, obesity, dislidemia, duration of disease and smoking contribute to occurrence of these complications. Microvascular complications are: diabetic neuropathy, nephropathy and retinopathy. Macrovascular complications are: heart attack, stroke and peripheral vascular disease. Clinical entity characterized with nerve damage during diabetes mellitus is called diabetic neuropathy. Together with vascular damage on lower extremities it is most common cause of diabetic foot. Ischemic foot without neuropathy is rarely seen in diabetic patients, and treatment is same as for neuroischemic foot. Patients with diabetes mellitus during life have 15 to 25% chance to develop plantar foot ulcer. Most of them (50 to70%) will have recurrence of ulcer in next five years. This condition leads to foot amputation in 85% of cases (Bulton 2008). Mortality rate after foot amputation due to diabetic foot is 13 to 40% in firs year, 35 to 65% in three year period, and 39 to 80% in five years which is significantly higher than in most of malignancy.

It is very difficult to directly measure the stress and deformation inside the foot biomechanics in vivo. In order to provide a supplement to the experimental inadequacy, many researchers had turned to the computational methods in search of more clinical information. Computational modeling, such as the finite element (FE) method has been used increasingly in many biomechanical investigations with great success due to its capability of modeling structures with irregular geometry and complex material properties, and the ease of simulating complicated boundary and loading conditions in both static and dynamic analyses. The FE analyses could allow efficient parametric evaluations for the outcomes of the shape modifications and other design parameters of footwear without the prerequisite of fabricated footwear and replicating patient trials.

Existing FE models of the foot or footwear in the literature (Bandak et al 2001, Chen et al 2003. Giddings et al 2000, Lemon et a 1997, Syngellakis et al 2000, Verdejo and Mills 2004) were developed under certain simplifications and assumptions such as a simplified or partial foot shape, assumptions of linear material properties, infinitesimal deformation and linear boundary conditions without considering friction and slip. Although several 3D foot models were developed recently to study the biomechanical behavior of the human foot and ankle, a comparison with foot pressure measurement has not been reported.

In this paper we firstly described finite element formulation, mesh generation procedure, material properties, boundary condition and clinical setup measurement for foot pressure for static and dynamic condition. Then some results for measurement for both static and dynamic condition are presented as well as numerical results for static condition. At the end some conclusions are given.

2. Methods

2.1. Finite element formulation

We used linear tetrahedron finite element (Fig. 1) where displacement field over the tetrahedron element is defined by the three components u_x, u_y and u_z. These displacements are linearly interpolated over the element from their nodal values

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} u_{11} & u_{12} & u_{13} & u_{14} \\ u_{21} & u_{22} & u_{23} & u_{24} \\ u_{31} & u_{32} & u_{33} & u_{34} \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix} \tag{1}$$

where N1, N2, N3, N4 are the interpolation functions which are simply the tetrahedral coordinates; and u11,….,u34 are the nodal displacements.

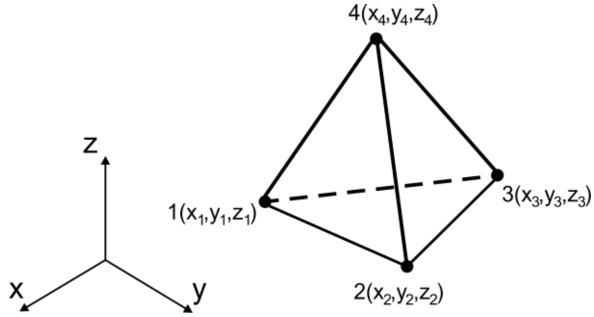

Fig. 1 The linear tetrahedron element

The internal virtual work can be expressed as (Kojic et al 2008)

$$\delta W^{\text{int}} = \int_V \delta \mathbf{e}^T \boldsymbol{\sigma} dV = \delta \mathbf{U}^T \int_V \mathbf{B}^T \mathbf{C} \mathbf{B} dV \mathbf{U} = \delta \mathbf{U}^T \mathbf{K} \mathbf{U} \tag{2}$$

where we have employed the relation for strain components:

$$\mathbf{e} = \begin{Bmatrix} e_{xx} \\ e_{yy} \\ e_{zz} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{Bmatrix} u_{1,1} \\ u_{2,2} \\ u_{3,3} \\ u_{1,2}+u_{2,1} \\ u_{2,3}+u_{3,2} \\ u_{1,3}+u_{3,1} \end{Bmatrix} = \begin{bmatrix} N_{1,1} & 0 & 0 & ... & N_{N,1} & 0 & 0 \\ 0 & N_{1,2} & 0 & ... & 0 & N_{N,2} & 0 \\ 0 & 0 & N_{1,3} & ... & 0 & 0 & N_{N,3} \\ N_{1,2} & N_{1,1} & 0 & ... & N_{N,2} & N_{N,1} & 0 \\ 0 & N_{1,3} & N_{1,2} & ... & 0 & N_{N,3} & N_{N,2} \\ N_{1,3} & 0 & N_{1,1} & ... & N_{N,3} & 0 & N_{N,1} \end{bmatrix} \begin{Bmatrix} U_1^1 \\ U_2^1 \\ U_3^1 \\ \vdots \\ U_1^N \\ U_2^N \\ U_3^N \end{Bmatrix} = \mathbf{BU} \tag{3}$$

from which $\delta \mathbf{e}^T = \delta \mathbf{U}^T \mathbf{B}^T$, and the constitutive relationship $\boldsymbol{\sigma} = \mathbf{Ce}$; here, **e** is the strain (used here in th form of the engineering strain vector), **U** is the vector of nodal displacements**, B** is the strain-displacement relation matrix, and **C** the material constitutive matrix. Clearly, the stiffness matrix $\mathbf{K}$ is

$$\mathbf{K} = \int_V \mathbf{B}^T \mathbf{C} \mathbf{B} dV \tag{4}$$

and the element internal force $\mathbf{F}^{\text{int}}$ is given by the expression $\mathbf{F}^{\text{int}} = \mathbf{KU}$. The stiffness matrix is symmetric and has dimensions $3N \times 3N$ (in our case 12×12) and the force vector $\mathbf{F}^{\text{int}}$ is of size $3N$, $\mathbf{F}^{\text{int}}\left(F_x^{(\text{int})1}, F_y^{(\text{int})1}, F_z^{(\text{int})1}, ..., F_x^{(\text{int})N}, F_y^{(\text{int})N}, F_z^{(\text{int})N}\right)$.

The external nodal forces resulting from the pressure on an element surface are calculated by employing again the equivalence of virtual work. A simple approximation for the 4-node tetrahedron element is to calculate the total force as $F_p = pA$ (where p is the mean pressure and A is the area of the element side) and use $F_p / 3$ at each node in the normal surface direction.

2.2. Mesh generation

The FE model of the human foot and ankle, as shown in Fig. 2, consisted of 28 bony segments, including the distal segments of the tibia and fibula and 26 foot bones: talus, calcaneus, cuboid, navicular, 3 cuneiforms, 5 metatarsals and 14 components of the phalanges.

We created a 3D FE model by using MIMICS software 3D DICOM CT slices (Fig. 2a). After smoothing of the surface boundary the final tetrahedral finite element mesh is generated. The finite element analysis was performed with program PAK (Kojic et al 1998). The finite element mesh was composed of 48447 nodes and 232187 linear tetrahedral elements.

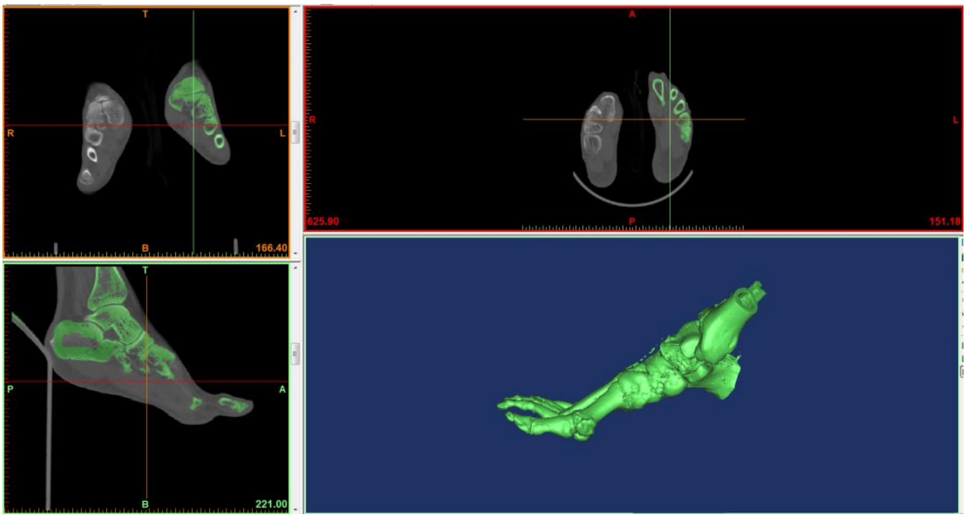

Fig. 2 3D foot reconstruction from DICOM CT slices

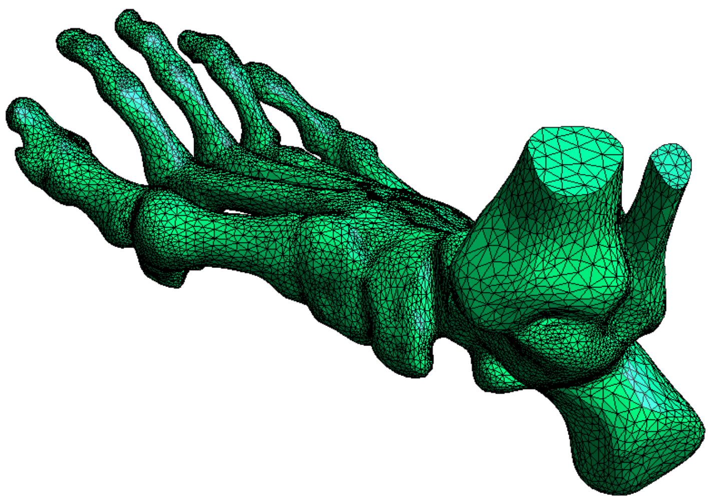

Fig. 3 3D finite element mesh of foot model after generation and smoothing techniques

2.3. Material properties and boundary conditions

We consider all material properties as homogeneous, isotropic and linearly elastic. The effective Young's modulus and Poisson's ratio for the bony structures were assigned as 7300 MPa and 0.3, respectively, according to the model developed by Nakamura et al 1981. The Young's modulus of the cartilage is 1 MPa (Athanasiou et al 1998) and the plantar fascia (Wright and

Rennels 1964) was selected from the literature. The cartilage was assigned with a Poisson's ratio of 0.4 for its nearly incompressible nature.

The load of half body weight 400 N was applied as it is presented in Fig 4. The plate which simulated foot pressure sensor was fixed as it is shown in Fig 4.

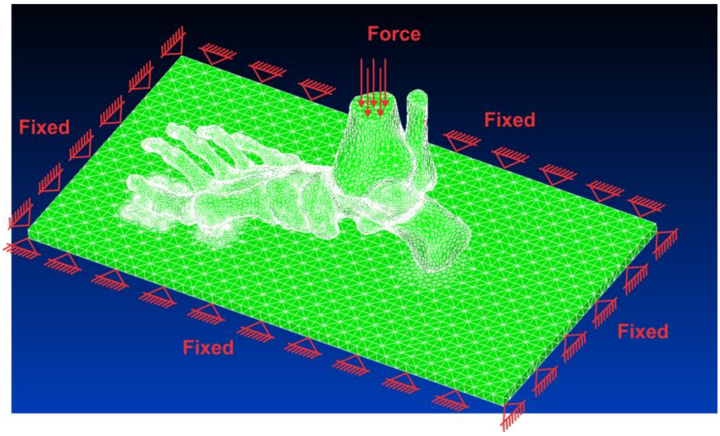

Fig 4. Loading of 400 N and fixed boundary condition

2.4. Clinical setup

We present a case of 63 year old male patient with diabetes mellitus. Main complaints were numbness in the feet, weakness in the legs and night pain in legs. He was diagnosed with diabetes at age 48, and was treated with oral antidiabetics until six years ago when he started insulin therapy in two daily doses, which was intensified after 3 months due to bad glycoregulation (HbA1C-9%). At the same time diabetic polyneuropathy was diagnosed on electromyiographic examination. Diabetic foot infection led to amputation of second toe on the left foot later that year. Recovery period and wound healing went uneventful. Since then he is on intensified therapy on four daily doses of human insulin. He is non-smoker and has hypertension and dyslipidemia. Other possible causes of neuropathy such as vitamin b12 deficiency, thyroid dysfunction, and alcohol abuse were excluded. Paitent has BMI 23,93kg/m2, arterial blood pressure 140/95mmHg, hearth rate 78/minute. His A1c is 7,3%, FBG 3,9-6.9mM, PPG 3.7-9.6mM, CCr 0.96ml/min, Esbach 0.24g/d, TSH 1.7, CRP 0.6. Both lower extremities are present. Peripheral arterial pulses are present on both feet. Skin was warm and dry. At the left foot second toe is absent. There is hallux valgus deformity (bunion) of the left foot. At both feet there are calluses. Using both feet ten point, nylon Semmes-Weinstein monofilament tests we found inability to perceive 10 grams of force in points MT1, MT5, as well as in the first and third toe of the left foot. Vibratory sensation was examined using tuning fork and found abnormal on both lateral malleolus. Computerized tomography of both feet shows osteoporosis of metatarsal bones, and marked hallux valgus deformity of the left foot. Static and dynamic measurement of plantar load distribution for each foot was conducted using pressure platform system.

Schematic foot pressure measurement procedure is presented in Fig. 5.

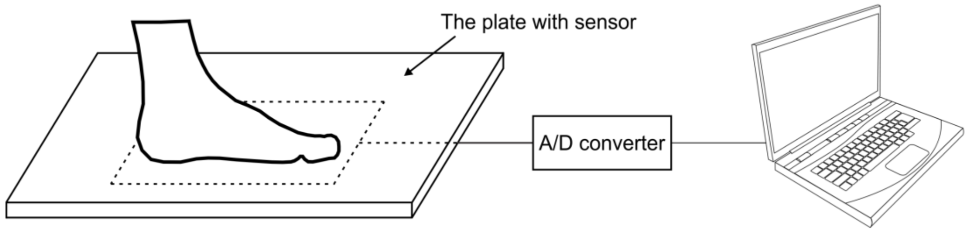

Fig. 5 Foot pressure measurement procedure

3. Results

3.1. Measurements

Static plantar load measurement is performed in following manner: before measuring for five seconds patient stands on platform barefooted, and then load is measured. Procedure is repeated three times. The foot was divided into 10 regions: heel, mid-foot, first, second, third, fourth and fifth metatarsal (MT) heads, hallux, second toe and third to fifth toes.

Results for left foot: max.124.74 kPa; MT max.118.63 kPa min 3.96 kPa; heel max.19.8 kPpa min.5.61 kPa are presented in Fig. 6. For the right foot measured values are: max.47.76 kPa; MTmax.47.8 kPa min.6.49 kPa; heel max.13.11 kPa min.3.49 kPa. For dynamic plantar load measurement the patient is standing one meter from platform. Then he starts walking with left foot first, and on the third step he stands barefooted on the platform with his left foot and keeps walking. After that the same measurement procedure is performed for the right foot. Device automatically measures load distribution changes in real time in three dimensions. Results are given both numerically and graphically. The results for left and right foot are presented in Fig. 7: left foot: MT(3) max 137.78 kPa heel max 26.82 kPa; right foot: MT(5) max 146 kPa, heel max.24.62 kPa. For dynamic plantar measurements for left and right foot the results have been shown in Fig 8: left foot max.137,78 kPa, rearfoot max 26.82 kPa; right foot: max.146 kPa, rearfoot max 24.62 kPa;

Effective stress distribution along plate for right and left foot are presented in the Figs 9,10 respectively.

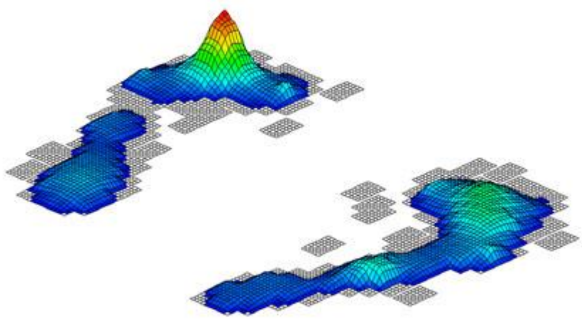

Fig 6. Results for static plantar measurements for left foot: max.124.74kPa; MT max.118.63 kPa min 3.96 kPa; heel max.19.8 kPa min.5.61kPa.

Fig 7. Results for dynamic plantar measurements for left and right foot: max.145.16 kPa for left foot and max.156.98 kPa for right foot;

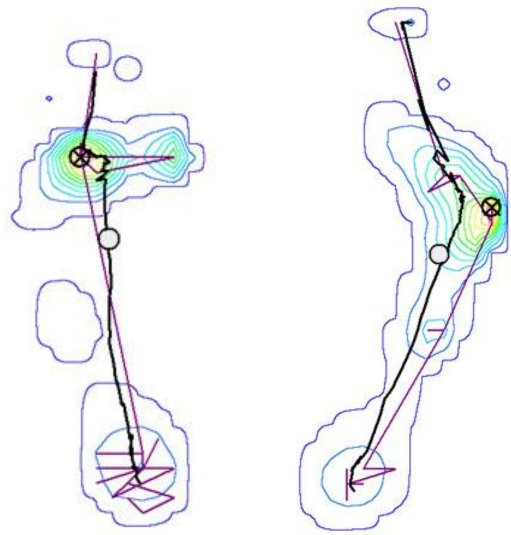

Fig 8. Results for dynamic plantar measurements for left and right foot: left foot max.137,78 kPa, rearfoot max 26.82 kPa; right foot: max.146 kPa, rearfoot max 24.62 kPa;

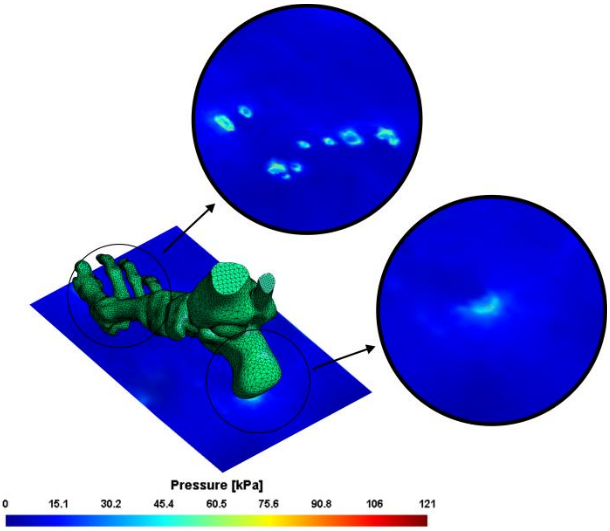

Fig 9. Effective stress distribution along plate for right foot

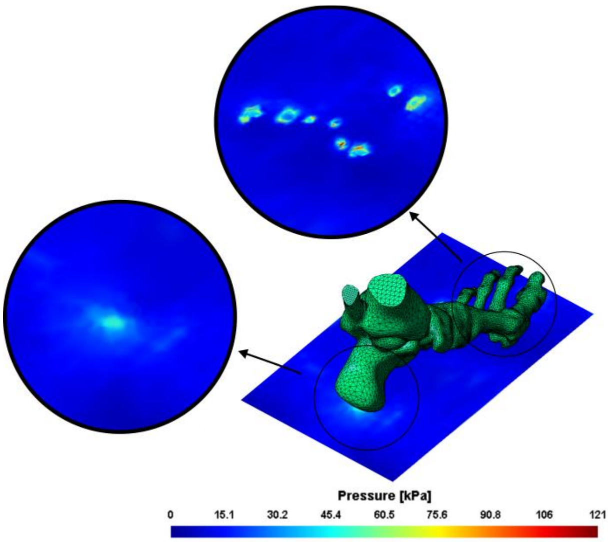

Fig 10. Effective stress distribution along plate for left foot

4. Conclusions

Numerous studies concluded that high plantar pressure, duration of diabetes mellitus longer than ten years, inadequate glycoreguation, foot deformation, male gender, one or more signs of diabetic neuropathy are significantly associated with foot ulcer occurrence (Lazaro et al 2011, Somai and Vogelgesang 2011, Singh et al 2005). In study Lavery et al 1998, 78% of patients with diabetic foot ulcer had some kind of foot deformity which was directly correlated with ulcer localization and maximum plantar pressure point. Vascular disease, nephropathy, retinopathy, obesity and level of education were not connected with foot ulcers (Lavery et al

2003). In prospective cohort studies using EMED pressure platform, a maximum barefoot dynamic pressure of 87.5N/cm2 had sensitivity of 64% and specifity of 46%, positive predictive value of 17%, and negative predictive value of 90% [19].

In our report results of both static and dynamic measurement of plantar pressure gave topographic distribution of high pressure points which is in correlation with clinical tests results. Static and dynamic results also correlated between each other.

Using dynamic foot pressure measuring, monofilament test and vibration fork test we can pinpoint location with highest risk of developing diabetic foot ulcer. Dynamic pressure measuring is not time consuming, and data obtained during examination are in digital form which makes them easily available and comparable.

Numerical simulation gave for static loading 121 kPa which is in good comparison with 124.74 kPa of foot pressure measurement. This can be efficient and inexpensive screening tool, which could give us a chance to prevent diabetic foot complications, associated with high mortality and morbidity that has significant economic impact on healthcare system.

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Извод

Статичко и динамичко мерење и компјутерска симулација биомеханике стопала код пацијента са diabetic mellitus дијагнозом

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Резиме

Циљ ове студије је процена резултата мерења и компјутерске симулације статичких и динамичких оптерећења стопала код пацијента са дијагнозом diabetes mellitus. Метод коначних елемената је коришћен за поређење са мерењима притиска добијених приликом оптерећења стопала. Модел стопала и чланка се састоји од 28 сегмената костију који су добијени 3Д реконструкцијом ДИКОМ ЦТ слика са пацијента код кога је дијагностициран diabetes mellitus. Све материјалне карактеристике су анализиране као хомогене, изотропне и линеарно еластичне. Мерења притиска при статичком и динамичком режиму су дала топографичку дистрибуцију високих зона притиска што је у корелацији са клиничким тестовима.

Мерењем добијени највећи притисак на левом стопалу од 124.74 kPa је упоредив са нумерички добијеним притиском од 121 kPa. Закључујемо да нумеричка симулација у комбинацији са мерењима оптерећења стопала може бити ефикасан и јефтин алат у праћењу пацијента и унапређивању превенције код пацијента са дијабетесом стопала што

може значајно смањити смртност ових пацијената и имати значајан економски ефекат на здравствени систем.

Keywords: Мерење притиска стопала; Diabetes mellitus пацијент, Метод коначних елемената.

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