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CONTRIBUTIONS TO THE STUDY OF LOWER LIMB BIOMECHANICS OF A HUMAN SUBJECT UNDO TO VIBRATION. PART III: INTEGRATED RESULTS

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Abstract: *In the paper makes a study on the behavior of complex biomechanical limb under the action of vibration. The request is applied through the sole of the foot and it propagates along the leg requested through thank and the femur. The second leg is placed on a surface considered fixed, therefore the linkage of given leg and the second leg, it may be considered a cylindrical joint in plane. Mechanical System (part I) is analyzed through integration into Matlab Simulink, and it has the system of differential equations (part II), which characterizes the dynamics of it. The integrated results obtained are comparable to those existing in the literature (part III).*
Key words: *biomechanics study, lower limb, human subject, vibrations.*

1. GENERAL CONSIDERATIONS OF BIOMECHANICAL 5LGGF SYSTEM

In the paper, extended in three parts, makes a study on the behavior of complex biomechanical limb under the action of vibration. The request is applied through the sole of the foot and it propagates along the leg requested through thank and the femur. The second leg is placed on a surface considered fixed, therefore the linkage of given leg and the second leg, it may be considered a cylindrical joint in plane. Mechanical System (part I) [Arg 16] is analyzed through integration into Matlab Simulink, and it has the system of differential equations (part II) [Fod 15], which characterizes the dynamics of it. The integrated results obtained are comparable to those existing in the literature (part III).

Mechanical model is shown in Figure 1, [Arg 16] and it prezints the mechanical system. It will be called 5LBGGF, specially made a system with five degrees of freedom which is composed of foot, shank, knee and femur. The meaning of notation is found in Romanian names, as they write: LaBa piciorului, Gambă, Genunchi şi Femur (5LBGGF).

The system of differential equations is given in the second part [Fod 15], and it is a system of second-order differential equations, homogeneous, with constant coefficients in the unknowns: z1, z2, z3, z4, d5, which give the coordinates of the center of masses of each element in the longitudinal direction.

The system first-order derivatives occurs each generalized coordinates that constitutes their speeds and second-order derivatives, which belong to the accelerations of each element individually.

2. ESTABKISHING OF KINEMATICS VARIATION LAWS OF BIOMECHANICAL 5LGGF SYSTEM

The system of differential equations noted (2) in the second part of paper [Fod 15] in integrated by the Runge-Kutta of 4.5 order, with variable pitch.

The purpose of the integration, it is given in the explicit form higher-order derivative in each equation, and keeps in mind that requires equal with one the first coefficient. With these explanations is obtained:

$$
\begin{cases}
\ddot{z}_1 = [c_1\dot{z} + k_1 z - (c_1 + c_2 + c_3)\dot{z}_1 - (k_1 + k_2 + k_3)z_1 + c_2\dot{z}_2 + c_3\dot{z}_3 + k_2 z_2 + k_3 z_3]/m_1 \\
\ddot{z}_2 = [c_2\dot{z}_1 - (c_2 + c_{41})\dot{z}_2 + k_2 z_1 - (k_2 + k_{41})z_2 + c_{41}\dot{z}_4 + k_{41}z_4]/m_2 \\
\ddot{z}_3 = [c_3\dot{z}_1 - (c_3 + c_{42})\dot{z}_3 + k_3 z_1 - (k_3 + k_{42})z_3 + c_{42}\dot{z}_4 + k_{42}z_4]/m_3 \\
\ddot{z}_4 = [c_{41}\dot{z}_2 - (c_{41} + c_{42} + c_5)\dot{z}_4 + k_{41}z_2 - (k_{41} + k_{42} + k_5)z_4 + c_{42}\dot{z}_3 + k_{42}z_3 + \\
\qquad - c_5\dot{d}_5\cos(\pi/2 - \varphi) + k_5 d_5\cos(\pi/2 - \varphi)]/m_4 \\
\ddot{d}_5 = [c_5\dot{z}_4 - c_5\dot{d}_5\cos(\pi/2 - \varphi) - c_6\dot{d}_5 + k_5 z_4 - k_5 d_5\cos(\pi/2 - \varphi) - k_6 d_5]/m_5
\end{cases}
\tag{1}
$$

The notation of the unknowquatities and them coeficients are given in the second part of this paper [Fod 16].

The request of leg by the vibrating platform is made after an harmonic variation law, which is given from the coordinate z figura 1 in the first part of this paper [Arg 16].

2.1. Initial conditions

Harmonic vibration force of vibratory platform has the expression:

$$z = 2\,Z_0\,sin\,(\omega t + \varphi_0) \tag{2}$$

Where:
- z – scalar value of harmonic vibration of vibrating platform [N];
- Z_0 – amplitude harmonic vibration force of vibratory platform [N];
- ω – vibration pulsation [rad/s], ω = 2*pi*f [rad/s];
- f – frequency [Hz];
- t – time [s].

Initial phase φ_0 may be considered null, if the system starts from the static equilibrium position. Amplitude request Z_0 = 3 mm and the pulsation ω depends on the frequency of platform and in this way the theoretical substantiation of the lower limb can deal with a wide range of frequencies.

3. KINEMATICS OF 5LBGGF SYSTEM SUBJECTED TO VIBRATIONS

LA VIBRAT

The request for the study of limb vibrations of an operator on a vibrating platform, applies to two groups of frequencies, thus:

- ✓ Frequencies set according to their own frequencies, proposed by various authors in studying the vibration of the human body. They are: 2Hz, 4Hz, 10Hz, 17Hz, 20Hz, 35Hz.
- ✓ Usual working frequencies of the platform: 23.4Hz, 24.9Hz, 26.3Hz..

Programming environment used is the OCTAVE, which he works under the operating system Linux. It has adopted this procedure, because it is much faster and can intervene in every stage in order to solv the problem.

3.1. The request at 2Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 2Hz, is in the sequence of figures 1, 2, and 3.

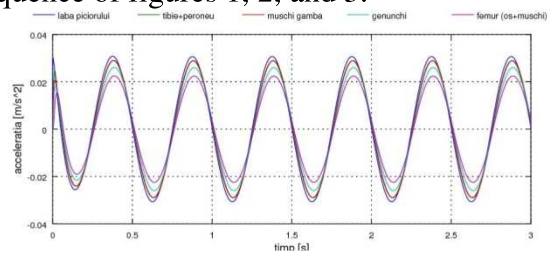

Fig. 1. The masses accelerations at 2Hz frequency

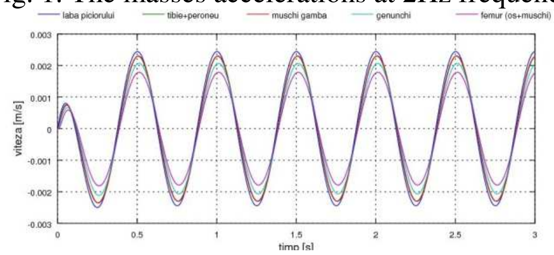

Fig. 2. The masses velocities at 2Hz frequency

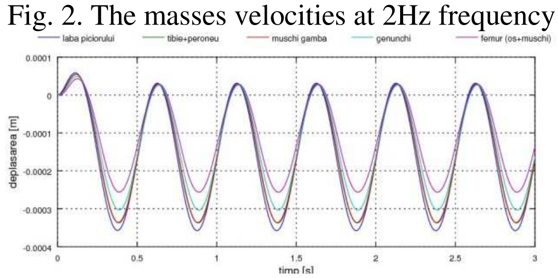

Fig. 3. The masses deplacements at 2Hz frequency

3.2. The request at 4Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 4Hz, is in the sequence of figures 4, 5, and 6.

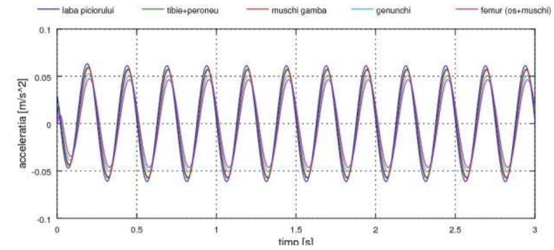

Fig.4. The masses accelerations at 4Hz frequency

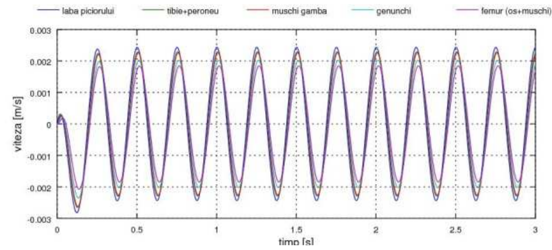

Fig.5. The masses velocities at 4Hz frequency

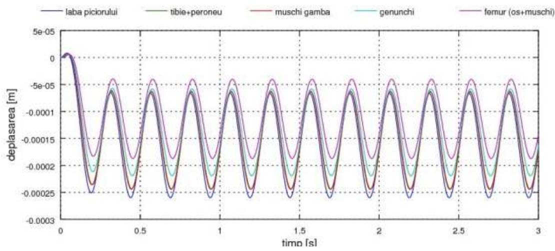

Fig.6. The masses deplacements at 4Hz frequency

3.3. The request at 10Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 10Hz, is in the sequence of figures 7, 8, and 9.

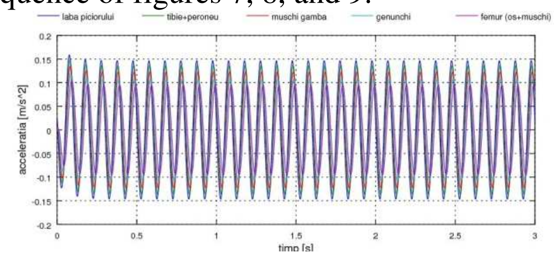

Fig.7. The masses accelerations at 10Hz frequency

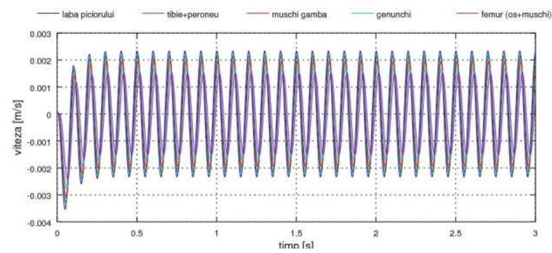

Fig.8. The masses velocities at 10Hz frequency

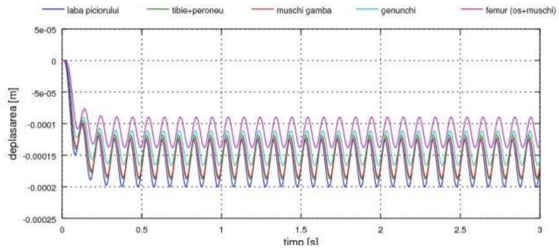

Fig.9. The masses deplacements at 10Hz frequency

3.4. The request at 17Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 17Hz, is in the sequence of figures 10, 11, and 12.

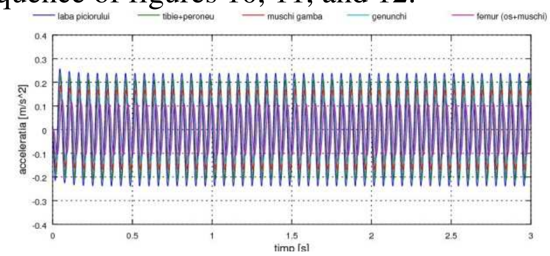

Fig.10. The masses accelerations at 17Hz frequency

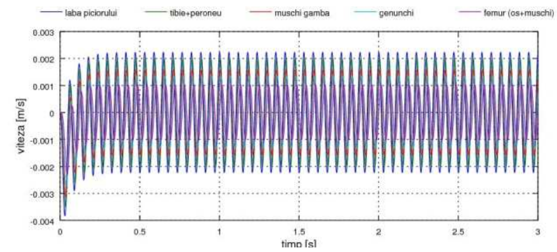

Fig.11. The masses velocities at 17Hz frequency

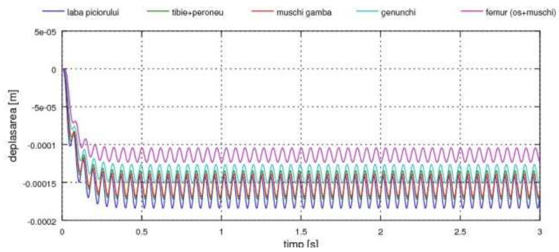

Fig.12. The masses deplacements at 17Hz frequency

3.5. The request at 20Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 20Hz, is in the sequence of figures 13, 14, and 15.

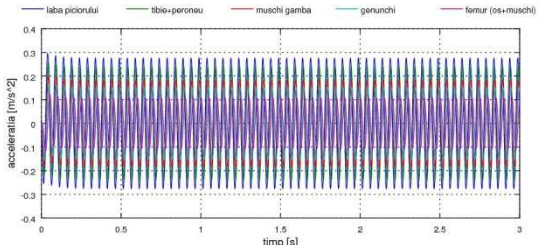

Fig.13. The masses accelerations at 20Hz frequency

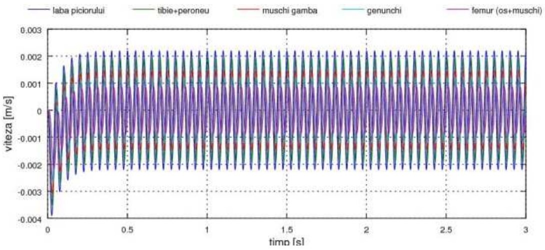

Fig.14. The masses velocities at 20Hz frequency

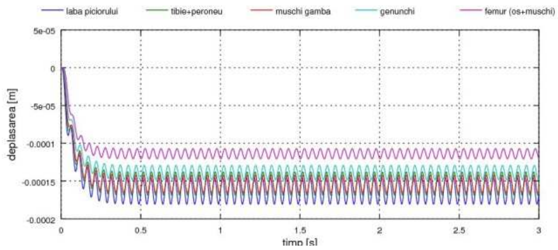

Fig.15. The masses deplacements at 20Hz frequency

3.6. The request at 23.4Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 23.4Hz, is in the sequence of figures 16, 17, and 18.

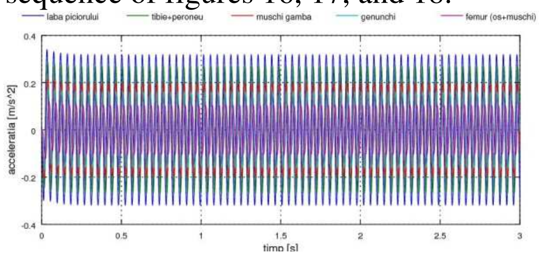

Fig.16. The masses accelerations at 23.4Hz frequency

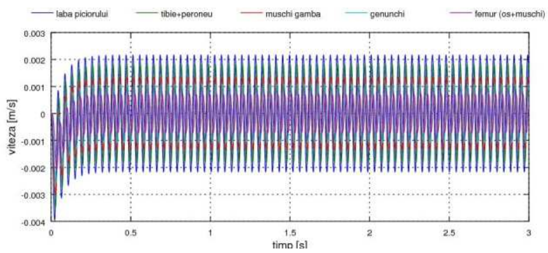

Fig.17. The masses velocities at 23.4Hz frequency

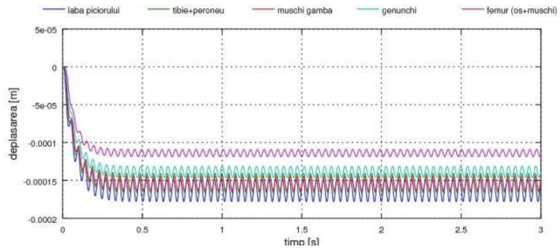

Fig.18. The masses deplacements at 23.4Hz frequency

3.7. The request at 24.9Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 24.9Hz, is in the sequence of figures 19, 20, and 21.

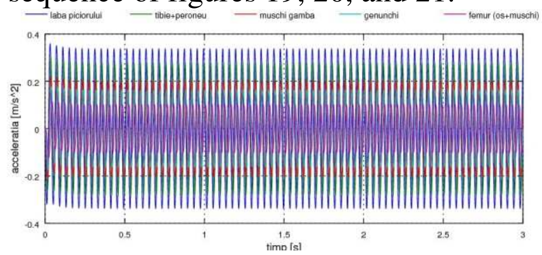

Fig.19. The masses accelerations at 24.9Hz frequency

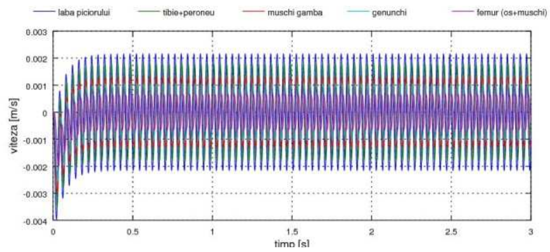

Fig.20. The masses velocities at 24.9Hz frequency

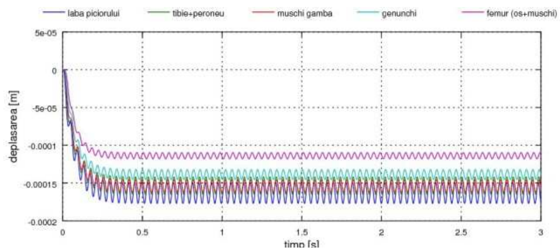

Fig.21. The masses deplacements at 24.9Hz frequency

3.8. The request at 26.3Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 26.3Hz, is in the sequence of figures 22, 23, and 24.

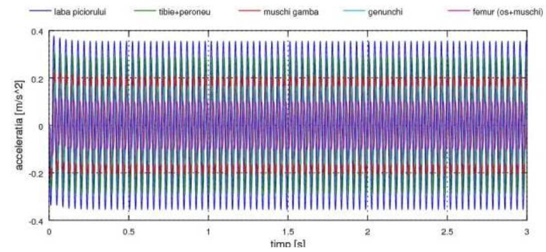

Fig.22. The masses accelerations at 26.3Hz frequency

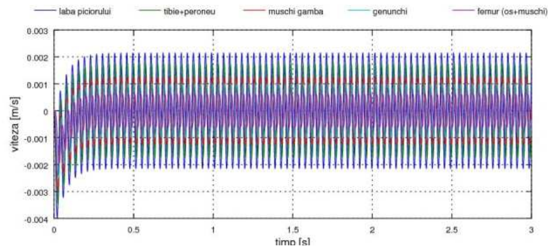

Fig.23. The masses velocities at 26.3Hz frequency

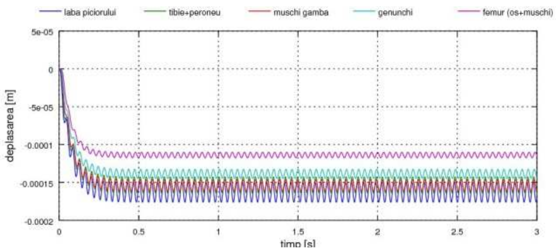

Fig.24. The masses deplacements at 26.3Hz frequency

3.9. The request at 35Hz frequency

System solution of differential equations (1) by the Runge-Kutta of 4.5 order, with variable pitch, for frequency of 35Hz, is in the sequence of figures 25, 26, and 27.

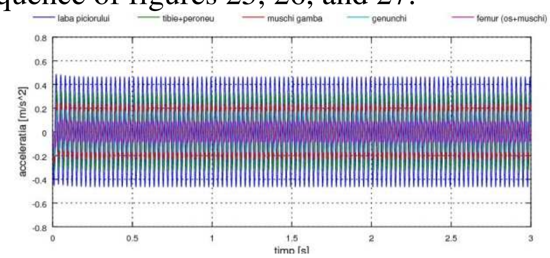

Fig.25. The masses accelerations at 35Hz frequency

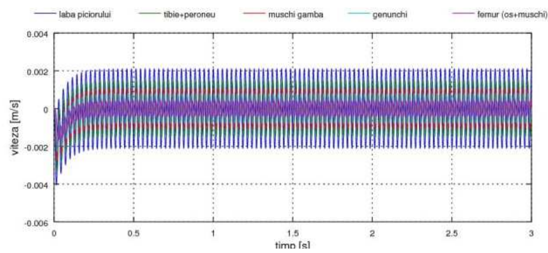

Fig.26. The masses velocities at 35Hz frequency

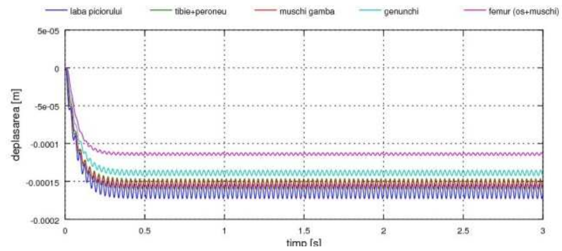

Fig.27. The masses diplacements at 35Hz frequency

3.10. MEANING OF COLORS

In the figures 1 – 27 the meaning of colors has the same usage for the different parts of the lower leg of the oppertor, who is situated on the vibrating platform. They are the followings:

- for foot;
- for shink bone (tibia and fibula);
- for shink muscle;
- for knee;
- for femur.

4. RESULTS ON INTEGRATION

The results of the system integration of the differential equations (1), for the inferior limb of an operator, subjected to vibrations on a vibrating platform, according to mechanical properties presented in the first part of the paper [Arg 16], it centralizes the tabular for each frequency separately, to which body was requested.

4.1. Centralized results for 2Hz frequency

The results of the integrated system for the 2Hz frequency for each part of the mechanical system are given in the table no. 1.

4.2. Centralized results for 4Hz frequency

The results of the integrated system for the 4Hz frequency for each part of the mechanical system are given in the table no. 2.

4.3. Centralized results for 10Hz frequency

The results of the integrated system for the 10Hz frequency for each part of the mechanical system are given in the table no. 3.

4.4. Centralized results for 17Hz frequency

The results of the integrated system for the 17Hz frequency for each part of the mechanical system are given in the table no. 4.

4.5. Centralized results for 20Hz frequency

The results of the integrated system for the 20Hz frequency for each part of the mechanical system are given in the table no. 5.

4.6. Centralized results for 23.4Hz frequency

The results of the integrated system for the 23.4Hz frequency for each part of the mechanical system are given in the table no. 6.

4.7. Centralized results for 24.9Hz frequency

The results of the integrated system for the 24.9Hz frequency for each part of the mechanical system are given in the table no. 7.

4.8. Centralized results for 26.3Hz frequency

The results of the integrated system for the 26.3Hz frequency for each part of the mechanical system are given in the table no. 8.

4.9. Centralized results for 35Hz frequency

The results of the integrated system for the 35Hz frequency for each part of the mechanical system are given in the table no. 9.

Table 1.

Kinematic values of 5LBGGF system at 2Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0.032	0.029	0.030	0.027	0.023
	Time [s]	0.45	0.45	0.45	0.47	0.48
	Axis position	Acceleration variation has zero for axis position.				
Velocity	Amplitude [m/s]	0.0025	0.0023	0.0023	0.0021	0.0018
	Time [s]	0.5	0.51	0.515	0.55	0.57
	Axis position	Velocity variation has zero for axis position.				
Displacement	Maximum displacement [m]x10^{-3}	-0.37	-0.345	-0.344	-0.301	0.26
	Time [s]	0.38	0.39	0.392	0.395	0.34
	Axis position	Symmetrical axis has moved to -0.00013 m, representations are superimposed, and the lower ones are differentiated.				

Table 2.

Kinematic values of 5LBGGF system at 4Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0.062	0.055	0.054	0.051	0.048
	Time [s]	0.2	0.22	0.23	0.24	0.25
	Axis position	Acceleration variation has zero for axis position.				
Velocity	Amplitude [m/s]	0.0024	0.0023	0.00228	0.002	0.0018
	Time [s]	0.25	0.26	0.275	0.28	0.3
	Axis position	Velocity variation has zero for axis position.				
Displacement	Maximum displacement [m]x10^{-3}	-0.25	-0.245	-0.243	-0.22	-0.18
	Time [s]	0.22	0.23	0.232	0.3	0.35
	Axis position	Symmetrical axis has moved to -0.00015 m, superior and inferior representations are differentiated.				

Table 3.

Kinematic values of 5LBGGF system at 10Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0.15	0.14	0.125	0.11	0.095
	Time [s]	0.25	0.252	0.254	0.256	0.26
	Axis position	Acceleration variation has zero for axis position				
Velocity	Amplitude [m/s]	0.023	0.021	0.018	0.016	0.014
	Time [s]	0.4	0.41	0.42	0.43	0.44
	Axis position	Velocity variation has zero for axis position				
Displacement	Maximum displacement [m]x10^{-3}	-0.2	-0.18	-0.175	-0.16	-0.14
	Time [s]	0.42	0.43	0.44	0.45	0.48
	Axis position	Symmetrical axis shifted to negative values, each coordinate has another of symmetry axis, which is closer to the axis neutral, when they advance in the system				

Table 4.

Kinematic values of 5LBGGF system at 17Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0. 42	0.21	0.17	0.115	0.11
	Time [s]	0.15	0.16	0.17	0.18	0.2
	Axis position	Acceleration variation has zero for axis position				
Velocity	Amplitude [m/s]	0.0022	0.002	0.0015	0.0013	0.001
	Time [s]	0.25	0.26	0.27	0.285	0.3
	Axis position	Velocity variation has zero for axis position				
Displacement	Maximum displacement [m]x10^{-3}	-0.18	-0.17	-0.166	-0.15	-0.12
	Time [s]	0.28	0.29	0.3	0.31	0.33
	Axis position	Symmetrical axis shifted to negative values, each coordinate has another of symmetry axis, which is closer to the axis neutral, when they advance in the system				

Table 5.

Kinematic values of 5LBGGF system at 20Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0.28	0.26	0.19	0.15	0.115
	Time [s]	0.13	0.132	0.134	0.138	0.14
	Axis position	Acceleration variation has zero for axis position				
Velocity	Amplitude [m/s]	0.022	0.00135	0.0014	0.0012	0.0009
	Time [s]	0.25	0.225	0.26	0.262	0.265
	Axis position	Velocity variation has zero for axis position				
Displacement	Maximum displacement [m]x10^{-3}	-0.17	-0.16	-0.155	-0.145	-0.12
	Time [s]	0.3	0.32	0.33	0.4	0.42

	Axis position	Symmetrical axis shifted to negative values, each coordinate has another of symmetry axis, which is closer to the axis neutral, when they advance in the system

Table 6.

Kinematic values of 5LBGGF system at 23.4Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0.36	0.32	0.2	0.18	0.15
	Time [s]	0.15	0.152	0.154	0.156	0.2
	Axis position	Acceleration variation has zero for axis position				
Velocity	Amplitude [m/s]	0.0022	0.0018	0.0013	0.00105	0.0007
	Time [s]	0.25	0.26	0.27	0.28	0.32
	Axis position	Velocity variation has zero for axis position				
Displacement	Maximum displacement [m]x10^{-3}	-0.17	-0.167	-0.165	-0.145	-0.12
	Time [s]	0.35	0.36	0.365	0.38	0.38
	Axis position	Symmetrical axis shifted to negative values, each coordinate has another of symmetry axis, which is closer to the axis neutral, when they advance in the system				

Table 7.

Kinematic values of 5LBGGF system at 24.9Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0.35	0.29	0.201	0.186	0.12
	Time [s]	0.2	0.21	0.22	0.24	0.26
	Axis position	Acceleration variation has zero for axis position				
Velocity	Amplitude [m/s]	0.00221	0.0018	0.0012	0.00102	0.0007
	Time [s]	0.25	0.252	0.254	0.258	0.31
	Axis position	Velocity variation has zero for axis position				
Displacement	Maximum displacement [m]x10^{-3}	-0.17	-0.16	-0.155	-0.148	-0.12
	Time [s]	0.35	0.36	0.365	0.4	0.45
	Axis position	Symmetrical axis shifted to negative values, each coordinate has another of symmetry axis, which is closer to the axis neutral, when they advance in the system				

Table 8.

Kinematic values of 5LBGGF system at 26.3Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude [m/s^2]	0.38	0.32	0.21	0.18	0.12
	Time [s]	0.2	0.21	0.22	0.23	0.25
	Axis position	Acceleration variation has zero for axis position				
Velocity	Amplitude [m/s]	0.0022	0.0017	0.0012	0.001	0.0006
	Time [s]	0.25	0.251	0.252	0.255	0.258
	Axis position	Velocity variation has zero for axis position				
Displacement	Maximum	-0.175	-0.162	-0.16	-0.14	-0.12

	displacement $[m]x10^{-3}$					
	Time [s]	0.3	0.32	0.34	0.35	0.36
	Axis position	Symmetrical axis shifted to negative values, each coordinate has another of symmetry axis, which is closer to the axis neutral, when they advance in the system				

Table 9.

Kinematic values of 5LBGGF system at 2Hz frequency

		Mass m_1	Mass m_2	Mass m_3	Mass m_4	Mass m_5
Acceleration	Amplitude $[m/s^2]$	0.38	0.32	0.21	0.18	0.12
	Time [s]	0.2	0.21	0.22	0.23	0.25
	Axis position	Acceleration variation has zero for axis position				
Velocity	Amplitude [m/s]	0.0022	0.0017	0.0012	0.001	0.0006
	Time [s]	0.25	0.251	0.252	0.255	0.258
	Axis position	Velocity variation has zero for axis position				
Displacement	Maximum displacement $[m]x10^{-3}$	-0.175	-0.162	-0.16	-0.14	-0.12
	Time [s]	0.3	0.32	0.34	0.35	0.36
	Axis position	Symmetrical axis shifted to negative values, each coordinate has another of symmetry axis, which is closer to the axis neutral, when they advance in the system				

5. CONCLUSIONS

It is considered a system with five freedom degrees [Arg 16] assimilated to foot human operator, who is supported on a vibrating platform, and it is subjected to vertical vibrations of this deep [Fod 15b].

It applies of the biomechanical system, be assimilated to a foot, a vibrating force, which delves through the sole of the foot, and it is propageted throughout the leg, until the cilindrical joint of the hip.

Request from vibrations is obtained with constant amplitude, and each request is given by one specified frequncy.

It has been applied a common range of parts or of various organs of the human body, considered as they are own frequencies of the human body, but also the common vibrating platform specific frequencies are given.

If it takes into account the succession of different frequencies, the solicitations can pull off in retail the following aspects:

- At the 2Hz frequency of oscillations, the differences between components are so low that the system appears as action as a solid stiff;
- At the 4Hz frequency of oscillations,
  - a small differences occur between the variations in time of extreme parts with displacement deviation toward the negative;
  - at the muscle and bone of shank, they have as monoblock reaction;
- At the 10Hz frequency of oscillations, significant deviations occur of dynamic axes coordinates;
- At the 17Hz frequency of oscillations, for the bone and muscle of lower leg varies with different amplitudes;
- At the 20Hz frequency of oscillations, symmetrical axis shifted to negative values, each coordinate has another axis of symmetry, which is closer to the neutral axis, in time than it progresses into the system;
- At the 23.4Hz frequency of oscillations,
- At the 24.9Hz frequency of oscillations, it can be said that the aging system it is noticed a pronounced differentiation of mechanical characteristic as, so the

transition from one element to another is made with strong mitigation

- At the 26.3Hz frequency of oscillations, the displacements are of the 10^{-5} order, which means that any application from the cylinder hinge in plane is imperceptible, for this frequency;
- At the 35Hz frequency of oscillations as:
  - a strong colours apart five parts;
  - the displacement of the amplitude is the of 10^{-7} m, which means that any application from the cylinder of the hip is imperceptible, for this frequency;
  - a movement of flow is stabilized at the distance of 1.5 x 10^{-4} m about the neutral axis, but some generalized coordinates are displaced above or below, this approach towards;
  - a difference between the dynamic axes is of the order of 10^{-6} m.

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Contribuţii la studiul biomecanicii membrului inferior al unui subiect uman supus la vibraţii. Partea III-a: Rezultatele integrării

Rezumat: *In lucrare se face un studiu complex, biomecanic asupra comportarii membrului inferior sub actiunea vibratiilor. Solicitarea se aplica prin talpa labei piciorului si se propagă de-a lungul piciorului solicitat prin gambă şi femur. Cel de al doilea picior se considera asezat pe o suprafata fixa, de aceea legătura dintre piciorul solicitat şi cel de al doilea picior, se poate considera o articulaţie cilindrică plană. Sistemul mecanic (Partea I-a) este analizat prin integrarea in MatLab Simulinc a sistemului de ecuatii diferentiale (Partea II-a), ce caracterizeaza dinamica acestuia. Rezultatele obtinute sunt comparabile cu cele existente in literatura de specialitate (Partea III-a).*

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