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DOCTORAL THESIS
-ABSTRACT-

BIOMECHANICAL MODELING OF THE JOINTS OF THE HUMAN BODY UNDER THE ACTION OF MECHANICAL VIBRATIONS

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1. INTRODUCTION

Vibrational phenomena can be found free in nature or can be generated by various devices. Regardless of their physical essence, vibrations have identical fundamental laws with similar mathematical formulations.

Mechanical oscillations affect the human body. For this reason, various researches have been carried out to determine the behavior of the human body under their action. The investigations determined an area where the influence of vibrations on the human body is positive, without insisting much on them. The negative effects of oscillations have been given increased attention in order to protect the human body.

The thesis research started as a continuation of the doctoral thesis completed by Radu Panaitescu-Liess in 2013 at UTCB. Along the way, I opted for the use of Arduino devices for experiments, after vibration measurements made in the ICECON laboratory.

Through this work, I aimed to create some biomechanical models that come close to explaining the phenomena and processes that take place in human joints exposed to vibrational phenomena. The experimental researches were carried out with the help of the existing professional equipment in the laboratory, but also with artisanal devices, which can be purchased with relative ease and can provide a starting point for deepening the studied phenomena.

2. DETERMINISTIC PARAMETRIC ANALYSIS OF VIBRATION ON CATEGORIES OF SIGNIFICANT PATTERNS

Oscillatory phenomena can be defined as a sequence of oscillations, and the oscillation of a material point represents the movement corresponding to a single passage through the same position and in the same direction [17].

Vibrations can be described with the help of elongation, speed or acceleration of the point. The devices used to measure vibrations are capable of measuring any of the three parameters, the option will be made depending on: the nature and dimensions of the subject that vibrates, the range of frequencies that constitute the vibration spectrum, the existing national or international norms regarding the admissible values and comparison of different categories of structures and machines, the dynamic field of vibrations on the entire frequency spectrum, etc [8].

The human body, considered a physical or biological system, is extremely complex, but seen as a mechanical system it contains a number of linear or non-linear elements, different from person to person.

The study of the response of the human body subjected to vibrations or shocks, from a biological point of view, must also follow the physiological and psychological effects. The effects of vibrations on the human body are not very well known, due to the complexity of these studies and because research cannot be done easily on separate parts of the body. In the literature, a series of harmful effects of vibrations are known, of an objective nature, under physical and physiological effect [8].

Mechanical vibrations act on humans in two ways: the whole body is affected (when the human is standing, sitting or lying down) or on some parts of the body, mainly the hand-arm system [8].

For the human body, the direction of the vibrations is also of interest: vertical, from the feet to the head (Oz); lateral, perpendicular to the chest (Ox) or left-right (Oy).

While the vibrations transmitted to humans in a vertical or sitting position lead to the appearance of physiological and vegetative effects (discomfort, relative displacements of various organs, rupture of ligaments or tissues, pulmonary hemorrhages in the case of low-frequency vibrations (5-15 Hz) and high accelerations (5-15g)), there is the category of hand-arm vibrations that can produce physical disturbances in blood circulation or local gangrene if the level and time of exposure is high enough.

If the person is simultaneously subjected to vertical and lateral vibrations, the ISO norms suggest taking into account the limits of each vibration category separately.

THE DYNAMIC RESPONSE WITH HARMONIC EXCITATION FOR A MODEL WITH ONE DEGREE OF FREEDOM [17][8]

Oscillating systems with one degree of freedom consist of one or more elastic elements and a rigid mass. The elastic elements join the rigid mass to a support. The rigid mass performs a translation or rotation movement, and its position can be established with a single scalar parameter [17].

The study of systems with one degree of freedom is a starting point to understand the phenomena that appear in complex systems with more degrees of freedom. In some real situations, we can reduce a complex system to one with a single degree of freedom.

An oscillating system (figure 1) with a degree of freedom is subjected to the action of a harmonic disturbing force.

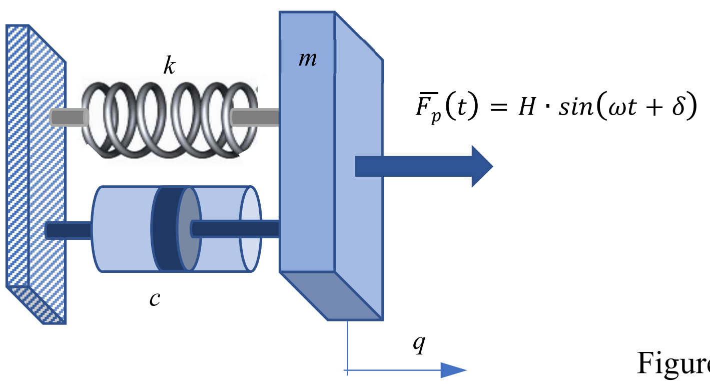


Figure 1

Differential equation of motion is:

$$m \cdot \ddot{q} + c \cdot \dot{q} + k \cdot q = H \cdot sin(\omega t + \delta) \quad (1)$$

or else

$$\ddot{q} + 2n \cdot \dot{q} + p^2 \cdot q = h \cdot sin(\omega t + \delta) \quad (2)$$

in which $2n = \frac{c}{m}$, $p^2 = \frac{k}{m}$, $h = \frac{H}{m}$.

Solving the differential equation gives:

$$\begin{cases} A = \dfrac{h}{\sqrt{\left(p^2 - \omega^2\right)^2 + 4 \cdot n^2 \cdot \omega^2}} \\ tg\varepsilon = \dfrac{2n \cdot \omega}{p^2 - \omega^2} \end{cases} \quad (3)$$

In the first stage of the movement, we have at the same time natural vibration and forced vibration, that is, a transient regime that will change into a permanent stationary regime – the natural vibration is dampened and the vibration of the oscillating system will be the same as the forced vibration.

THE DYNAMIC RESPONSE WITH POLYHARMONIC EXCITATION FOR A MODEL WITH A FINITE NUMBER OF DEGREES OF FREEDOM

Systems with one degree of freedom prove ineffective if the goal of modeling is to get as close as possible to the real system (the human body in our case).

Several types of excitations (harmonic, periodic, any) can act on systems with two or more degrees of freedom. The high number of degrees of freedom leads to laborious calculations, although the principles used in the study of vibrations remain the same. Specialized programs and high-performance electronic equipment are used to make calculations easier.

One of the methods with which the differential equations of vibrations can be written is the modal analysis method, briefly presented in the following. With its help, the modal parameters of the human structure (frequencies, damping, modal shape) can be identified for the relevant modes [8].

Consider a discrete system with a finite number of degrees of freedom, subject to the action of forced and damped vibrations. The general equation of motion of such a system is:

$$[m]\cdot \ddot{q} + [c]\cdot \dot{q} + [k]\cdot q = \{F_p(t)\} \tag{4}$$

The linear transformation is used

$$\{q\} = [\mu]\cdot\{\xi\}$$

where $[\mu]$ is the square modal matrix;

$$\{\xi\} = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \dots \\ \xi_n \end{pmatrix}$$ - the column vector.

Equation (4) can be decoupled only if the damping is proportional (of Rayleigh type). The damping matrix is a linear combination of the inertia and stiffness matrices [8].

After completing the necessary steps, the solution is of the form:

$$\begin{aligned}\xi_i(t) = {} & \frac{1}{\omega_i \cdot \sqrt{1-\zeta_i^2}} \cdot \int_0^t P_i(t)\cdot sin\left[\omega_i\sqrt{1-\zeta_i^2}\,(t-\tau)\right]d\tau + \\ & + e^{-\zeta_i\omega_i t}\left[\frac{\xi_i(0)}{\left(1-\zeta_i^2\right)^{\frac{1}{2}}} cos\left(\omega_i\sqrt{1-\zeta_i^2}\,t-\varphi_i\right) + \frac{\xi_i(0)}{\omega_i\left(1-\zeta_i^2\right)^{\frac{1}{2}}} sin\left(\omega_i\sqrt{1-\zeta_i^2}\,t\right)\right]\end{aligned} \tag{5}$$

3. BIOMECHANICAL MODELING OF THE ELBOW AND KNEE

Biomechanics deals with living tissues, and these have properties totally different from those of the materials used in various branches of engineering: they have the ability to grow, resorb, and self-repair. Living tissue can change its dimensions and mechanical properties. These changes are related both to certain external requests, but also to biochemical processes that represent its intrinsic properties [6].

Trying to reproduce, copy and explain what he saw in the surrounding environment, man adopted the notion of model, using it since ancient times. Along with the development of civilization, the fundamental concepts of elementary mechanics were also defined, later developed and used to describe the movements of the human body.

ELBOW AND KNEE SHAPING

For the purpose of studying the human body from a mechanical and mathematical point of view, some clarifications are necessary. For the muscular, bone, joint system, internal organs, tissues, at the cellular level the movement is governed by the laws of Newtonian mechanics. On the smaller scale of atoms and molecules, Newton's laws no longer apply. They are replaced by the laws of quantum mechanics.

The human body is particularly complex, and the biomechanical modeling of the processes inside it is quite difficult. However, the strict principles and rules of mechanical engineering apply in this case as well. One can study the conditions of equilibrium under the action of the applied forces, disregarding the movement, obtaining a static model. Following only the geometric aspect of the movement, without considering masses and forces, a kinematic model results (only the notions of space and time intervene). In a dynamic model all the fundamental notions will come into play: space, time and mass. In any of these situations, the motion laws of the component elements can be written [14].

The basic structural elements specific to a synovial joint are presented in figure 2. The synovial articular cavity and the articular cartilages are what separate the joint bones, thus reducing the friction of the joint surfaces and absorbing the shocks produced during body movement [2].

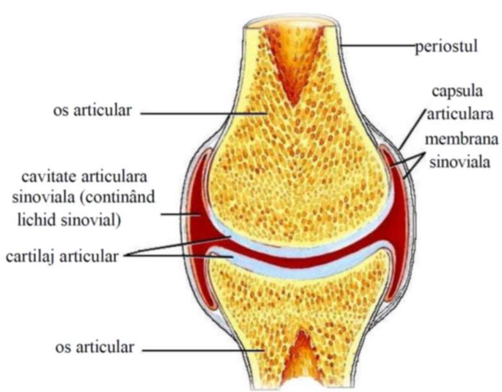


Figure 2

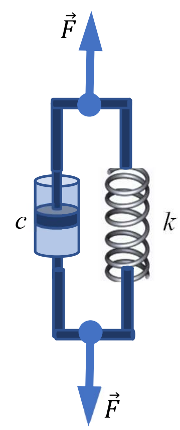


Figure 3

The mathematical modeling of the joint investigates its working mode, the way the interaction of the elements affects its kinematics, the resistance to overload, breakage, fatigue and vibrations.

The human joint can be defined as a constraint between two rigid bodies. Thus, the human skeleton can be represented as an articulated figure comprising several links that interact through the joints.

A special interest is the joint's ability to interactively change the orientation and position of the axis or center of rotation [10].

Bone is considered a viscoelastic material because, with increasing stress, its strength and modulus of elasticity increase up to a certain limit. The physical model of such a material is represented in figure 3. They were noted with k – the coefficient of elasticity, and by c – the damping coefficient, measured in [Ns/m].

BIOMECHANICAL MODELS AS A BASIS FOR DYNAMIC ANALYSIS A HUMAN ORGANISM

A model with three-degree-of-freedom of the human finger was made and presented in the framework of the doctoral thesis by Mr. Radu Panaitescu-Liess, member of the Department of Construction Machinery and Mechatronics within U.T.C.B. The bones of the finger, called phalanges, are short, three for each finger, except for the thumb which has two (figure 4) [14].

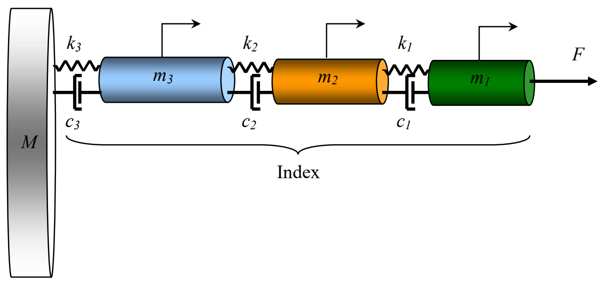


Figure 4. The Panaitescu-Liess Model [14]

In the same paper, Mr. Radu Panaitescu-Liess presented a model with 8 degrees of freedom of the hand-forearm-arm system and calculated, with the help of the Matlab program, its pulsations and its own frequencies (figure 5). System dampings have been neglected.

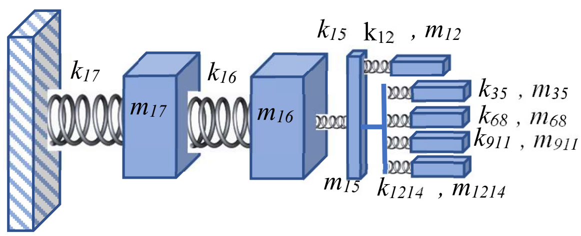
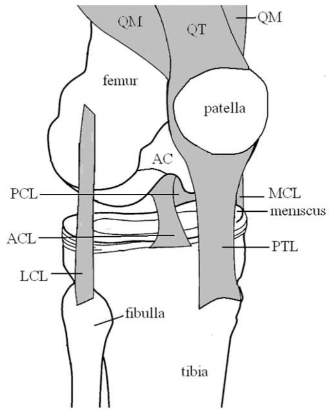


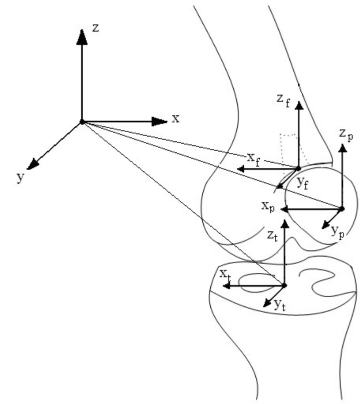
Figure 5. The Panaitescu-Liess Model with 8 degrees of freedom [14]

Research on the hand-arm system was also carried out by Marco Tarabini, Bortolino Saggin, Diego Scaccabarozzi, Giovanni Moschioni. They studied its resistance to the action of random vibrations (2013).

The 3D model with 12 degrees of freedom proposed by Moşneguţu and Chiroiu (2013) resulted from a critical analysis of two outstanding works in the field: Shelburne, Pandy, Anderson and Torry (2004) and Wolf and Degani (2007).

A model of the lower limb, in the standing position in the sagittal plane, of the triple pendulum type is presented in the 2015 paper by researchers Akio Yamamoto, Shun Sasagawa, Naoko Oba, Kimitaka Nakazawa (figure 7).





Knee muscles and ligaments Local and global coordinate systems

Figura 6. The model proposed by Moşneguţu and Chiroiu (2013)[9][10]

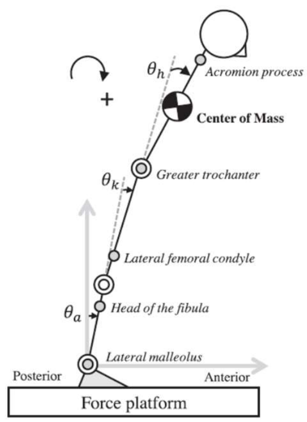


Figure 7. Diagram of the vertical triple-link inverted pendulum model standing in the sagittal plane. Common angles (θa, θk, θh) are defined as positive clockwise. Gray circles represent spherical markers placed on anatomical landmarks. The tilt of the body is exaggerated for the convenience of the reader [34].

L. M. Roseiro, M.A. Neto, A.M. Amaro, C.J. Alcobia and M.F. Paulino from the University of Coimbra, Portugal followed the behavior of the human body and the hand-arm system under the influence of vibrations generated by the sports activities of moto-cross and cycling (2016).

A study on the elbow joint was presented by Munsur Rahmana, Akin Cil and Antonis P. Stylianou in 2016. The purpose of the research was to create a model that would allow tracking the behavior of the cartilages of the humerus, ulna and radius during repeated flexion-extension movements.

Human walking, described with the help of the rigid or spring pendulum, was the subject of the 2016 article published by Hyunggwi Song, Heewon Park, Sukyung Park (Figure 8).

Xueyan S. Xu, Ren G. Dong, Daniel E. Welcome, Christopher Warren, Thomas W. McDowell, John Z. Wu tracked how vibrations are transmitted through the body starting from the hand to the arm, shoulder, back, neck and head (2017).

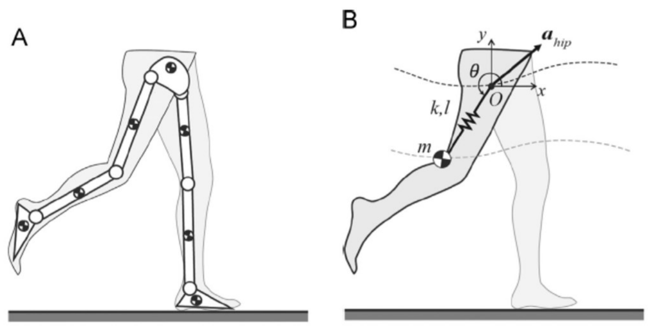


Figure 8. A) Inverse dynamics of a 7-segment rigid pendulum model used to calculate internal hip forces. (B) A spring pendulum model of the oscillating leg attached to the hip joint O [22]

With the help of software programs such as Visual3D, Nexus, Cortex and OpenSim, researchers Julia K. Nichols and Oliver M. O'Reilly obtain information about the knee joint subjected to various stresses, in two different coordinate systems (2017) (figure 9).

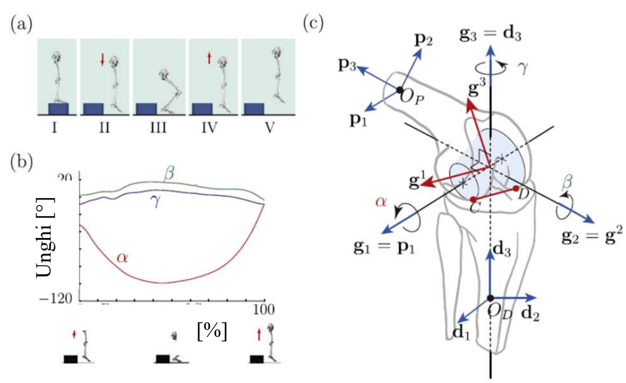


Figure 9. (a) Schematic of the five stages of the vertical jump task. (b) Variation of right knee joint angles during a vertical jump task. [12]

Although they started as a desire of people to study and eventually solve the problems of movement, biomechanics and vibration research is important because it addresses interesting topics for athletes, coaches, researchers, doctors, engineers. Motion optimization or physical limitation is studied. The created models help to improve working conditions in various fields or in everyday life.

4. BIOMECHANICAL MODELS OF ELBOW AND KNEE JOINTS

BRIEF PRESENTATION OF THE HUMAN LOCOMOTOR APPARATUS

The locomotor system consists of the skeletal system (bones and joints) and the muscular system (muscles). The bone system has the role of levers of the locomotor apparatus, on which the muscular system acts, ensuring support and movement of the body.

By the movement of a body is understood the action of its displacement under the influence of all the forces acting on it. This movement can be quantified by the values, changed over time, of some coordinates with respect to a geometric reference system. The movement can be analyzed without taking into account causes, respectively forces, only based on some geometric considerations, and the analysis is called kinematics. If the interaction of all the forces acting on the body is taken into account, the analysis is called dynamics. In the case of the human body, it can be considered either the movement of the entire body, viewed as a unitary whole, or the differentiated movement of different segments or sets of body segments [2].

The pivoting joint of the elbow joins the humerus bone of the arm with the radius and ulna bones of the forearm. The relationship between the radius and the ulna allows for rotational movements of the elbow, the radius bone rotating around the ulna, thus turning the hands [2].

The knee is one of the most complex joints in the body. It connects the thigh and calf. The knee skeleton consists of the lower extremity of the femur (thigh bone), the upper extremities of the two bones of the calf: the tibia and the fibula, and the region's own bone, the patella (patella).

This joint falls into the category of pivoting joints (which accept movement in a single plane, example: bending/straightening the knee) (figure 10). It does, however, allow some forward and backward gliding movements and a reduced level of rotational movements. The knee is a joint capable of lifting weights [13].

Figure 10

BIOMECHANICAL MODEL FOR THE ELBOW JOINT

The forearm-arm system can be viewed in the form of a model with two degrees of freedom, consisting of two cylindrical bodies (with masses m_i, radii r_i, lengths l_i), articulated by means of a torsion bar of negligible mass (figure 11) [5].

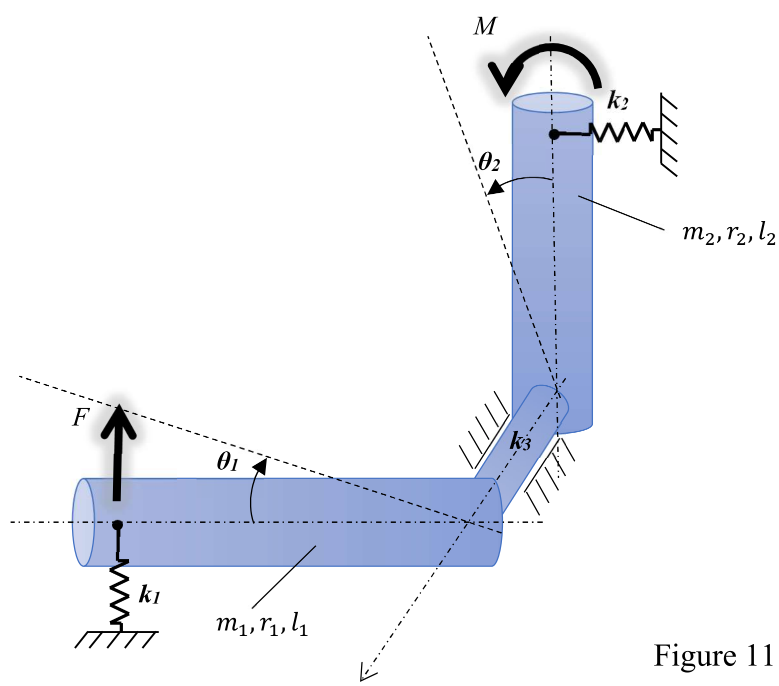


Figure 11[15]

The proposed biomechanical model is considered to be acted upon by a disturbing force F, which can be given by the use of a portable work equipment (for example: drill), which is opposed by a resisting moment M acting in the upper arm area (the worker's shoulder) [5].

The differential equations of motion of the mechanical system are:

$$\begin{cases} m_1 \cdot \left[3r_1^2 + l_1^2 + \left(\frac{l_1}{2}\right)^2\right] \cdot \ddot{\theta}_1 + (k_1 \cdot l_1^2 + k_3) \cdot \theta_1 + k_3 \cdot \theta_2 = F_1 \cdot l_1 \cdot sin\omega t \\ m_2 \cdot \left[3r_2^2 + l_2^2 + \left(\frac{l_2}{2}\right)^2\right] \cdot \ddot{\theta}_2 + k_3 \cdot \theta_1 + \left(-\frac{m_2 \cdot g \cdot l_2}{2} + k_2 \cdot l_2^2 + k_3\right) \cdot \theta_2 = M_2 \cdot sin\omega t \end{cases} \quad (4.22)$$

The system of equations is solved and its own pulsations of the form result:

$$p_{1,2} = \sqrt{\frac{(k_{11} \cdot m_{22} + m_{11} \cdot k_{22} - 2 \cdot k_{12} \cdot m_{12})}{2 \cdot (m_{11} \cdot m_{22} - m_{12}{}^2)} \pm \frac{\sqrt{(k_{11} \cdot m_{22} - m_{11} . k_{22} + 2 \cdot k_{12} \cdot m_{12})^2 - 4 \cdot (k_{11} \cdot k_{22} - k_{12}{}^2) \cdot (m_{11} \cdot m_{22} - m_{12}{}^2)}}{2 \cdot (m_{11} \cdot m_{22} - m_{12}{}^2)}}$$

Own pulses determined for a human subject (total mass 104 kg, arm length 32 cm, forearm length 24 cm):

$p_1 = 2{,}56604\ s^{-1}$ and $p_2 = 8{,}33947\ s^{-1}$

BIOMECHANICAL MODEL FOR THE KNEE JOINT

Starting from the study of joint mobility of the lower and upper limbs presented in [14], the biomechanical model of the foot-calf system was extended to the entire lower limb. If for the purpose of the work mentioned, it was not necessary to make a complete model of the lower limb, for the next level of research, namely, the study of the elbow and knee joints, the biomechanical models must in turn become more complex.

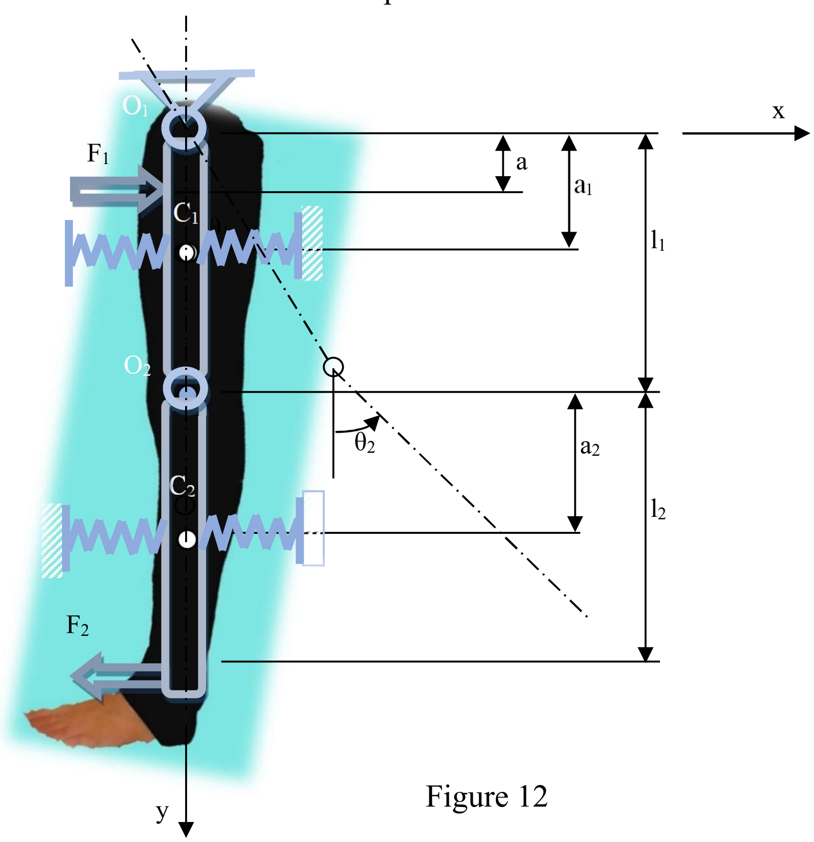


Figure 12

The calf and leg were considered in the form of a bar hinged at one end, assembled with another bar (thigh), the model taking the form of a double physical pendulum (figure 12). Next, it was assumed that two disturbing forces F1 and F2 act on the model, one on the thigh, the other on the calf-foot assembly. Two pairs of springs were positioned in the center of gravity of the bars to limit the movement of the model and dampen vibrations.

Starting from Lagrange's equations of the second kind, the determination of the equation of motion of the considered model was pursued.

For the considered model, the differential equations of the mechanical system considered are obtained in matrix form:

$$\begin{bmatrix} \frac{m_1 l_1^2}{3} + m_2 l_1^2 & m_2 l_1 a_2 \\ m_2 l_1 a_2 & \frac{m_2 l_2^2}{12} + m_2 a_2^2 \end{bmatrix} \begin{Bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{Bmatrix} + \\ + \begin{bmatrix} m_1 g a_1 + m_2 g l_1 + 2k_1 a_1^2 + 2k_2 l_1^2 & 2k_2 l_1 a_2 \\ 2k_2 l_1 a_2 & m_2 g a_2 + 2k_2 a_2^2 \end{bmatrix} \begin{Bmatrix} \theta_1 \\ \theta_2 \end{Bmatrix} = \begin{Bmatrix} F_{O1} a \\ F_{O2} l_2 \end{Bmatrix} sin\omega t \quad (4.13')$$

Solving the system of differential equations and applying the anthropometric data of a human subject (total mass 104 kg, arm length 32 cm, forearm length 24 cm) we obtain the pulsation equation of the form:

$$(244.127 - 3.638 \cdot p^2) \cdot (55.431 - 0.863 \cdot p^2) - (66.302 - 1.271 \cdot p^2)^2 = 0$$

The own pulsations have the following values:

$p_1 = 7{,}74089\ s^{-1}$ and $p_2 = 10{,}0018\ s^{-1}$

MODELING LIMBS AS PENDULUM SYSTEMS IN MOTION OF HUMAN ORGANISM

It is believed that human limbs can be modeled in the form of a double inverted pendulum. Figure 13 shows the system with two degrees of freedom, on which two disturbing forces act, F_1 and F_2. Initially, the model is assumed to be composed of two bodies modeled as bars of the same mass m and the same length l.

The differential equations of motion of the considered model in analytical form:

$$\begin{cases} \frac{4 \cdot m \cdot l^2}{3} \cdot \ddot{\theta}_1 + m \cdot l^2 \cdot \ddot{\theta}_2 + \frac{1}{2} \cdot (3 \cdot m \cdot g \cdot l + k \cdot l^2) \cdot \theta_1 + k \cdot \frac{l^2}{4} \cdot \theta_2 = F_{01} \cdot \frac{l}{2} \cdot sin\omega t \\ m \cdot l^2 \cdot \ddot{\theta}_1 + \frac{m \cdot l^2}{3} \cdot \ddot{\theta}_2 + k \cdot \frac{l^2}{4} \cdot \theta_1 + \frac{1}{2} \cdot \left(m \cdot g \cdot l + \frac{1}{2} \cdot k \cdot l^2\right) \cdot \theta_2 = F_{02} \cdot \frac{l}{2} \cdot sin\omega t \end{cases} \quad (4.18^o)$$

The system is solved.

In order to determine the numerical values of the own pulsations, the laws of motion and the own modes of vibration, the anthropometric dimensions for four people between the ages of 15 and 43 will be entered (tables 1 and 2).

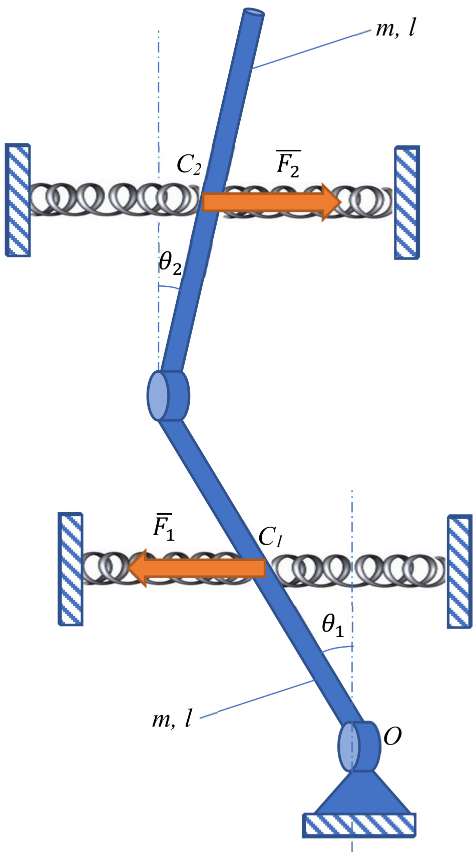


Figure 13

Tablel 1. Anthropometric data upper limb subjects

The subject	Total weight [kg]	Arm length [m]	Forearm length [m]	Arm weight [kg]	Forearm weight [kg]	The CG position of arm [m]	The CG position of forearm [m]
A	104	0,32	0,24	2,80	1,87	0,139	0,103
B	54	0,34	0,25	1,45	0,97	0,148	0,107
C	45	0,30	0,25	1,21	0,81	0,130	0,107
D	80	0,29	0,24	2,16	1,44	0,126	0,103

Table 2. Anthropometric data lower limb subjects

The subject	Total weight [kg]	Thigh length [m]	Calf height [m]	Foot height [m]	Thigh weight [kg]	Calf weight [kg]	The CG position of thigh [m]	The CG position of calf [m]
A	104	0,50	0,47	0,08	10,5	5,61	0,216	0,238
B	54	0,55	0,48	0,08	5,45	2,91	0,238	0,207
C	45	0,53	0,45	0,07	4,54	2,43	0,229	0,194
D	80	0,41	0,34	0,07	8,08	4,32	0,177	0,147

The results obtained are presented in table 3.

Tabelul 3. Own pulsations/laws of motion

- for upper limb:

- in the case of the subject A:

Own pulsations:	Own frequencies:
p1=132.638 rad/s	f1=21.11 rad/s
p2=132.395 rad/s	f2=21.071 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(132.638t + \beta_1) + C_2 \cdot sin(132.395t + \beta_2)$$
$$\theta_2 = -1.33 \cdot C_1 \cdot sin(132.638t + \beta_1) - 1.33 \cdot C_2 \cdot sin(132.395t + \beta_2)$$

- in the case of the subject B:

Own pulsations:	Own frequencies:
p1=55.657 rad/s	f1=8.858 rad/s
p2=55.037 rad/s	f2=8.759 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(55.657t + \beta_1) + C_2 \cdot sin(55.037t + \beta_2)$$
$$\theta_2 = -1.316 \cdot C_1 \cdot sin(55.657t + \beta_1) - 1.315 \cdot C_2 \cdot sin(55.037t + \beta_2)$$

- in the case of the subject C:

Own pulsations:	Own frequencies:
p1= 46.001 rad/s	f1=7.321 rad/s
p2 = 45.165 rad/s	f2=7.188 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(46.001t + \beta_1) + C_2 \cdot sin(45.165t + \beta_2)$$
$$\theta_2 = -1.305 \cdot C_1 \cdot sin(46.001t + \beta_1) - 1.304 \cdot C_2 \cdot sin(45.165t + \beta_2)$$

- in the case of the subject D:

Own pulsations:	Own frequencies:
p1 = 82.788 rad/s	f1=13.176 rad/s
p2 = 82.309 rad/s	f2=13.1 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(82.788t + \beta_1) + C_2 \cdot sin(82.309t + \beta_2)$$
$$\theta_2 = -1.324 \cdot C_1 \cdot sin(82.788t + \beta_1) - 1.324 \cdot C_2 \cdot sin(82.309t + \beta_2)$$

- for lower limb:

- in the case of the subject A:

Own pulsations:	Own frequencies:
p1 = 453.583 rad/s	f1=72.19 rad/s
p2 = 453.542 rad/s	f2=72.183 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(453.583t + \beta_1) + C_2 \cdot sin(453.542t + \beta_2)$$
$$\theta_2 = -1.333 \cdot C_1 \cdot sin(453.583t + \beta_1) - 1.333 \cdot C_2 \cdot sin(453.542t + \beta_2)$$

- in the case of the subject B:

Own pulsations:	Own frequencies:
p1 = 216.474 rad/s	f1=34.453 rad/s
p2 = 216.380 rad/s	f2=34.438 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(216.474t + \beta_1) + C_2 \cdot sin(216.380t + \beta_2)$$
$$\theta_2 = -1.332 \cdot C_1 \cdot sin(216.474t + \beta_1) - 1.332 \cdot C_2 \cdot sin(216.380t + \beta_2)$$

- in the case of the subject C:

Own pulsations: p1 = 178.661 rad/s p2 = 178.543 rad/s	Own frequencies: f1=28.435 rad/s f2=28.416 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(178.661t + \beta_1) + C_2 \cdot sin(178.543t + \beta_2)$$
$$\theta_2 = -1.332 \cdot C_1 \cdot sin(178.661t + \beta_1) - 1.332 \cdot C_2 \cdot sin(178.543t + \beta_2)$$

- in the case of the subject D:

Own pulsations: p1 = 300.575 rad/s p2 = 300.482 rad/s	Own frequencies: f1=47.838 rad/s f2=47.823 rad/s

Laws of motion:

$$\theta_1 = C_1 \cdot sin(300.575t + \beta_1) + C_2 \cdot sin(300.482t + \beta_2)$$
$$\theta_2 = -1.332 \cdot C_1 \cdot sin(300.575t + \beta_1) - 1.332 \cdot C_2 \cdot sin(300.482t + \beta_2)$$

5. EXPERIMENTAL ASSESSMENTS OF BEHAVIOR OF THE HUMAN ORGANISM TO VIBRATIONS TRANSMITTED FROM THE ENVIRONMENT

The experimental part of this work was carried out at: I) Research Institute for Construction Equipment and Technologies - ICECON S.A.; II) Arduino; III) Catelu Road. The objective pursued in the three locations was to determine some characteristic values of the vibrations acting on the elbow and knee joints.

The measurements were performed on four people between the ages of 15 and 43, who mainly use their right hand in their daily activities.

I. Measurement group within ICECON S.A.

At ICECON S.A., the measurements were made with professional vibration sensors, used in various static demanding situations. The purpose of these tests was to determine the accelerations in different possible situations: a) in empty, b) in wood, c) in concrete.

The measurements were performed on a single person, noted in the following with the letter A. To achieve them, the accelerometers were attached one by one to: 1) the drill, 2) the elbow and 3) the knee of the human subject. The person on whom measurements were made within ICECON is male, 43 years old.

The devices used are shown in figure 14.

The accelerometers used were attached alternately to the drill, to the subject's elbow, and to his knee during the experiments. Each test lasted approximately 10 seconds. The results obtained were processed using the LABVIEW program.

Accelerometer type 4506-B

Vibration measurement kit with accelerometer type 4374

USB

Figure 14

a) The sensor 4506-B 003 fixed in the elbow joint area

b) The sensor 4506-B 003 (left) şi HVA 4447 (right) fixed on the knee joint area

Figure 15 The mode of fixing the sensor

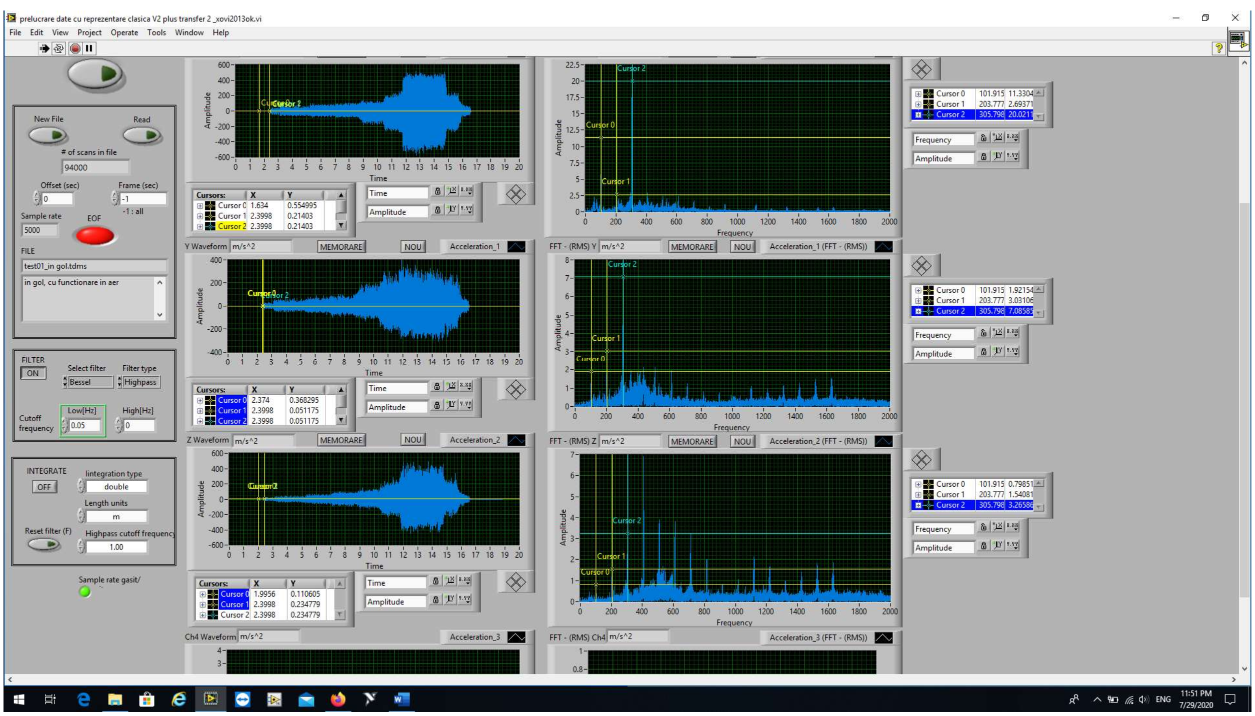


Figure 16. Preparation test with the accelerometer 4506-B 003 mounted on the drill

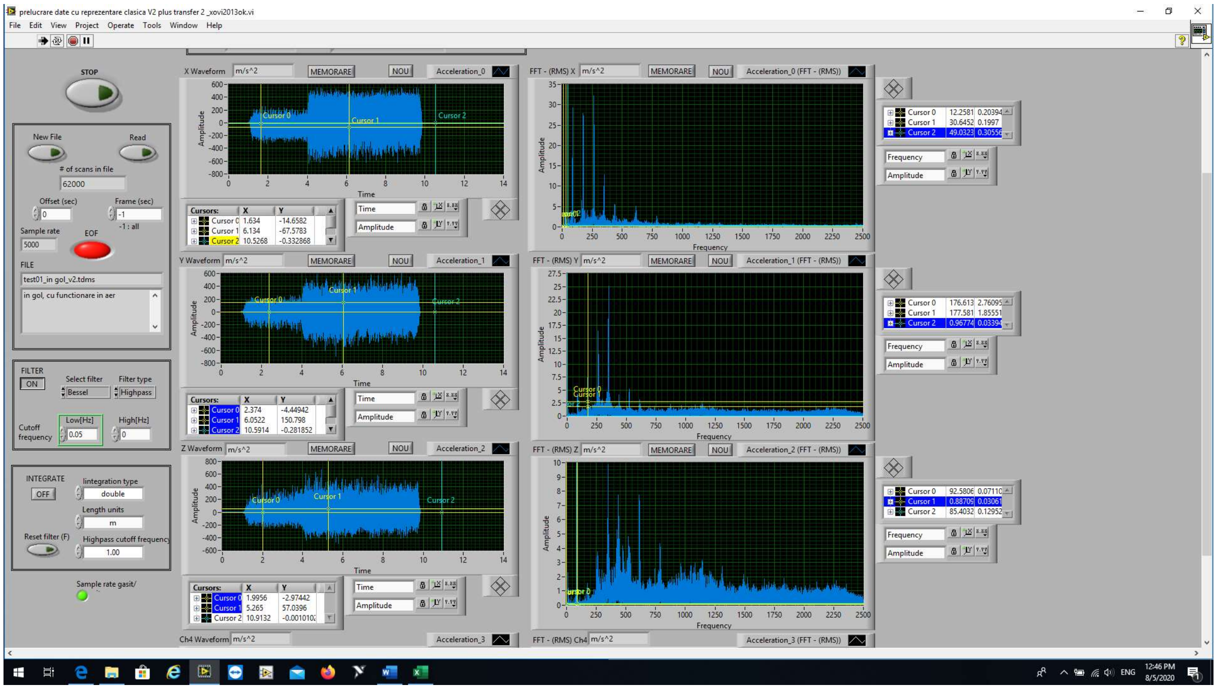


Figure 17 FFt response to the signal received from the sensor located on the drill – IA1a

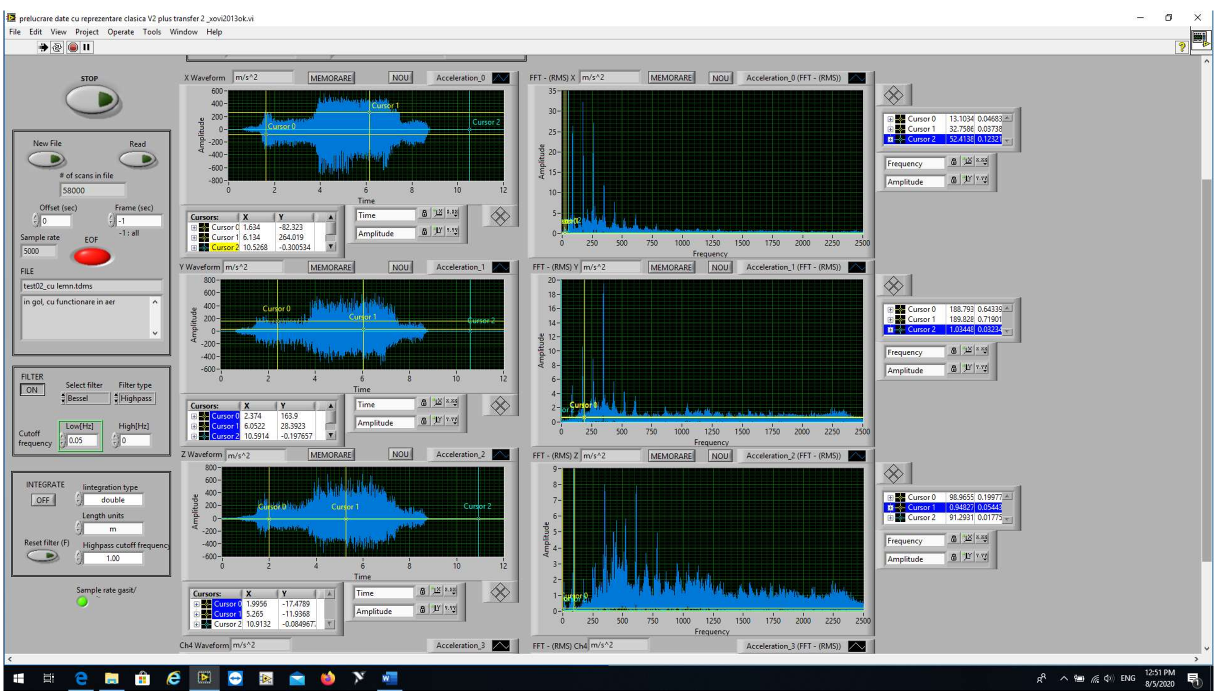


Figure 18 FFt response to the signal received from the sensor on the drill – IA1b

II. Measurement group with Arduino

In the second part of the experiments, ARDUINO components were used to measure the vibrations generated by using the drill, the same from the first set of tests (group I).

These measurements were made simultaneously on the drill, elbow, and knee with the help of the ADXL 345 accelerometer. Four people took part in the tests. The tests were carried out: a) in empty, b) in wood and c) in concrete.

Four people between the ages of 15 and 43 participated in the Arduino sensor tests.

a) ADXL 345 accelerometer b) ARDUINO UNO R3 development board

Figure 19 Arduino devices used in the experiments

The Arduino devices used for the experiments were: ADXL 345 accelerometer, ARDUINO UNO development board. The data transmitted by the sensors were processed using a laptop.

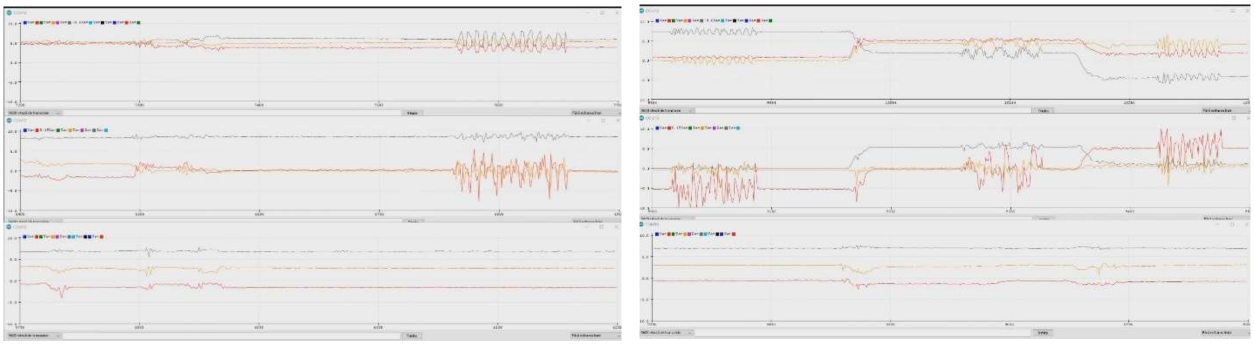
Figure 20 Subject B prepared for the tests

The information, played in real time by the serial plotter, was recorded with the help of a free video processing program called VLC Media Player. Images were captured from the moment of the tests, presented in the following.

Each sensor, connected to the arduino board, provides information about the behavior on the three coordinate axes (x, y, z). Each axis is represented by a color (x-axis – red, y-axis – orange, z-axis – black) in the graphs below. The USB ports are as follows: COM12 sensor located on the elbow, COM13 sensor located on the drill, COM18-sensor located on the knee. The results of the behavior of the elbow and knee joints during the operation of the drill, obtained with the ADXL 345 accelerometer, are presented in the following.

The order of the recordings is: elbow sensor (COM12), drill sensor (COM 13) and knee sensor (COM18).

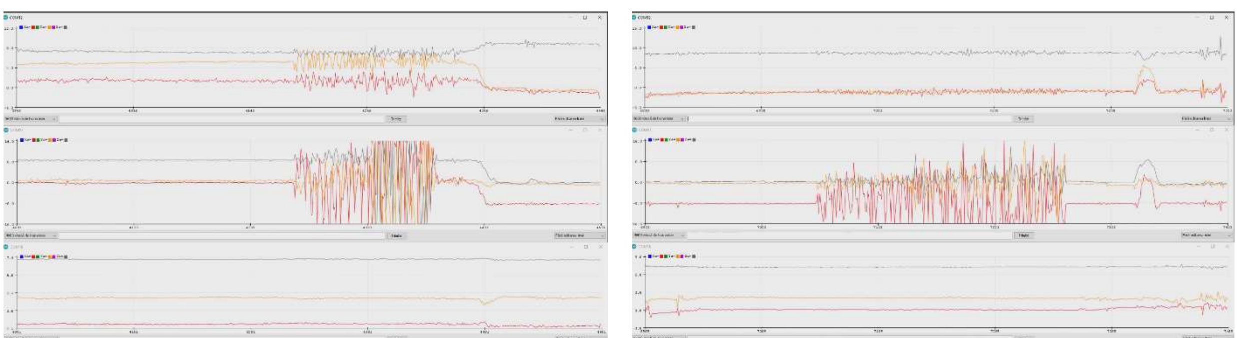
In the case of subject A, with the position of the arm in relation to the forearm - a) 90°, b) 180°, when using an empty drill, the recordings are presented in figure 21.



a) b)

Figure 21

The results below were obtained with the drill empty, subject B having the position of the arm in relation to the forearm at 90° (figure 22 a) and at 180° (figure 22 b).



a) b)

Figura 22

Compared to the experiments carried out in the ICECON laboratory, the measurements performed on the knee area with the ADXL345 accelerometer were not conclusive.

III. Test group Catelu Road

Tests measuring vibrations during mobility on scooters conclude this chapter of experiments. Two scooters (one with damping system and one without damping system), three ADXL 345 accelerometers, three Arduino UNO boards and a laptop were involved. The accelerometers were arranged as follows: one on the scooter, the second on the elbow and the third on the knee. Each accelerometer was connected, by means of data cables, to an Arduino board and laptop. Three people participated in the tests. Two routes with different coverage were used. A video camera was attached to the scooter. The road was traveled one by one by the subjects with each type of scooter.

The equipment used is shown in figure 48. In figure 49, images of the three subjects during the tests are shown.

Figure 23 Scooter, elbow rest, knee brace with accelerometers

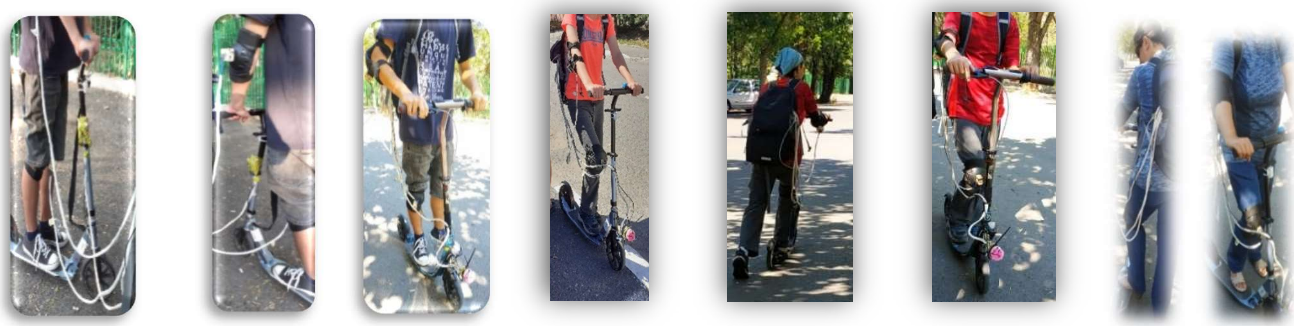
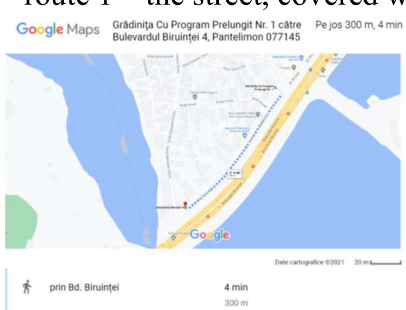


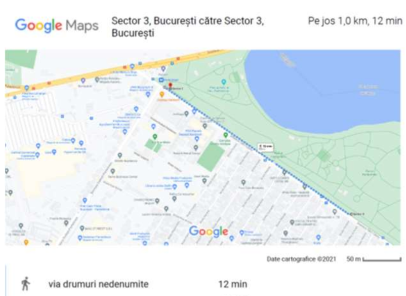
Figure 24

With the help of Google Maps, the two routes taken for the experiments are presented.

- route 1 – the street, covered with asphalt:

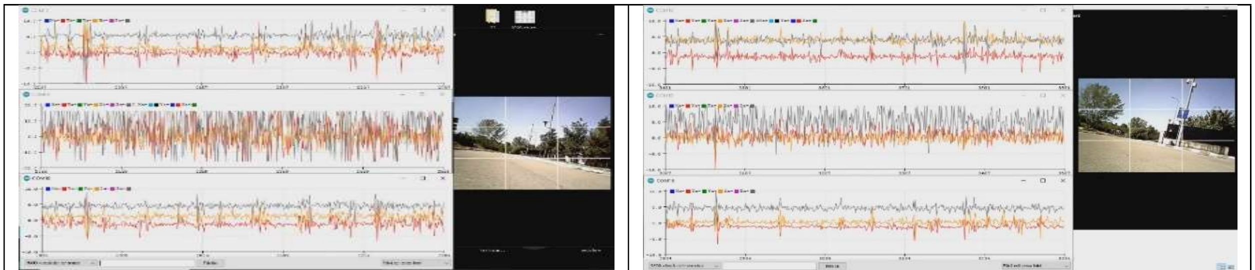


- route 2 - car park, covered with asphalt and pavers:



The information from the three USB ports is played by the serial plotter in the following order: COM 12 – the sensor is on the elbow; COM 13 – the sensor is on the scooter; COM 18 – the sensor is on the knee. In the graphs below, the three axes are represented with the following colors: x-axis - red, y-axis - orange and z-axis - black.

Screenshots of the data recorded during the trips are presented below.



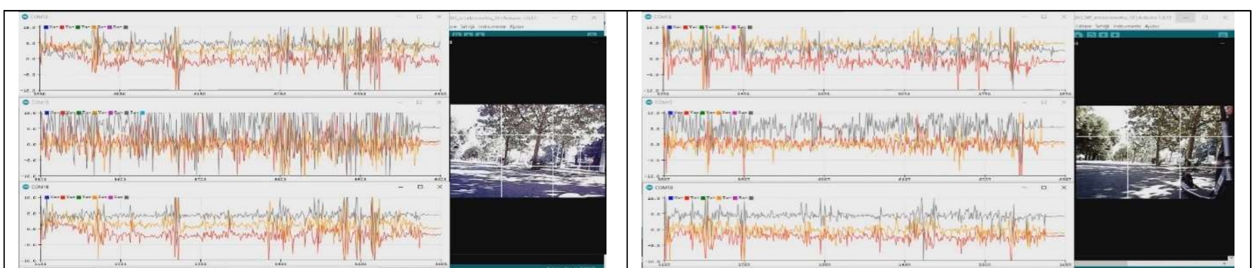
scooter without damper	scooter with damper

Figure 25 Subject A, route 1, asphalt road, rectilinear route

scooter without damper	scooter with damper

Figure 26 Subject A, route 2, car park, constant straight path

Subjects A and B performed several jumps with the scooter. The result is shown below.



scooter without damper	scooter with damper

Figure 27 Hopping, asphalt, subject A

6. GENERAL CONCLUSIONS, ORIGINAL CONTRIBUTIONS AND DIRECTIONS FUTURE FOR STUDY

CONCLUSIONS

This paper, entitled "Biomechanical modeling of the joints of the human body under the action of mechanical vibrations", followed the behavior of the elbow and knee joints under the action of mechanical oscillations.

The specific objectives of the doctoral thesis consisted in:
- modeling elbow and knee joints;
- measurement of vibrations with professional devices in the area of the elbow and knee joints during the use of the drill;
- measurement of vibrations with Arduino devices in the area of the elbow and knee joints during the use of the drill;
- measurement of vibrations with Arduino devices in the area of the elbow and knee joints while using the scooter.

Vibrations can occur at the workplace, while traveling with various means of transport (with or without a motor) or while performing various activities around the house (domestic or repair). Handling modern devices exposes users to possible mechanical oscillations of different intensities.

The measurements were performed on four subjects, members of the same family, properly informed about the way of conducting the research, its purpose and possible effects.

The experiments were carried out according to the norms in force.

Graphical methods allow human errors to occur.

The models used for the study of the elbow and knee joints led to theoretical results close to the experimental measured values. The measurements made with the arduino devices were close to the values obtained with the professional accelerometers on the x and y axes.

Moving with a scooter is quite demanding for the joints studied (elbow and knee), depending on the type of road traveled and the obstacles encountered on the way (if passing curbs or stops). A well paved road offers pleasant conditions to use the scooter.

In the short term, using the scooter without cushioning can be as demanding as handling a small mechanized tool.

From the study of the resulting graphs and the comparison with the values of the frequencies obtained on the theoretical models, the following emerges:

1. The results obtained were similar in the case of tests with sensors (professional and Arduino) attached to the drill.

2. Person A is the one who went through the experiments in the ICECON laboratory and those with Arduino, he was also considered the main landmark in the theoretical part of the thesis. In the following, the results obtained after the measurements performed on the elbow with the professional accelerometer and ADXL 345 are presented. The sensor was fixed in the elbow area of subject A, who handled the drill for the experiment.

Some values of the accelerations obtained with the professional sensor when measured in empty condition:

On the x axis: t=0.425 ax=1.47544; t=0.4292 ax=1.4774 ; t=0.427 ax=1.46852

On the y axis: t=0.425 ay=0.915416 ; t= 0.4292 ay=1.02028 ; t= 0.427 ay=1.02999

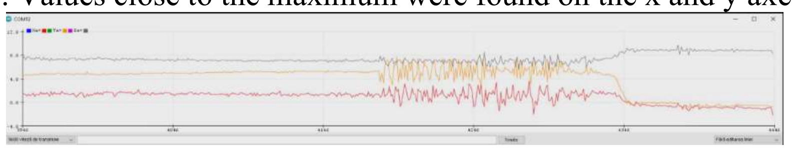
On the z axis: t=0.425 az=1.03094 ; t= 0.4292 az=0.97429; t= 0.427 az=0.952022

The Arduino led to the following results in the case of subject A, elbow measurements with an empty drill:
Elbow 90
20:27:41.366 -> Xa= 1.47 Ya= 0.91 Za= 7.22
20:27:43.373 -> Xa= 1.47 Ya= -2.50 Za= 7.50
Elbow 180
20:29:41.008 -> Xa= -1.47 Ya= -0.34 Za= 6.25
20:29:43.671 -> Xa= -1.47 Ya= -2.56 Za= 7.13
Comparing the results from the two data sets, it is found that they have close values.

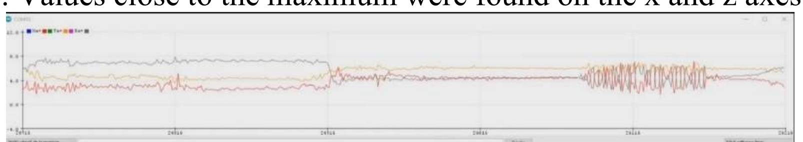
3. Taking into account the age and weight of the subjects, an evaluation can be made by group of the results obtained:
- Group I subjects B and C (age 17 and 14 respectively, weight 54 and 45 kg respectively).

The drill was used empty and under load, with sensors located on the elbow, knee and drill. Measuring device: ADXL 345 sensor. Data collected with Arduino program. At the knee, accelerations could not be measured with this sensor.

The acceleration measured in the elbow area (90), empty, for subject B was approximately 4g (39.2 m/s2). Values close to the maximum were found on the x and y axes.



The acceleration measured in the elbow area (90), empty, for subject C was approximately 4g (39.2 m/s2). Values close to the maximum were found on the x and z axes.

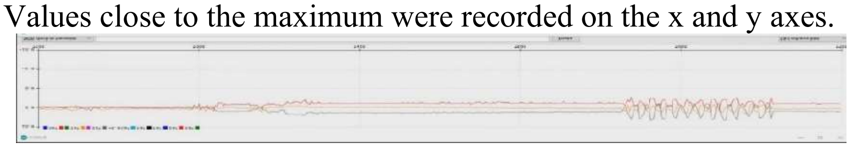


The graphs on the three axes have similar shapes and values for the two.

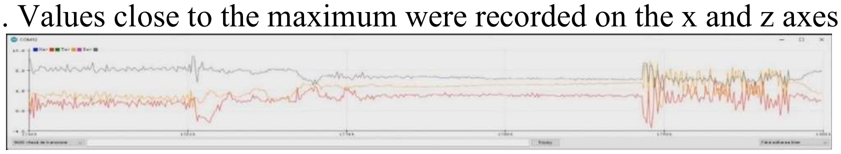
- Group II subjects A and D (age 42 and 41 respectively, weight 104 and 80 kg respectively).

The drill was used empty and under load, with sensors located on the elbow, knee and drill. Measuring device: ADXL 345 sensor. Data collected with Arduino program. At the knee, accelerations could not be measured with this sensor.

The acceleration measured in the elbow area (90), empty, for subject A was approximately 5g (49 m/s2). Values close to the maximum were recorded on the x and y axes.

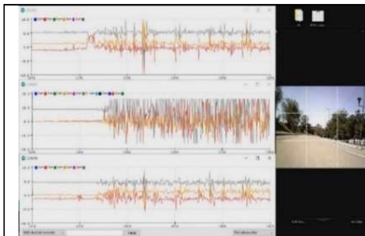
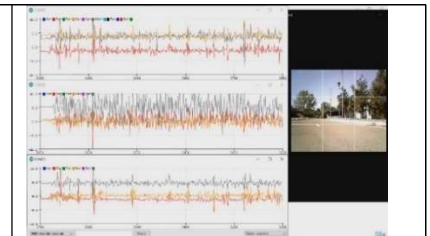


The acceleration measured in the elbow area (90), empty, for subject D was approximately 4g (39.2 m/s2). Values close to the maximum were recorded on the x and z axes.

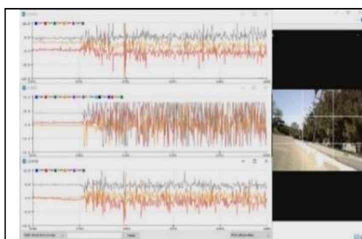
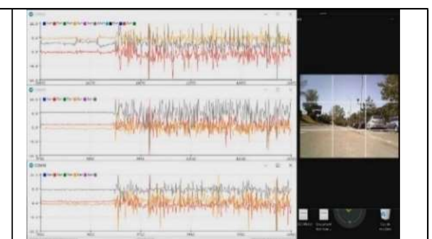


The two subjects have similar acceleration values when they use the drill to make holes in the material. When used empty, differences appear. Another difference is the evolution on the y-axis of the acceleration for the subjects during the load measurements.

4. Subjects A (17 years, 54 kg) and B (14 years, 45 kg) wore the test equipment on scooters with and without cushioning. The method of making the measurements was previously presented. The two covered a route of about 1.3 km. The journey time was 14 minutes. The movement was carried out on an asphalt surface and with paving stones. The recorded values of the accelerations were in the range of ±16g (156.8 m/s2). The results recorded with the Arduino sensor are similar for the two subjects.
Subject A, route 1, paved road:

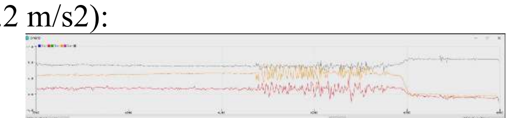
	
scooter without damper	scooter with damper

Subject B, route 1, paved road:

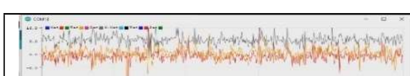
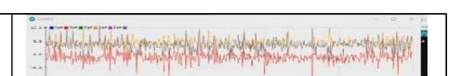
	
scooter without damper	scooter with damper

5. For person B, the behavior of the elbow is studied under the conditions of using the drill and while moving with the scooter.

The graphs obtained in the 2 situations are presented below:
Elbow at 90, empty, estimated acceleration 4g (39.2 m/s2):



Traveling by scooter:
Route 2, car park, estimated acceleration 8g (78.48 m/s2):

	
scooter without damper	scooter with damper

The results obtained are similar in the two cases.

6. In the case of the knee, the measurements made with the HVA 4447 professional sensor led to the following average acceleration values:
- in the case of using the machine tool empty: 9.24 m/s2;

- in the case of using machine tools under load: 5.22 m/s2 (wood); 5.64 m/s2 (concrete).

The experiments carried out validated the theoretical models chosen to a good extent.

Arduino sensors can be an inexpensive and fast alternative to measure the effect of vibrations on the human body.

In the conditions where vibration measurements are required, Arduino can be an alternative, if it is well calibrated and there is the possibility of appropriate attachment on the monitored area to be able to gather information.

As part of the thesis, I made measurements with the ADXL345 accelerometer and the HVA 4447 and 4506-B 003 professional accelerometers.

The results were surprisingly close, but reflect the need for a better calibration of the Arduino and some improvements needed to the measurement equipment.

ORIGINAL CONTRIBUTIONS

As part of my doctoral thesis, I followed the behavior of the elbow and knee joints under the influence of vibrations at the workplace, but also in the case of travel during free time with a means of transport such as a scooter.

Personal contributions:

- The systemic presentation of the most spectacular mathematical models of the human organism;
- The development of two original biomechanical models for the elbow and knee joint;
- Determining the main parameters of the forced vibrations that act on the elbow, respectively the knee in the case of people who use a rotary impact machine;
- Determination of the main parameters of the forced vibrations that occur accidentally during the use of a scooter;
- Validation of the biomechanical models proposed for the joints by comparing the theoretical and experimental sizes.

DIRECTIONS FUTURE FOR STUDY

During the research carried out for the realization of the thesis, I found that studies were carried out that showed the negative effects of vibrations (discomfort, fatigue, fear, serious injuries to the muscular and bone system or internal organs), but there are also methods and technologies that use vibrations for therapeutic purposes.

In the future, to continue the research started in this thesis, the following are proposed:

Determining the values of accelerations and frequencies in the elbow and knee areas based on measurements made with the help of a vibrating plate and small mechanized tools.

More efficient calibration for the ADXL345 accelerometer to achieve more accurate measurements. Better sensor calibration leads to increased sensitivity and more accurate data.

The creation of new biomechanical models for the joints of the human body in which the non-linearities in the links are taken into account in order to increase the precision.

The use of small mechanized equipment and fitness equipment to make comparative vibration measurements on the elbow and knee joints.

With the help of 3D printing, the elbow or knee joint should be modeled and in vitro measurements should be made on the printed models.

The purchase of professional equipment for performing vibration measurements such as professional Arduino sensors and microcontrollers.

Starting from the idea of achieving a distribution of the points of the human body exposed to oscillations presented by Mr. Panaitescu-Liess, a Romanian research platform is proposed in the field of mechanical vibrations and biomechanics through which tests can be done to see the influence of construction equipment on users and the integration of dynamic models into complex robotic models. A calculation model of the human body and its components can be created for vibration-type stresses taking into account the parametric distribution on length, surface and volume. The purpose of this platform is to create vibration control mechanisms - assessment, measurement, reporting - to prevent negative effects through prolonged exposure to vibrations. The research and architecture of the platform could be carried out within the faculty together with the interested students.

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