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Research Article

Extracting the Optimal Vibration Coefficients of Forefoot Offloading Shoes Using Genetic Algorithms

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A b s t r a c t

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Diabetes is one of the main causes of foot health related diseases and suitable footwear plays a crucial role in foot health condition. Forefoot offloading shoes (FOS) are commonly used for treatment of plantar ulcers in diabetic foot. In this study, technical improvements of these shoes are primarily influenced by the optimisation of the transferred vibration energy during foot/ground interactions. The shoe considered as a body segment in the whole body vibration analysis. The aim of this study was to determine the optimal spring/damper coefficients of a vibration model of FOS from Lucro Schein Company (Code-Nr.322147) in order to minimize the total absorption of vibration energy of the human body during gait. Genetic algorithms were implemented to obtain the solution of optimisation problem because of its high speed of calculation and accuracy based fitness. Speed of calculation plays a critical issue in footwear industry. The model can suitably simulate the role of mechanical characteristics of footwear in the absorption of vibration energy during gait. Obtained optimised vibratory coefficients of two different regions of shoe, which have been determined by Genetic Algorithms, indicates that mechanical properties, namely stiffness and damping characteristics of each part of the diabetic shoe should be specified separately. The results indicate the necessity of adopting dissimilar materials or different production techniques for different parts of the sole.

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1. Introduction

Patients with diabetes are at increased risk of developing neuropathic ulcers on the plantar surface of their feet. In severe cases, these ulcerations can lead to amputation [1]. Adjustments of plantar foot pressure should thus be considered in promoting the healing of plantar ulcers [1, 2]. Footwear is a matter of great importance to diabetic patients especially when they lose sensation in their feet [3].

Forefoot offloading shoes are specifically designed to offload the patient's forefoot by re-distributing the plantar pressure to other foot regions [4]. In this type of shoe, plantar pressure loading under the forefoot has been severely reduced. This condition promotes the healing of existing foot wounds. One of the main causes of physical stress is the amount of absorbed power during exposure to vertical vibration. The effect of footwear upon the absorbed power during exposure to vertical whole body vibration (WBV) has been addressed in many studies [5, 6]. In order to study the energy content of the vibration transmitted to the whole body, different biodynamic models have been proposed [5]. Energy is a scalar quantity and thus a detailed evaluation of energetic contributions of individual elements of aspring-mass-damper system could be used to obtain a single representative value [7]. To achieve this, a WBV model of human body associated with both hard and soft tissues was adopted [8, 9]. The wide range of possible parameters for vibration elements of these shoes meant that the solution space created by suitable combination of coefficients could pose a challenge. The approach made in this study was to adopt Genetic Algorithms for the optimization process. Genetic algorithms were therefore used to obtain optimal lumped parameters, describing vibration characteristics associated with different regions of a specific type of diabetic shoes. The assessment took place through simulation, using MATLAB software (version 8.3).

2. Methods

2.1. Vibration model

In this study a fifteen-degrees-of-freedom lumped-parameter vibratory model of human body was implemented (see Fig. 1). The lumped parameters of vibratory model have been determined through the physiological and anthropometric data [6, 10]. An expression capable of directly relating the transmitted power to the whole human body vibration had to be derived.

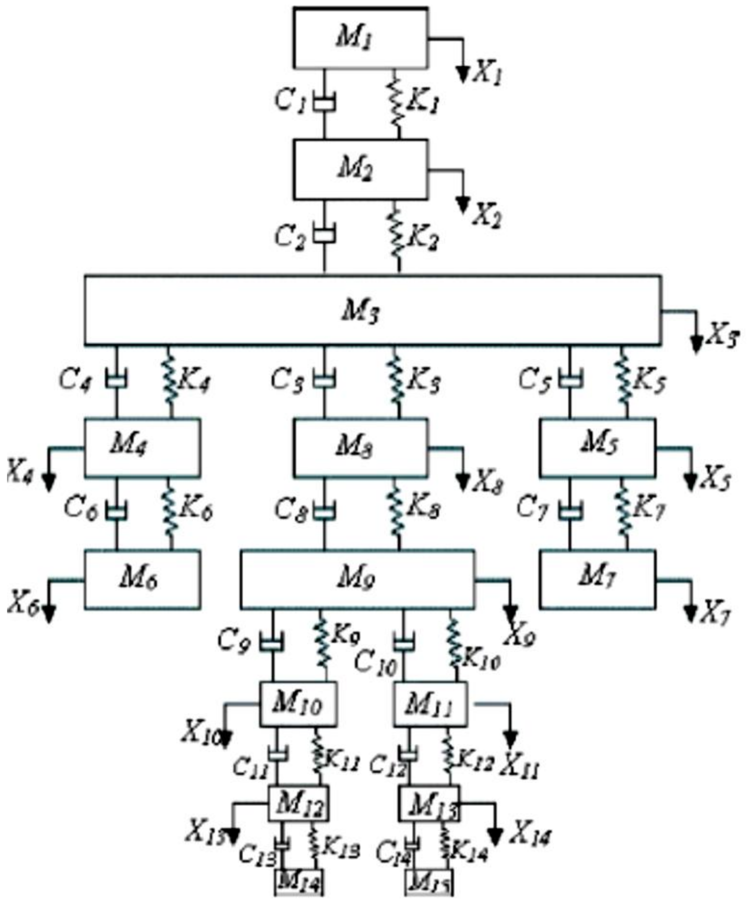

Fig. 1. Schematic drawing of the vibratory model of human

The power transmitted to the body which is directly related to the whole body vibration is represented by expression 1.

$$P_{\mathrm{tr}}(t) = F(t)v(t) = P_{\mathrm{abs}}(t) + P_{\mathrm{el}}(t) \tag{1}$$

Where, $F(t)$ and $v(t)$ represent the force acting on the body and the input velocity, respectively. Moreover; $P_{\mathrm{abs}}(t)$ and $P_{\mathrm{el}}(t)$ which are expressing the unweighted absorbed power and elastic power respectively, can be calculated as below:

$$P_{\mathrm{el}} = \frac{E_{el}}{\Delta T} = \sum_{i=1}^{n}\left(\frac{0.5}{\Delta T} K_i\, x_i^2\right), \quad P_{\mathrm{abs}} = \frac{E_{abs}}{\Delta T} = \sum_{i=1}^{n} C_i\, x_i^2 \tag{2}$$

Where n is the number of spring and dampers in model, K is spring stiffness of each segment, x is spring displacement, $\dot{x}$ is the velocity of displacement of parallel spring and damper and T is time duration of spring and damper displacement. Total vibration energy function consists of the elastic energy of the springs (E_{el}), dissipated energy by dampers (E_{abs}) and gravitational potential energy of masses. This function is then associated with the lumped parameters. Total vibration energy (J) could be considered as the objective function

$$J = E(C_{\text{midfoot}}, K_{\text{midfoot}}, C_{\text{heel}}, K_{\text{heel}}) \tag{3}$$

J_E can thus be defined as

$$J_E = \sum_{i=1}^{n} \left| P_i(C_i, K_i) \right| \tag{4}$$

Therefore J_E is a function of $C(s)$ and $K(s)$, which should be minimized in order to reduce stresses which could induce unpleasant physical effects caused by absorbed vibration energy. To minimize the function of total vibration energy, optimized values of K and C in J_E expression were determined.

2.2. Optimization problem

Optimization of objective functions of this nature is a complex non-linear problem and methods such as genetic algorithms, neural networks and simulated annealing which have been successfully applied to similar problems in other disciplines [11-13], could also be used here. In this paper, the GA was used to obtain optimized vibration coefficients of diabetic shoes through minimization of the whole body vibration. The GA optimization is essentially a recursive process where a large population of lumped parameters requires a search based strategy to find a global optimum solution. Application of GA to human WBV model required the establishment of the relationship between solutions and chromosomes through encoding.

Advantages such as speed, accuracy in calculations and abundant genetic operators lead to adoption of Float encodes. The solutions are then initialized with colonies prior to evolution process which was in effect similar to biological mechanisms where good properties enhances the chances of survival. By crossing and mutating among individuals, the colonies kept the information variable. The Fitness function provided the tool for colony evaluation and the maximum evaluation generation provided termination.

2.3. Simulation

The vibration model of human body with diabetic shoes has been simulated for a US man with weight and height of 73 kg and 168.67 cm, respectively. SimMechanics (MATLAB) was used for this simulation. All body segments were assumed to be centralized masses connected by spring and damper blocks through prismatic joints to impose vertical vibration. FOS shoes from Lucro Schein Company have been modelled using mass-less springs and dampers located under the heel and midfoot for specific angle of rocker bottom in the selected type of FOS. The company has been modelled using mass-less springs and dampers located under the heel and mid-foot for specific angle of rocker bottom in the selected type of FOS. Geometric characteristics of this type of FOS were derived from the Lucro Schein specifications (see Fig. 2).

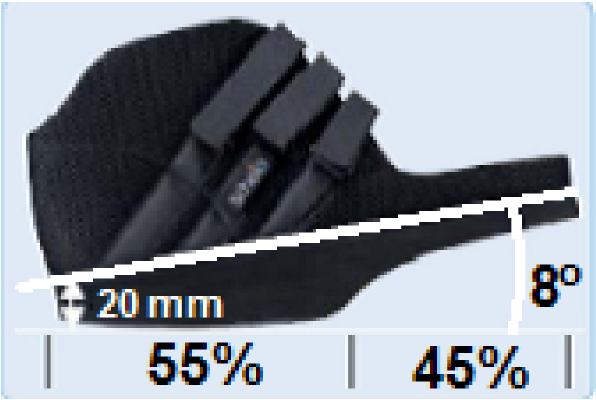

Fig. 2. Study shoe-FOS from Lucro Schein Company (Code-Nr.322147)

An input signal was built as an actuator in order to simulate the influence of ground reaction force on the model. Diagram of ground reaction force for a normal man [14] is shown in figure 3. This diagram has been used to achieve acceleration in vertical direction.

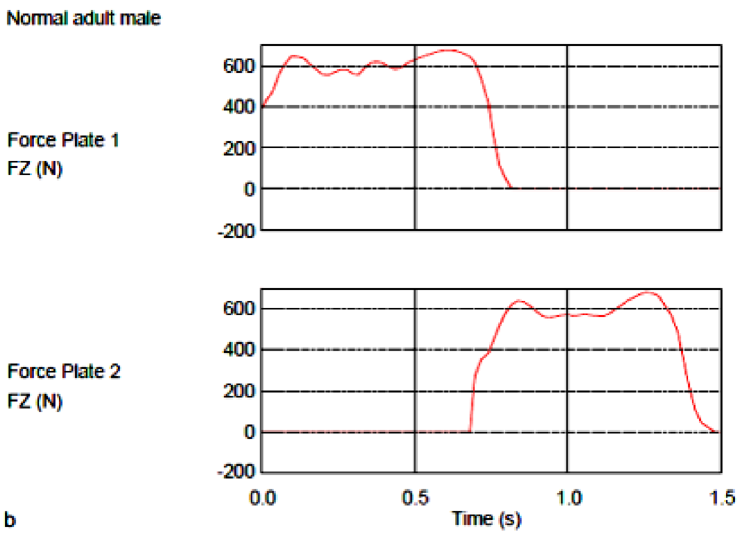

Fig. 3. Ground reaction force

In order to get deformation velocity of sole, we would integrate the acceleration. With respect to conservation of linear momentum, the impulse which is entered from ground to the sole has direct relationship with sole deformation velocity during stance phase. Thus, the load changes applied to the sole of the shoe can be considered the same as the rate of changes in the sole.

$$\int F \, \mathrm{d}t = mv_2 - mv_1 \cdot \tag{5}$$

Therefore by integrating the velocity function, deformation of sole which is in contact with ground can be calculated. Maximum deformation of sole has been considered in the range of millimeter. Acceleration, velocity and position diagrams will be entered as an actuator to the vibration model (see Fig. 4).

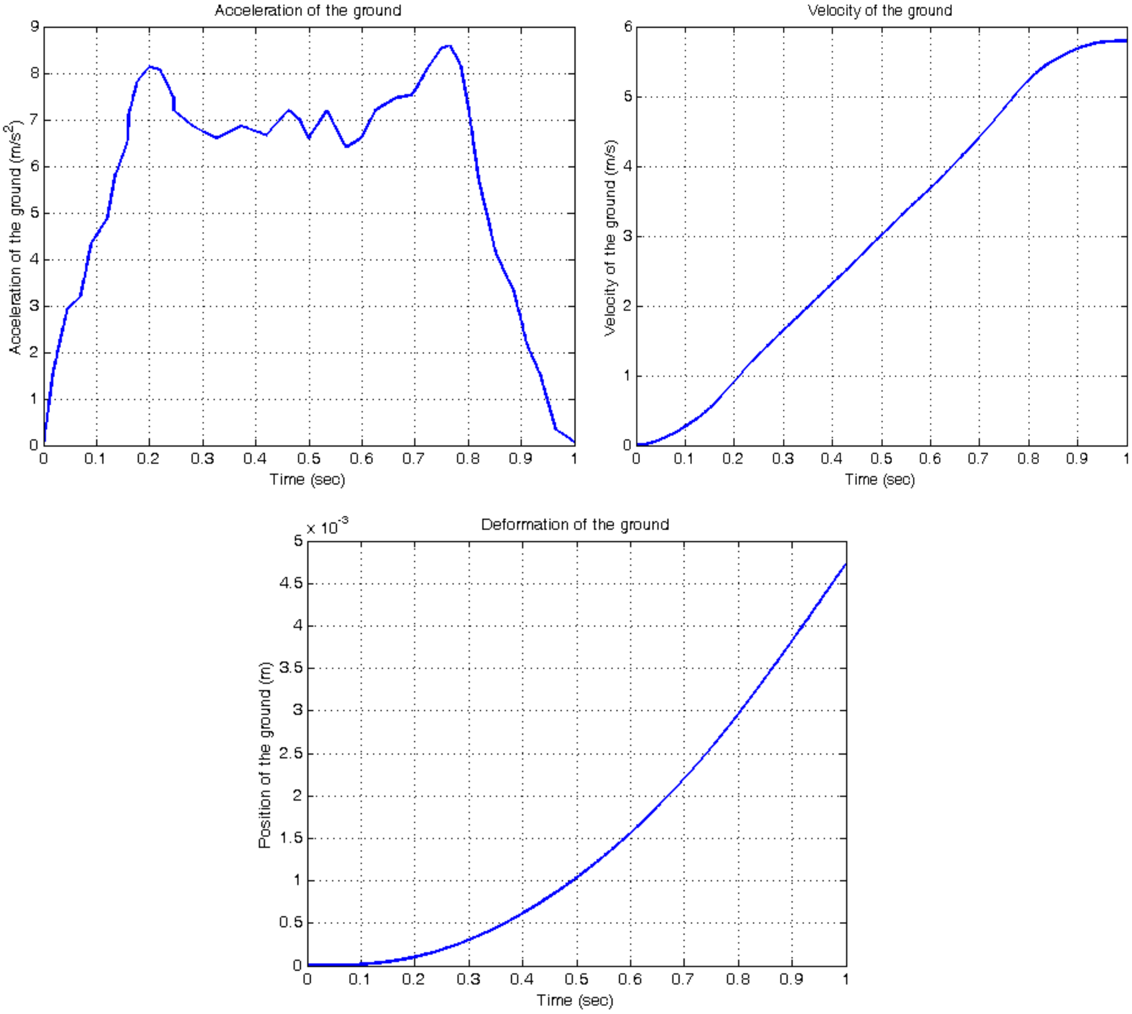

Fig. 4. System input signals (Actuator)

3. Results

In the next step we will use Genetic algorithms for optimization process. Fig. 5 shows total vibration energy and the RMS vs time, applying some arbitrary selected pairs of (C, K) constants. As shown, RMS graphs are smoother compared to the graphs of total vibration energy. Thus using RMS graphs are much more appropriate for solving optimization problem.

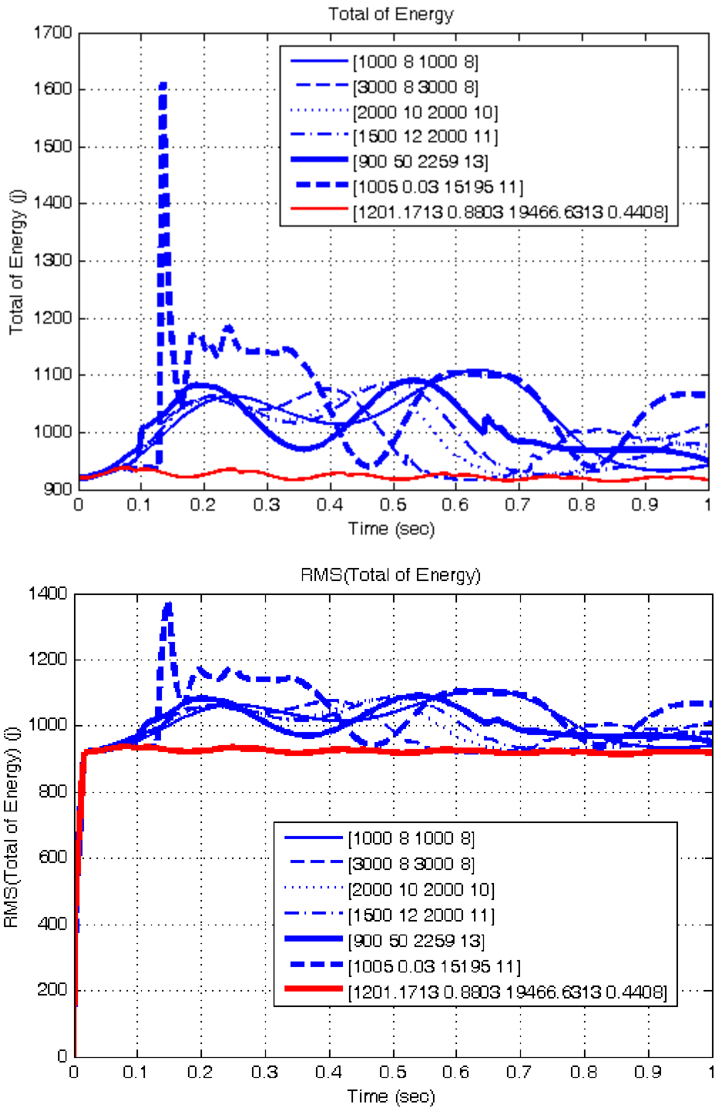

Fig. 5. Comparison of total vibration energy

WBV energy profile is made suitable for the application of GA through adoption of equivalent RMS (root mean square) values to represent the objective function of the algorithm. The function is expressed as follows:

$$f_{\mathrm{rms}} = \sqrt{\left(\frac{1}{T_2 - T_1}\right) \int_{T_1}^{T_2} [\, f(t)]^2 \mathrm{d}t} \cdot \qquad (6)$$

To prevent disorder and sudden changes of the target function and also to improve the program preference, the target function was converted to the RMS. Thus the target function graph became smoother and also could optimize and minimize the extremum values. As can be seen from the Fig. 5, optimizing the RMS of target function can optimize and minimize the target function. This can increase the accuracy and decrease the error of the GA program, which result in the objective of the study. During GA optimization procedure, increasingly better solutions were evolved in each iteration of the algorithm.The optimized results of total vibration energy and the RMS is depicted in red colour. There is a significant difference between the value of optimized total vibration energy as a function of optimal parameters and the values of energy as a function of arbitrary pairs of (C,K) constants.Obtained optimal vibratory coefficients for two different regions of the foot (i.e. heel and midfoot) are:

$$K_{\text{heel}} = 1201.1713\,(\text{N/m}),\ C_{\text{heel}} = 0.8803\,(\text{Ns/m}),$$
$$K_{\text{midfood}} = 19466.6313\,(\text{N/m}),\ C_{\text{midfood}} = 0.4408\,(\text{Ns/m})\cdot$$

The optimized results for the system parameters (i.e. stiffness and damping coefficients of two different regions of selected FOS shoe) were in the range of the values expressed in experimental researches [17].

4. Discussion

In this study, GA based method effectively could solve the problem of optimization. The values obtained from this method indicate that for making minimum the total vibration energy and as a result of that, the absorbed power; (C,K) the constants should be different in heel and midfoot area. The results expressed that damping coefficient in heel should be greater than midfoot while midfoot needs greater stiffness coefficient value than heel.

There are reliable dynamics measurement systems of suppliers showing pressure distribution between the sole of the foot and the insole [15]. Study of the plantar pressure distribution analysis for Lucro Schein FOS shoes indicates that significant amount of peak pressure is distributed in heel region [16]. Therefore damping coefficient should be greater in heel region in order to absorb shocks and this fact is conformable to the results of our optimization.

5. Conclusion

A vibration model of human body was studied, considering vibration characteristics of special kind of diabetic shoes. The optimal values of (C,K) coefficients for two distinct part of one special kind of footwear were obtained by means of Genetic algorithms.Since the main strength of GA is its fast convergence, Genetic algorithms were used in this article. This article aims to design software in order to suggest appropriate material for customised footwear production industry. Therefore speed is a critical issue in this concern.

These optimal values play an essential role in minimizing the whole body vibration which leads to more physical comfort and better health condition for diabetic patients.

In next studies some more detailed researches can be done in biomaterial area in order to find appropriate materials and techniques of production

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