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Novel training machine for stimulation of blood circulation in feet

M. Venslauskas*, V. Ostasevicius, V. Jurenas*****
**Kaunas University of Technology, Studentu 56, 51424 Kaunas, Lithuania, E-mail: mantas.venslauskas@ktu.edu*
***Kaunas University of Technology, Studentu 56, 51424 Kaunas, Lithuania, E-mail: vytautas.ostasevicius@ktu.lt*
****Kaunas University of Technology, Studentu 56, 51424 Kaunas, Lithuania, E-mail: vytautas.jurenas@ktu.lt*

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1. Introduction

People with diabetes can develop many different feet problems. Even ordinary problems can get worse and lead to serious complications. Poor blood flow or flow changes in the shape of the feet or toes may also cause problems. People might not notice a foot injury until the skin breaks down and becomes infected. Walking on an ulcer can make it get larger and force the infection deeper into the foot. The fundamental of diabetic foot problem - insufficient blood supply. Poor blood flow can make the foot less able to fight infection and to heal. Diabetes causes blood vessels of the foot and leg to narrow and harden. From the three main types of blood vessels - arteries, veins and capillaries - the most important are capillaries.

Vibrational training is advantageous to improve muscle strength, power, coordination and even cardiovascular system. Our earlier studies have showed that vibration training affects blood pressure and respiration rate [1]. It is well known that the primary hypertension is characterized by elevated cardiac output, whereas in later stages the increased blood pressure is due to increased peripheral resistance. Blood vessels are able to control blood flow rate by changing its diameter because of elastic properties. When pressure is constant fluid volume flow rate is reduced. This permanent reaction can be characterized as structural auto regulation [2].

It is known that lower density of capillaries in limbs tissues occur in patients with essential hypertension. The capillarity exercise methodology was investigated by registering temperature changes in hand’s fingers before and after the exercise. It was noted 0.8 C degree raise of temperature (not published data). Most are being aware of hypertension only after suffering heart attack or stroke. The majority of patients with hypertension do not know what steps to take to lower blood pressure. In the foreign research databases could be found lots of testimonies that high blood pressure is directly related to the rarefaction of capillary density in body tissues [3-5]. Above mentioned problems are caused by the various circulatory disorders.

Results of studies on vibration training influence on cardiovascular system has showed that capillaries are probably opened in order to keep a necessary level of cardiac output needed for the body [6].

The effect of whole-body vibration on leg blood flow was investigated. Young adult males completed a set of random vibration and nonvibration exercise bouts whilst squatting vibrating plate. Blood pressure of the common femoral artery and blood cell velocity were measured in a standing or rest condition prior to the bouts and during and after each bout. The results show leg blood flow increased during the squat or nonvibration bouts and systematically increased with frequency in the vibration bouts [7].

The purpose of other study was to investigate the effects of whole-body vibration on blood flow velocity and muscular activity after different vibration protocols in Friedreich's ataxia patients. Ten patients received whole body vibration treatments with random combination of frequency and protocol. Femoral artery blood flow velocity, vastus lateralis and vastus medialis electromyography, and rate of perceived exertion were registered. Peak blood velocity was increased. Electromyography amplitude was increased and frequencies decreased during the application of whole body vibration. The results suggest that whole body vibration is an effective method to increase blood flow in patients with Friedreich's ataxia [8].

Other study partly aimed to determine the effects of vibration on leg blood flow after intense exercise. Twenty-three participants performed an exercise tests followed by a recovery period using whole-body vibration or a passive control in the seated position and blood flow was assessed. Results showed that whole body vibration decreased pulsatility index in the popliteal artery following maximal exercise and was effective to increase performance in a later exercise tests [9, 10].

The aim of this study was to identify Eigenfrequencies of novel legs’ vibration machine depending on different human weight and make an experiment identifying blood circulation changes in foot using thermovision camera.

2. Materials and methods

2.1. Computer modelling

Comsol Multiphysics software with the structural mechanics module were used for calculations. The Structural Mechanics Module is tailor-made to model and simulate applications and designs in the fields of structural and solid mechanics. The module is dedicated to the analysis of mechanical structures that are subject to static or dynamic loads. The eigenfrequency analysis was computed for the natural frequencies of the unloaded and loaded structures.

Rectangle solid model of 0.485 m length and 0.004 m thickness was designed. Glass epoxy material properties with density of 2000 kg/m^3, Young’s modulus of 17 KPa and Poisson’s ratio of 0.32 was assigned to the model [11]. Model was fixed on left end. Imitating motors’ weight load was set on the right end with vertical direction and on the top of the model legs weight imitating load was prescribed. Loads of leg mass of 25.02 kg (Fig. 1, blue arrows along beam’s length of vertical down direction) and motors bulk mass of 6.43 kg (red arrow of vertical down direction) were added to the beam model at relevant places as on vibrational training machine.

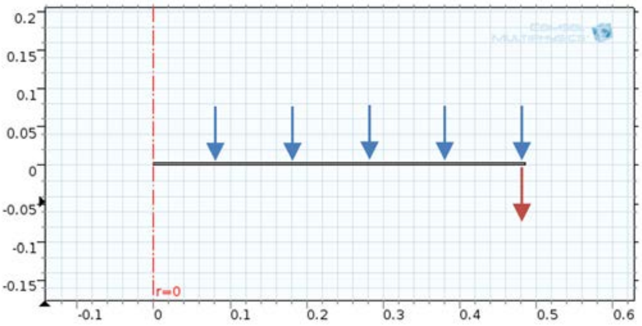

Fig. 1 Glass epoxy beam model with legs mass load (blue arrows) and motors weight load (red arrow), fixed edge is by dotted red line

Designed model could be easily adjustable considering variations of input parameters such as length, width or load either material. The model is simplified and requires minimal time resources for making high amount of calculations. This model will be used for further studies on purpose of identifying eigenfrequency values of different heights of vibrating glass epoxy plate. 3D model was rejected due to the low efficiency of the use of time for calculations.

2.2. Experimental setup

Vibration motors that could be find in the market are specific and it would be difficult to adopt in this research area. For this reason unbalanced mass was designed on SolidWorks software with parameters given on Table 1. Two identical unbalanced masses were made from the steel. These masses were made with the aim to induce vibrations and generate force to glass epoxy plate by mounting and fixing them on the motor's rotor. Main parameters of these masses are given in Table 1.

Table 1

Unbalanced mass parameters

Parameter	Value
Bulk mass	616,8 g
Mass without unbalance	212,92 g
Unbalance mass	403,88 g
Diameter	66 mm
Diameter without unbalance	36 mm

Two DOGA D.C. motors (Table 2) with mounted unbalanced masses were used to create beating phenomenon and higher force comparing to one vibration motor. Revolutions per minute of each motor were controlled by changing supplied voltage on power suppliers. Two vibrations with slightly different frequencies (supplied voltage values) induce the beats phenomenon. It is well known that beats occur when two frequencies are close together. Transfer of energy takes place in the coupled system which could induce vibration in the primary system instead of suppressing them. The coupled equations of motion without damping in both systems can be obtained from Eq. 1 by setting damping in each system equal to zero.

$$\begin{bmatrix} 1+\mu & \alpha\mu \\ \alpha & 1 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix}+\begin{bmatrix} \omega_1^2 & 0 \\ 0 & \omega_2^2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (1)$$

The modal frequencies of this system are given by:

$$\bar{\omega}_{1,2}=\sqrt{\frac{\omega_1^2+\omega_2^2(1+\mu)\pm\prod}{2\left(1+\mu-\alpha^2\mu\right)}} \quad (2)$$

The coupling parameter α in the mass matrix is responsible for the beat phenomenon.

Table 2.

DOGA D.C. motor parameters

Parameter	Value
Bulk mass	2,6 kg
Nominal voltage	24 V
Nominal Torque	0,75 Nm
Nominal speed	1000 rpm
Nominal current	5,5 V

Investigated leg mass calculations were based on Plagenhoef et al. (1983) studies [12]. Total leg weight is equal to 16.68% of total male weight and 18.43% of total female weight. Calculations of leg mass depending on different body weight were made and can be found in

Table 3. These values are necessary for executing eigenfrequency analysis on Comsol Multiphysics software.

Table 3

Leg mass calculations

Body weight	Leg mass
55 kg (female)	20,273 kg
60 kg (female)	22,116 kg
65 kg (female)	23,959 kg
70 kg (female)	25,802 kg
75 kg (male)	25,02 kg
80 kg (male)	26,688 kg
85 kg (male)	28,356 kg
90 kg (male)	30,024 kg
95 kg (male)	31,692 kg
100 kg (male)	33,36 kg

Experimental setup is presented in Fig. 2. Training machine (Fig. 2, (1)) model was designed with SolidWorks software. Machine was developed with the ability of changing plate's angle where tested person's legs are fixed. The glass epoxy plate was chosen as vibrating part because of its cyclic durability of the flexural strength. The plate was covered with a foam for a better comfort reason. Plate's length can be adjustable depending on human's height or leg's length. Motors were adjusted to give an inward rotation to unbalanced masses so creating force to vertical direction. Motors were fixed motionlessly next to each other. Beating phenomenon enables to induce sufficient force by using low voltage and small size motors for making vibrational movement of adequate displacement. Vibrations' data was gathered from Robotron 00032 with low frequency acceleration sensor KB12 with resolution of 300 mV per 1 m/s^2 and processed with Picoscope 3424 in

Picoscope PC software. Motors were supplied by Digimess HY3020 power suppliers (1ch, 30V, 20A, adjustable).

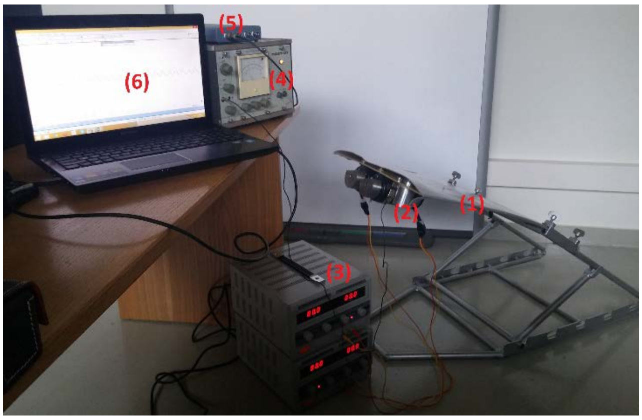

Fig. 2 Experimental setup: *1* - Legs vibrating machine with motors and unbalanced masses; *2* - Acceleration sensor KB12; *3* - Power suppliers (0-30V/20A, adjustable); *4* - Robotron 00032; *5* - Picoscope 3424; *6* - PC with Picoscope 6 software

Legs vibrational training machine was developed with the aim to eliminate negative effects of standing human vibrations that are described on various studies. For example on ISO 2631-1 guidelines on Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration is written that long-term high-intensity whole-body vibration indicates an increased health risk to the lumbar spine. It is noted that this may be due to the biodynamic behaviour of the spine: horizontal displacement and torsion of the segments of the vertebral column. Furthermore whole-body vibration exercise may worsen certain endogenous pathologic disturbances of the spine. Developed legs' vibrating machine eliminates negative vibrational excitation effects that are caused by standing position. Further studies are planned for physiological parameters measurement after affecting human in prescribed protocol of vibrations using developed legs' vibrating machine.

Fig. 3 High-sensitivity infrared thermal imaging camera FLIR-t62101

Vibrational excitation influence is widely defined in previous studies mentioned in the Introduction chapter. To identify vibrational excitation influence on foot blood flow high-sensitivity infrared thermal imaging camera was used (Fig. 3). Four points on right foot (Hallux toe, Long toe, right point on the foot and left point on the foot) were monitored before and after experiment and temperature difference was registered by making thermal images.

3. Results

First, eigenfrequency analysis of epoxy glass plate was made with Comsol multiphysics software. Primary calculations were made without adding leg mass and after then prescribing legs weight of 75 kg weight male (equal to tested person). Eigenfrequency of glass epoxy beam without leg mass load was equal to 9.05 Hz (Fig. 4). After adding leg mass of 25.02 kg and motors bulk mass of 6.43 kg eigenfrequency value decreased to 3.28 Hz (Fig. 5).

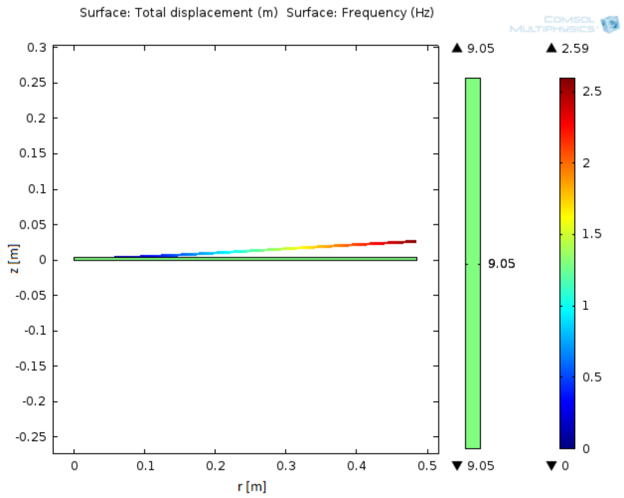

Fig. 4 Eigenfrequency value of first vibration mode without load

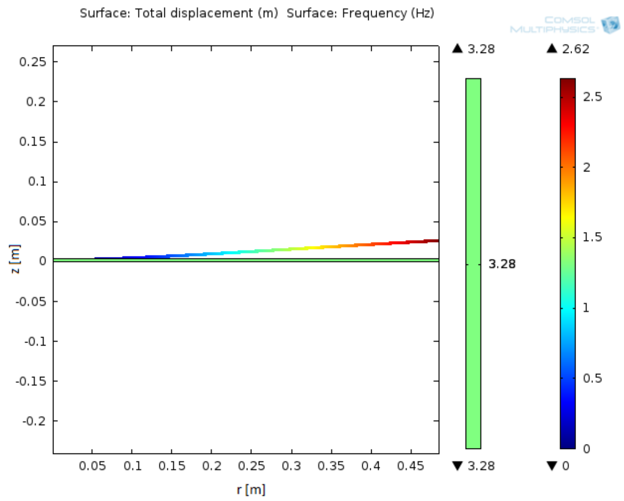

Fig. 5 Eigenfrequency value of first vibration mode with load

Further calculations with aim to identify frequency range of different weight male and female persons were made by changing legs mass load on beam regarding to Table 3. Frequency values from 3.47 to 3.25 Hz for females at 55 to 70 kg weight range and frequency range from 3.28 to 3.02 Hz for males at 75 to 100 kg range were calculated and are given in Table 4.

Table 4

Eigenfrequency value differ depending on body mass and gender

Body mass, kg	Gender	Eigenfrequency, Hz
55	Female	3.47
60	Female	3.39
65	Female	3.32
70	Female	3.25
75	Male	3.28
80	Male	3.22
85	Male	3.17
90	Male	3.11
95	Male	3.06
100	Male	3.02

Next experiments with legs vibrating machine identifying working frequencies were executed. Beating phenomenon was induced during vibrational excitation in order to establish higher force. Knowing the importance of higher displacement amplitudes, frequency value has to be as close to eigenfrequency value as possible for each leg mass mean. Experiment was conducted with 75 kg weight person. Voltage values were chosen according to tested person's vibrational excitation impact feeling. Beating phenomenon frequencies ranging from 0.5 Hz to 4.8 Hz were registered (Figs. 6-11).

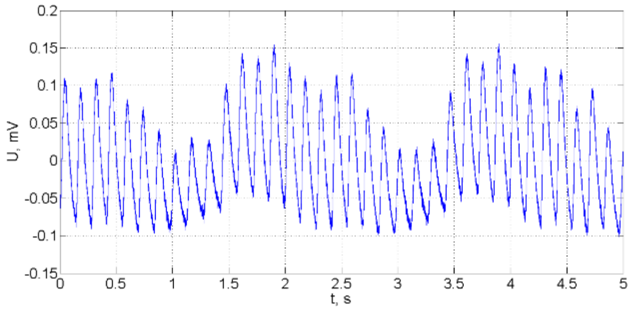

Fig. 6 Voltage: 7.8-7.4 V; beating frequency: 0.5 Hz; force to legs: 44.68 N

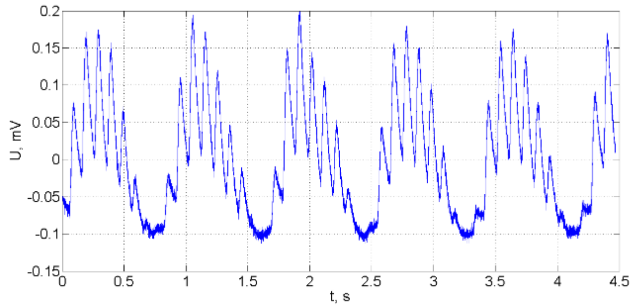

Fig. 7 Voltage: 10.7-9.6 V; beating frequency: 1.168 Hz; force to legs: 78.12 N

Low voltage causes low revolution per minute number and lower force mean. Glass epoxy plate and feet displacement is significantly smaller comparing to frequency values that are close to eigenfrequencies. That means minor influence on stimulating foot blood circulation. Therefore higher voltage values were used for further investigations (Figs. 8-11). In all of them clear beating phenomenon could be defined from diagrams. It is important to note that natural frequencies of the motors has not been felt by tested person.

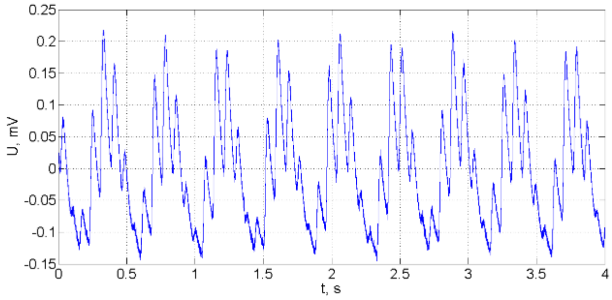

Fig. 8 Voltage: 11.2-13.8 V; beating frequency: 2.217 Hz; force to legs: 117.78 N

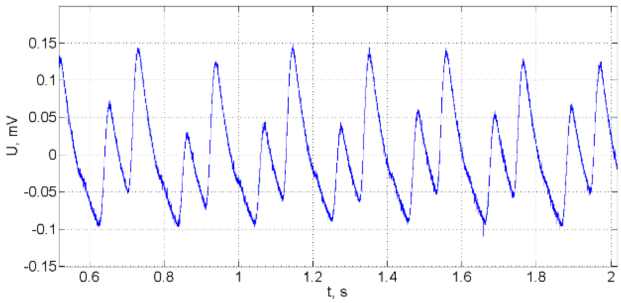

Fig. 9 Voltage: 15.1-10 V; beating frequency: 4.844 Hz; force to legs: 137.10 N

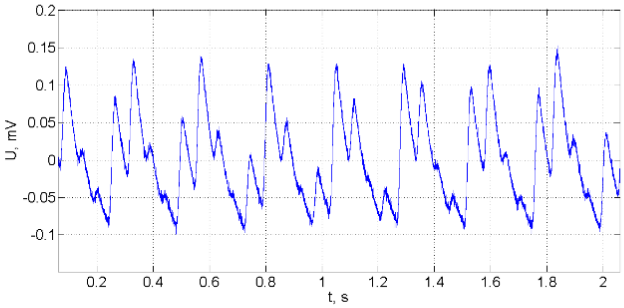

Fig. 10 Voltage: 16.9-12.4 V; beating frequency: 4.152 Hz; force to legs: 116.30 N

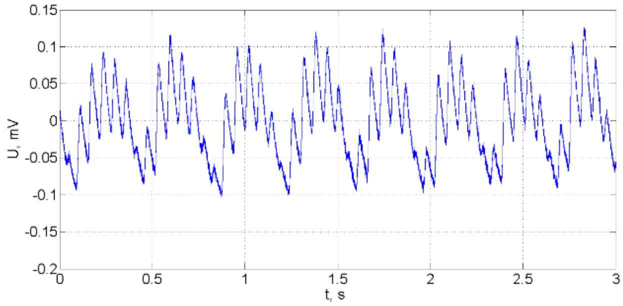

Fig. 11 Voltage: 16.9-13.9 V; beating frequency: 3.311 Hz; force to legs: 180.2 N.

Voltage values of 16.9 V and 13.9 V (Fig. 11) were chosen for further experiments to register vibrational excitation influence on blood circulation at foot. The frequency of 3.311 Hz were the closest value to eigenfrequency value that was calculated at Comsol multiphysics software. Motors with unbalanced masses working on these voltage values generate 180.2 N force.

Temperature was monitored on four points: two on different toes (Hallux and Long) and two points on feet (one on the left and one on the right). Temperature changes were recorded right after the exercise and after resting 3 and 5 minutes. Peak temperature rise values were registered after resting 3 minutes after the vibrational excitation. Temperature rise of 0.7 C on Hallux toe (Fig. 12), 1 C on Long toe (Fig. 13), 0.9 C on right foot point (Fig. 14) and 1.5 C on left foot point (Fig. 15) were captured.

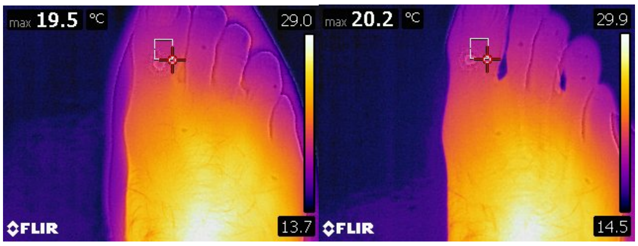

Fig. 12 Hallux toe temperature before (left) and after (right) vibrating legs

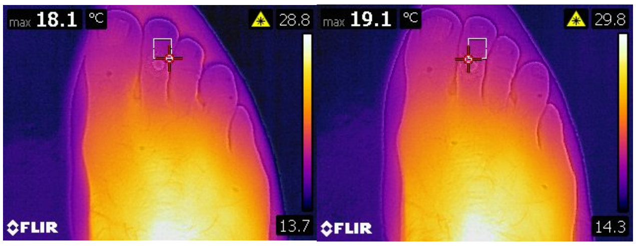

Fig. 13 Long toe temperature before (left) and after (right) vibrating legs

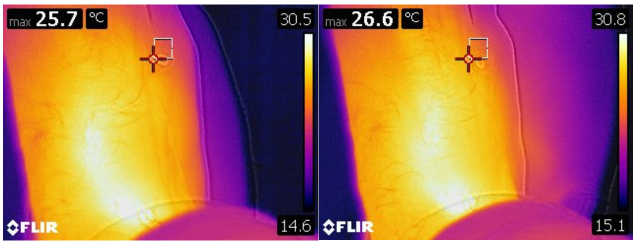

Fig. 14 Right foot point temperature before (left) and after (right) vibrating legs

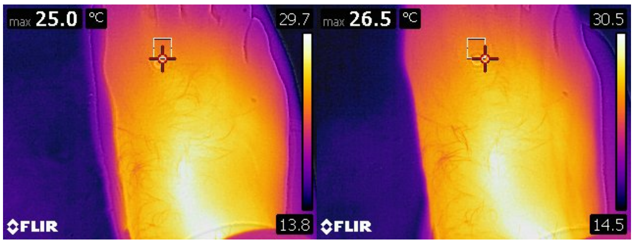

Fig. 15 Left foot point temperature before (a) and after (b) vibrating legs

4. Conclusions

1. Beam natural frequencies without leg's weight load were 9.05 Hz and assessing 75 kg male's legs weight – 3.28 Hz. This value is close to determined frequency range from earlier experiments with highest impact cardiovascular parameters and liquid (blood) properties changes.

2. Eigenfrequency values of 3.47-3.25 Hz for females (weight: 55-70 kg) and 3.28-3.02 Hz (weight: 75-100 kg) for males were calculated. These values indicates different working regimes and supplied voltage parameters depending on human weight and will be implemented in device control algorithm.

3. Experiment with legs vibrating machine was conducted to identify working regimes and necessary voltages for each motor to generate eigenfrequency value of 3.28 Hz for 75 kg weight male. 16.9 V and 13.9 V supply voltage for each motor respectively generated beating vibrations of 3.311 Hz. Thermal analysis of the feet was executed at this frequency range. Further experiments to identify cardiovascular parameters changes will be conducted on identified working frequencies.

4. Vibrational effect assessing experiment was made on 3.311 Hz beating vibrations registering temperature changes on four points of the foot. Temperature raise of 0.7 C on Hallux toe, 1 C on Long toe, 0.9 C on right foot point and 1.5 C on left foot point were registered. These values are very close to earlier experimental results of exciting human hand and monitoring temperature changes [13].

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M. Venslauskas, V. Ostasevicius, V. Jurenas

NOVEL TRAINING MACHINE FOR STIMULATION OF BLOOD CIRCULATION IN FEET

S u m m a r y

The aim of the current work was to identify vibrational machine glass epoxy plate eigenfrequencies, numerically identify working regimes on different input parameters and investigate the blood flow in foot after vibrational excitation using high-sensitivity infrared thermal imaging camera. Novel training machine has been designed for this purpose. Two vibrating motors rotating on different revolution per minute value were used to induce beating phenomenon and create sufficient force. Comsol Multiphysics model was designed for eigenfrequency analysis of machines' vibrating glass epoxy plate. Natural frequency of 3.28 Hz has been observed on loaded beam. Experiments with training machine were executed with the purpose of identification of beating phenomenon induction regimes on vibrating frequencies close to calculated eigenfrequencies values. Motors supplied by 16.9 V and 13.9 V respectively created beating frequency of 3.311 Hz and generated force to legs of 180.2 N. After that foot temperature was registered. Temperature raise of 0.7 C on Hallux toe, 1 C on Long toe, 0.9 C on right foot point and 1.5 C on left foot point were noted.

Keywords: vibrations, blood circulation, beating phenomenon.

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