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DEVELOPMENT AND APPLICATION OF A NUMERICAL MODEL THAT SIMULATES THE HUMAN BODY'S BIOMECHANICAL RESPONSE

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Resumo
Neste trabalho será desenvolvido e aplicado um modelo numérico que simula a resposta biomecânica do corpo humano. Este modelo numérico multi-nodal será utilizado na avaliação das vibrações das diferentes secções do corpo humano, em condições de regime transitório.
A integração do sistema de equações de segunda ordem, baseado na equação de Newton, após convertido num sistema de primeira ordem, é resolvido através do método de Runge-Kutta-Fehlberg com controlo de erro.
Este modelo numérico multi-nodal será usado, neste trabalho, no estudo das vibrações a que um indivíduo em pé está sujeito quando são aplicadas solicitações nos pés. Serão analisadas as influências de dois tipos de solicitações, com irregularidades aleatórias, na resposta dinâmica das vibrações em diferentes secções do corpo humano. Serão apresentados os sinais das solicitações, da deslocação de algumas secções do corpo e do especto de potencia dos mesmos sinais.

Palavras-chave: resposta biomecânica do corpo humano, vibrações no corpo humano, equação de Newton, método de Runge-Kutta-Fehlberg.

Abstract
In this paper is developed and applicated a numerical model that simulates the human body's biomechanical response. This multi-nodal numerical model is applied in the vibrations of the different sections of the human body, under transient conditions.
The integration of second order equations systems, based in Newton equation, after being converted in a first order equation system, is solved through the Runge-Kutta-Fehlberg method with error control.
This multi-nodal numerical model will be used, in this work, in the study of the vibrations that a standing person is subjected when solicitation are applied in the feet. The influence of two types of solicitations is analyzed, with random irregularities, in the dynamic response of the vibrations in different sections of the human body. The signals of the stimuli, the displacement of some sections of the body and the power spectrum of the same signals will be presented.

Keywords: biomechanical response of the human body, vibrations in the human body, Newton's equation, Runge-Kutta-Fehlberg method.

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1 Introduction

In occupied spaces the occupants are subjected to thermal comfort, indoor air quality, noise, vibrations and others factors Silva (2002) [1]. All factors affect the human comfort. However, in this work only the vibrations is analised.
In order to evaluate the human body vibrations, in transient conditions, in accordance with the model presented in the present work, the human geometry and the human temperature distribution is an import input.
In the human thermal response and the human body's biomechanical response are important the design of the human body geometry. The human geometry, the human thermal response, the thermoregulatory system and the clothing thermal response are presented in detail in Conceição (1999) [2], Conceição (2000) [3], Conceição and Lúcio (2001) [4], Conceição et al. (2002) [5], Conceição et al. (2006) [6] and Conceição et al. (2007) [7], Conceição e Lúcio (2010) [8], Conceição et al. (2010) [9] and Conceição and Lúcio (2011) [10]. The human geometry was developed using empirical equations, the human thermal response was developed using energy and mass balance integral equations, the thermoregulatory system is based in empirical equations and the clothing thermal response was developed using energy and mass balance integral equations.
The combination of the human thermal response with other numerical models, as human biomechanical response, are used in different applications. As example, the coupling of human thermal response and the Computational Fluids Dynamics, in order to evaluate simultaneously the human temperature field and the space environmental variables can be analysed in Conceição et al. (2013) [11] and Conceição et al. (2016) [12]. The coupling considers simultaneously the human geometry and the compartment geometry and the input of the human thermal response are the output of the Computational Fluids Dynamics and the input of the Computational Fluids Dynamics are the output of the human thermal response.
In the human body's biomechanical response, present in this work, the Runge-Kutta method or the Runge-Kutta-Fehlberg method, with error control, is used. The Runge-Kutta method in applied in Conceição et al. (2000) [13] and Conceição (1996) [14], in vehicles, while the Runge-Kutta-Fehlberg method, with error control, is applied in Conceição et al. (2004) [15], Conceição and Lúcio (2006) [16], Conceição et al. (2008) [17], in buildings, and in Conceição (1988) [18] and Conceição et al. (2017) [19], in human termal response.
To evaluate the human body vibrations, using a numerical model, different works were developed considering the human body divided in several elements. In Grieve and Goldman (1988) [20] were considered the head, upper torsos, arm-shoulders, thorax-abdomen, spinal column, hips and legs and in the Bruel and Kjaer (1989) [21] were analysed the head, eyeballs, shoulders girdle, lower arms, arms, hands, chest wall, abdominal mass, spinal column, hips, legs and feet. In Wu et al. (1999) [22] and Wu et al. (1999) [23] used a human-seat and a human-seat-suspension models to analyse the human body vibrations, Tregoubov (2000) used the biomechanical model in order to identify the human body under vibration, Mitsunori et al. (2001) [24] analysed the vibration model for humans and AlShabi et al. (2016) [25] studied the effect of mechanical vibrations in human body. In Bruel and Kjaer (1989) [21] were also indicated the vibration resonance frequencies for each human body section.
The biomechanical numerical model calculates the displacement, the velocity and the acceleration that each body element is subjected. The displacement, using the power spectrum software, is used to evaluate the dominants vibration frequencies. However, in Zhou and Melikov (2002) [27], the equivalent frequency concept is presented.

The present study is a continuation of Conceição and Lúcio (2004) [26] and of Conceição et al. (2020) [28]. In Conceição and Lúcio (2004) [26], a biomechanical model calculates the acceleration, velocity and displacement in the different human body sections and evaluates the Runge-Kutta-Fehlberg performance, when the human body was divided in 42 elements and when the body is subjected to local stimuli. The influence of a stimulus in the feet in the human body human mechanical vibrations was made. In Conceição et al. (2020) [28] the human thermal response, the validation and three application are made. In the human thermal response, the human geometry and human temperature distribution is evaluated. In the validation tests the comparison between calculated, of the biomechanical human body numerical model, and measured, presented in specialized bibliography, of the resonance vibration frequencies was made. In order to evaluate this comparison a numerical test is made, when a standing occupant is subjected to a stimuli in the feet. The vibration and the power spectra, was developed. In accordance with the obtained results, was possible to verify that, in general, the obtained results are in accordance with the suggested values presented in the bibliography. In the three application were evaluate the influence of periodical and random vibration in the human mechanical vibrations. In accordance with the obtained results is verified that the amplitude of vibrations are more attenuated in the upper human body sections when is applied the periodical vibration in the floor level than when is applied the random vibration. The amplitude of vibrations are more attenuated in the lower human body sections when is applied the random vibration in the floor level than when is applied the periodical vibration in the floor level.

In the actual work, the biomechanical human body numerical model is used to evaluate the influence of two different random vibration, with the same amplitude, in the human mechanical vibrations.

2 Numerical Model and Metodology

The human thermal response numerical model generated the human body geometry and calculated the human body thermal variables, while the biomechanical numerical model calculates the human vibrations.

2.1 Numerical Model

The human thermal response numerical model considers the human body divided in 24 cylindrical and 1 spherical elements, being each one divided in 4 parts (core, muscle, fat and skin), sub-divided in several layers and could be still protected from the external environment through some clothing layers. The human thermal system considers the energy balance integral equations, for the human body tissue and for the clothing, and the mass balance integral equations for the blood and transpired water in the skin surface and in the clothing layers.
More details can be analysed in Conceição (1999) [2], Conceição (2000) [3], Conceição and Lúcio (2001) [4], Conceição et al. (2002) [5], Conceição et al. (2006) [6], Conceição et al. (2007) [7], Conceição e Lúcio (2010) [8], Conceição et al. (2010) [9] and Conceição and Lúcio (2011) [10].

The biomechanical numerical model is divided in 42 elements (head, eyeballs, maxillary, spinal column, chest wall, thorax and abdominal mass, shoulders, arms, hands, fingers, hips, thighs, legs and feet). Each element is represented by its equivalent mass, elastic and damping elements.
The biomechanical numerical model is developed based in Newton equation applied in each element. The obtained second-order integral equations system, that considers the elastic and damping forces, is converted in a first-order integral equations system.
More details about the biomechanical numerical model can be analysed in Conceição and Lúcio (2004) [26].

2.2 Numerical Methodology

In this study tow different random vibration signal of the floor are simulated. In the random vibration two simulations, during two seconds, were made:

- Case A: floor vibrations with amplitude of 0.002 m (RMS=0,000574 m);
- Case B: floor vibrations with amplitude of 0.002 m (RMS=0,00058 m).

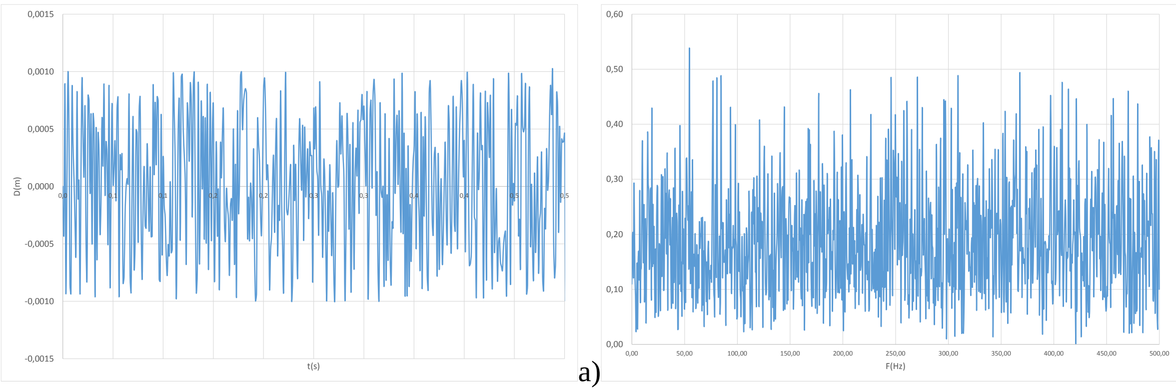
The numerical simulation is made during 2 seconds, with an acquisition rate of 1000 values per second.

3 Results

In figure 1 is presented the vibration and power spectra in the floor, for the Case A, that the human body is subjected, during the first 0.5 s. In figure 2 is show the vibration and power spectra in the head and abdominal mass, for the Case A. In figure 3 is presented the vibration and power spectra in the shoulder, arm and hand, for the Case A. In figure 4 is show the vibration and power spectra in the thigh, leg and foot, for the Case A.

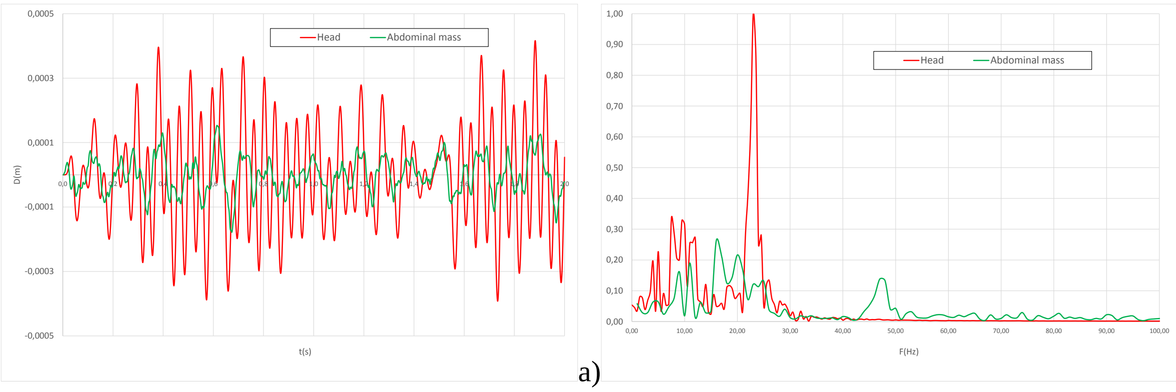
The vibration and power spectra in the floor, for the Case B, that the human body is subjected, during the first 0.5 s, is presented in figure 5. The vibration and power spectra in the head and abdominal mass, for the Case B, is show in figure 6. The vibration and power spectra in the shoulder, arm and hand, for the Case B, is presented in figure 7. The vibration and power spectra in the thigh, leg and foot, for the Case B. is show figure 8.

When is applied a random vibration in the floor, in general, the amplitude of the vibration in the human body are verified. The amplification of the amplitude of the vibration in the upper body section are higher than in the lower body section.



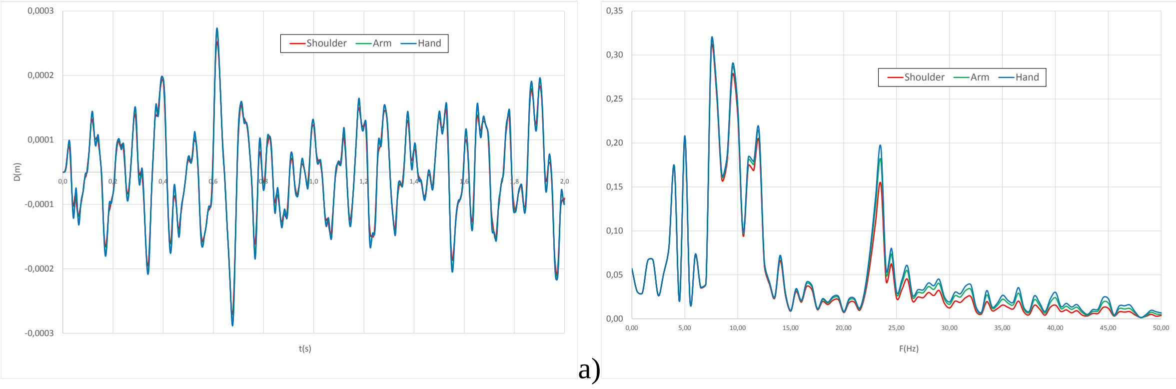
a) b)

Figure 1 – Vibration (a) and power spectra (b) in the floor, for the Case A.



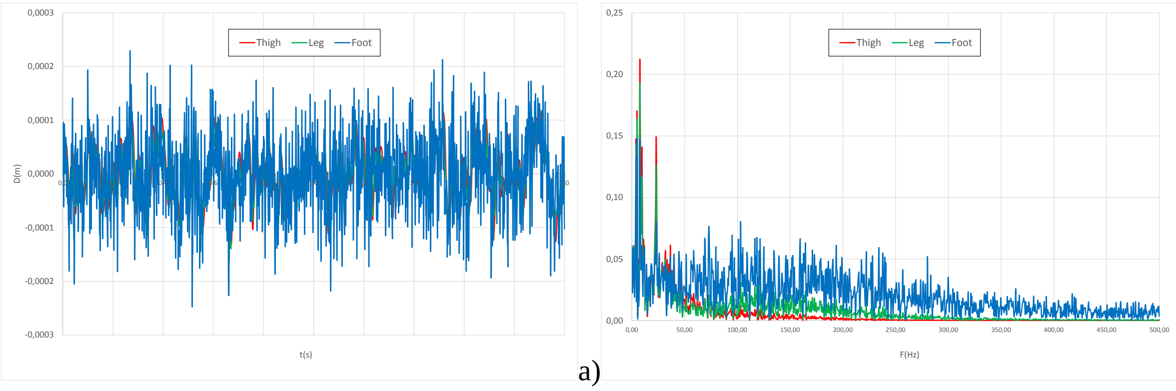
a) b)

Figure 2 – Vibration (a) and power spectra (b) in the head and abdominal mass, for the Case A.



a) b)

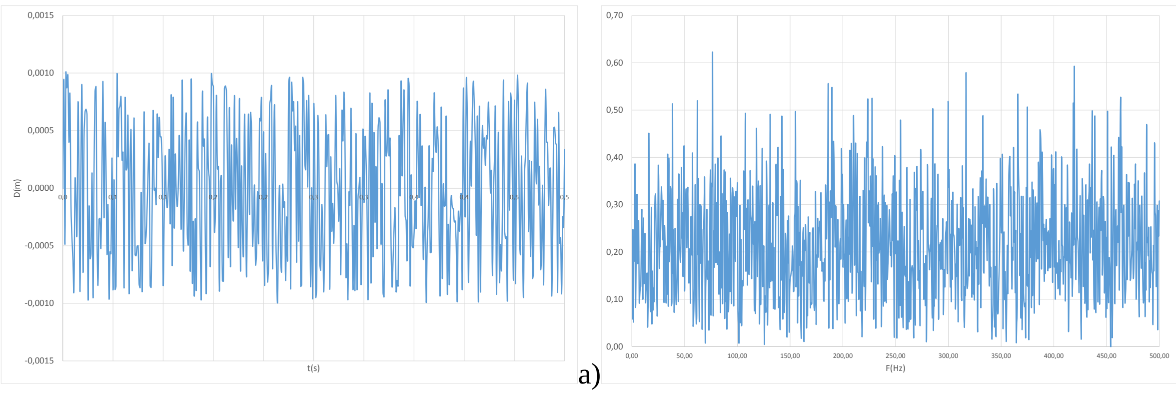
Figure 3 – Vibration (a) and power spectra (b) in the shoulder, arm and hand, for the Case A.



a) b)

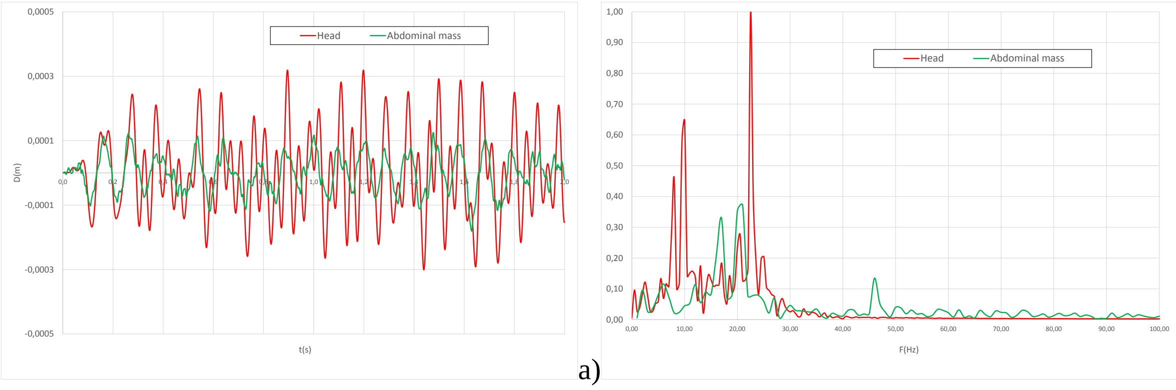
Figure 4 – Vibration (a) and power spectra (b) in the thigh, leg and foot, for the Case A.

The dominant frequencies and equivalent frequency and the power spectra, presented for 12 elements of the human body, for the Case A and B are presented in table 1. The RMS represents the Root Mean Square, the (V) are associated with the velocity vibration, (A) are associated with the acceleration vibration, A are associated with the vibration amplitude, F are associated with the vibration frequency obtained by the power spactra and EF represent the equivalent frequency.



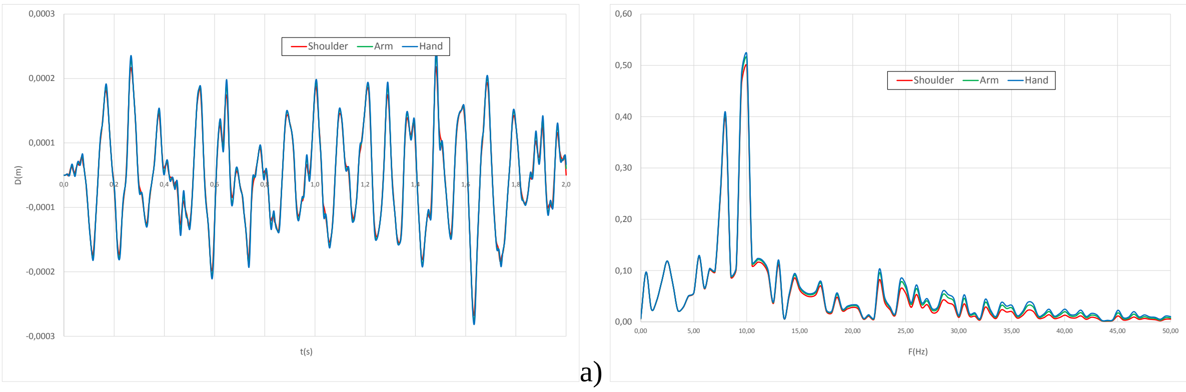
a) b)

Figure 5 – Vibration (a) and power spectra (b) in the floor, for the Case B.



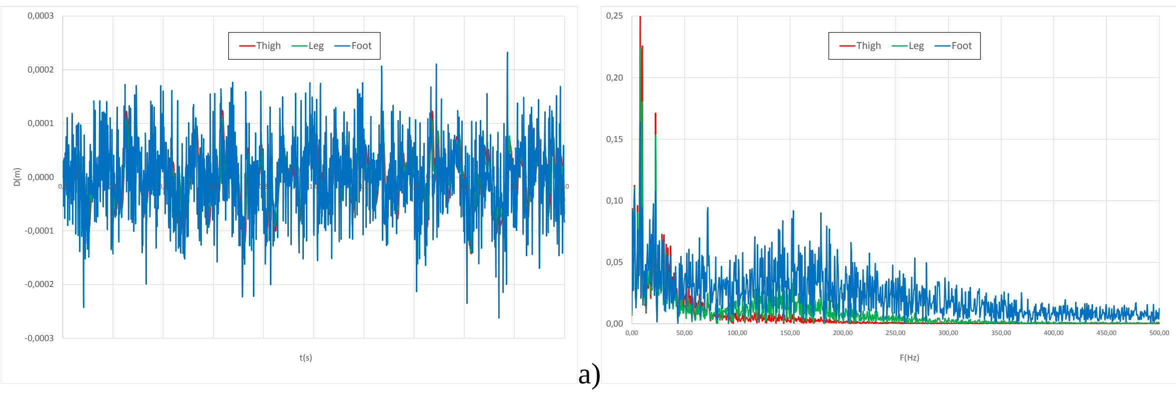
a) b)

Figure 6 – Vibration (a) and power spectra (b) in the head and abdominal mass, for the Case B.



a)
b)

Figure 7 – Vibration (a) and power spectra (b) in the shoulder, arm and hand, for the Case B.



a) b)

Figure 8 – Vibration (a) and power spectra (b) in the thigh, leg and foot, for the Case B.

Table 1: Dominant frequencies and equivalent frequency presented for 12 elements of the human body element, for the two Cases.

	Case A				Case B			
	A (0,002m/s)				A (0,002m/s)			
	RMS(V)	RMS(A)	EF (Hz)	F(Hz)	RMS(V)	RMS(A)	EF (Hz)	F(Hz)
Head	0,00015	0,02103	20,979	23,02;7,51;10,01;12,01;5,01;4,00	0,00013	0,01493	18,215	23,52;10,01;8,01;10,51
Eyeball	0,00015	0,02105	20,983	23,02;7,51;10,01;12,01;5,01;4,00	0,00013	0,01494	18,22	23,52;10,01;8,01;10,51
Chest	0,00006	0,00494	11,767	8,01;9,51;12,01;5,01;23,52;4,00	0,00007	0,00491	10,992	10,01;8,01
Heart	0,00006	0,00509	12,017	8,01;9,51;12,01;5,01;23,52;4,00	0,00007	0,00503	11,164	10,01;8,01
Abdominal mass	0,00005	0,00525	14,883	7,51;9,51;5,01;4,00;23,02	0,00005	0,00491	13,599	10,01;8,01;22,52
Spinal column	0,00005	0,00589	15,916	7,51;9,51;5,01;4,00;23,02	0,00005	0,00544	14,481	10,01;8,01;22,52
Shoulder	0,00006	0,00512	12,063	8,01;9,51;12,01;5,01;23,52;4,00	0,00007	0,00506	11,195	10,01;8,01
Arm	0,00007	0,00575	12,969	8,01;9,51;12,01;5,01;23,52;4,00	0,00007	0,00553	11,823	10,01;8,01
Hand	0,00007	0,0062	13,657	8,01;9,51;12,01;5,01;23,52;4,00	0,00007	0,0059	12,355	10,01;8,01
Thigh	0,00004	0,00769	24,982	8,01;5,01;23,02;7,51	0,00004	0,00742	24,402	8,01;22,52;2,5
Leg	0,00004	0,01709	58,092	8,01;5,01;23,02;7,51	0,00004	0,01723	59,128	8,01;22,52;2,5
Foot	0,00007	0,06558	144,138	8,01;5,01;23,02;7,51	0,00007	0,06438	144,772	8,01;22,52;2,5

In accordance with the obtained results is possible to verify that the frequencies in the feet are similar to the floor. The body structure reduces the vibration frequency. The frequencies values in the upper body section are lower than the in the lower body section.
Different random vibrations applied in the floor in this study promotes different vibration in the human body. However, the frequencies obtained in the human body present some similarities.
In accordance with the obtained results, the equivalent frequencies values is near the frequency obtained in the power spectra, when is verified a dominant frequency in the power spectra. In this study this statement is verified in the upper bodies sections.

4 Conclusions

In this study is developed and applied a numerical model that simulates the human body's biomechanical response. Two different random vibration signal of the floor are simulated.
In accordance with the obtained results, when is applied a random vibration in the floor, in general, the amplitude of the vibration in the human body are not amortized. The amplification of the amplitude of the vibration in the upper body section are higher than in the lower body section.
The frequencies in the feet are similar to the floor. The body structure reduces the vibration frequency. The frequencies values in the upper body section are lower than the in the lower body section. The different random vibrations applied in the floor in this study promotes different vibration in the human body. However, the frequencies obtained in the human body present some similarities.

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