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Biomechanical models used in the analysis of vibrations induced to the human organism

Modele biomecanice utilizate în analiza vibrațiilor induse organismului uman

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Summary. An analysis of the biomechanical models associated with the human body is performed (from 1 degree of freedom to 4 degrees of freedom).
Following the analysis of the biomechanical models, the average frequencies found in different components of the human body are presented.

Abstract. This paper focus on biomechanical models analysis of human body from one to five degree of freedom. As result of this analysis the medium frequencies of different human body elements are found.

Key words: vibrations, human body, biomechanical models

INTRODUCTION

This article presents a synthesis of the biomechanical models associated with the human body from models with 1 degree of freedom to models with 16 degrees of freedom. After a detailed discussion of each biomechanical model, the document ends with a table in which the average frequencies found in different components of the human body are presented.

1. THE MODEL NOTION

The concept of a model has appeared since ancient times, initially being an attempt to represent, imitate and explain the environment through cave drawings.

Throughout the development of human civilization, fundamental concepts of elementary mechanics have been developed. These concepts were later developed and used in successfully describing the movements of the human body.

The fragility of the human being that also manifests itself in the case of exposure to vibratory phenomena has led to in-depth research in the area of determining and combating negative effects (causing occupational diseases) that vibrations have on the human body. The area of beneficial effects was not neglected either, although the research was of a smaller scale.

All these findings realize the importance of the biomechanical modeling of the human body subjected to the action of vibrations. Although it is rarely possible to check the results obtained on the basis of a model with those obtained from determinations on the real model, simulations on different models can be done to identify the optimal model.

Biomechanical models associated with the human body [30],[92], they underwent successive transformations that increased the complexity and accuracy of explaining the phenomena and processes that occur in the human body.

These models to be viable, must be found on the border between complexity and simplicity.

1.1. The evolution of the biomechanical modeling concept over time

The concept of model has been used since ancient times, at the beginning being an attempt to represent, imitate and explain the environment.

As human civilization developed, fundamental concepts of elementary mechanics were defined. These notions were later developed and used to successfully describe the movements of the human body. In the following lines, some of the significant figures of history and the chronology of some of the most important discoveries and researches in this field are shown.

- Aristotle (384-322 B.C.) – he is the one who stated the first notions in treatises about the parts of animals and their movements in works such as ”De Partibus Animalium”, ”De Motu Animalium”, ”De Incessu Animalium”.
- Archimedes (287-212 B.C.) – discovers the principles of hydrostatics relative to the floating of bodies, still used today in the biomechanics of swimming, explained the law of levers and made studies on the center of mass.
- Heron of Alexandria (10-70 A.D.) – he carried out research on levers and is considered the father of the polytechnic school.
- Galen (131-201 A.D.) – studies movements, distinguishes between sensory and motor nerves, between agonist and antagonist muscles,

describes muscle tone and introduces the terms diarthrosis and synarthrosis still used today in biomechanics.

- Pappus (290-350 A.D.) – define with precision the center of mass and describe some of its properties.
- Philoponus (490-570 A.D.) – is the one who brought up the concept of "inertia" for the first time.
- Leonardo da Vinci (1452-1519) – the famous Renaissance artist, studied most of the elements related to the mechanics and anatomy of the human body and the center of gravity. He described the action of synergistic muscles that participate in walking, jumping and running.
- William Harvey (1578-1657) – is considered to be the father of fluid biomechanics.
- Alfonso Borelli (1608-1679) – through his remarkable studies of biomechanics he showed that the bones and segments of the human body act like levers that are moved by muscles, according to some principles of classical mechanics.
- Giorgio Baglivo (1668-1706) – distinguishes for the first time between smooth and striated muscles. He shows that the former are responsible for sustained contractions and the latter for rapid movements.
- Nicolas Andry (1658 – 1742) – names and defines, right in the title of his work Orthopedia, the art of preventing and correcting the deformations of the child's body.
- Weber brothers – substantiates on scientific bases the research in the field of biomechanics started by Borelli.
- Jansen – using serial photographs to study the revolution movement of the planet Venus, proposes the same method for the study of the human body.
- E. Muybridge (1831-1904) – he is the first to succeed in motion capture, making the first serial photographs of the movement of a racehorse.
- Marey and Demeny – prints on the photographic plate the successive positions of a movement, obtaining the cyclogram of the movement.
- C. W. Braune (1831-1892) – his experiments and conclusions on movement and walking are still valid today.
- Julius Wolff (1836-1902) – formulated what is known as "Wolff's Law" which describes the relationship between mechanical influence and bone geometry. He considered that the modification of the internal structure and configuration of man is the result of the change of shape and function of the bones, in correspondence with the laws of mathematics.

The parameters characterizing a biomechanical system will depend on the type of model used. For a physical biomechanical system there are two general methods of approach, which lead to the determination of the parameters that characterize the dynamic behavior of the system, namely: the analytical method and the experimental method.

These methods are shown schematically in the figure 1.1.

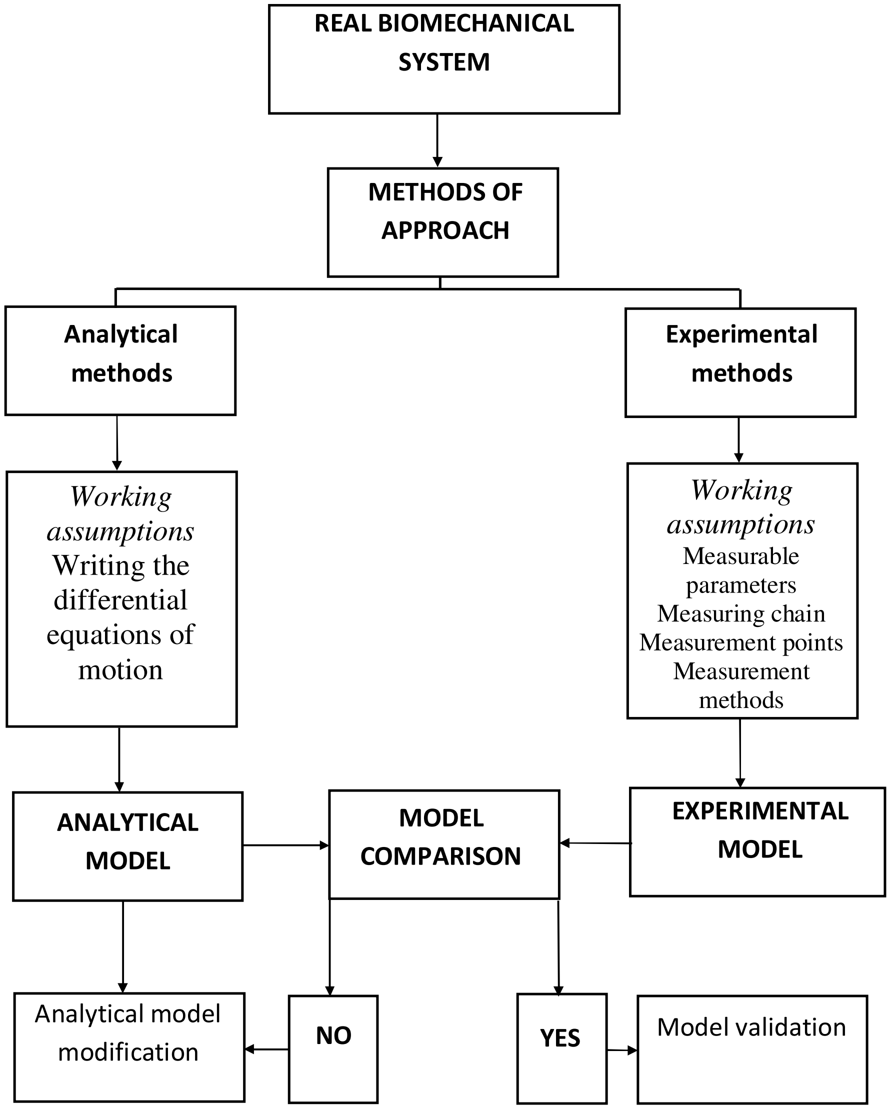


Fig. 1.1. General methods of approach to biomechanical systems [12],[17]

2. The human body – associated biomechanical models

The biodynamic study of humans can be traced back to 1918, when Hamilton (1918) investigated the effects of vibration on workers in limestone quarries. Many experimental evidences have shown that a human body can be injured by vibrations. Approximately 12 million workers in the US were reported to be affected by vibration (Amirouche, 1987), [7]. It is also well known that vibration can fracture the spine when subjected to strong vertical acceleration. In addition, the transmission of vibrations to the human body can reduce comfort or even have a negative effect on health. If the vibration is very severe, for example in an off-road vehicle, injuries to passengers and the driver can become a problem.

Research into the effects of vibration on seated workers indicated that the after-effects could be very harmful and in some cases lead to permanent injury (Kelsey and Hardy, 1975),[65]. Some results have suggested that low back pain is the result of continuous exposure to vibration (Pope et al., 1986),[101] and occurs more frequently among vehicle drivers than in representative control groups (Pope et al., 1987, [102]). As travel length increase, the driver is more exposed to vibrations that come mainly from the interaction between the road profile and the vehicle.

Therefore, in recent years people have become more concerned about vibrations and are looking for a more comfortable environment. In general, the study of biodynamic responses in humans can be classified into statistical (experimental) and analytical methods. According to different test subjects, the experimental study can be further classified into two groups.

In the study of mechanical injury to humans, animals (rats, pigs, etc.), human cadavers and mannequins are usually selected as test subjects to avoid injury to human beings. Cesari and Ramet (1982),[34], used impact tests to obtain the maximum fracture load on the pelvis and established pelvic injury criteria accordingly. Alem et al. (1984),[4], performed axial impact tests on 19 human cadavers to study the mechanical properties of the head-neck-vertebral structure and defined the injury standard.

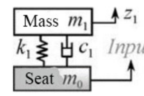
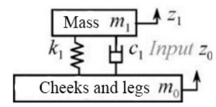
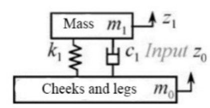
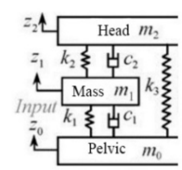
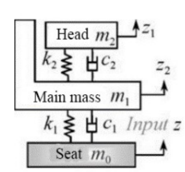
Pintar and Yoganandan (1989),[99], embedded six axial load sensors in and on the skin of seven cadavers to study the biodynamic and anatomical responses of the neck and cervical spine. Bohman et al. (2000),[22], implemented a series of tests using the Hybrid III 50% manikin to investigate the influence of the restraint system on neck loads in frontal impacts.

In addition, Yoganandan et al. (2000),[133], studied the biomechanical studies of one male and four female human cadaver in rear impact situations. Therefore, the forces and moments in occipital conditions were evaluated but also the risks of neck injury.

In an effort to define general values to characterize the biodynamic response of the seated body in the most commonly encountered work environments, Boileau et al. (1998),[22],[23] identified seat-to-head transmissibility (STH), driving point mechanical impedance (DPM) and apparent mass (AP) from prevailing published data by synthesizing and creating envelopes of different sets of selected dates. Those values of the various biodynamic response functions are defined for subjects maintaining an upright sitting posture without backrest support, with the feet resting on a vibrating platform.

Table 1.

One- and two-degree-of-freedom lumped parameter models of seated human subjects

Author	Biomechanical parameters			Remarks	Schematic of the model
	Mass (kg)	Damping (N-s/m)	Stiffness (N/m)		
Coermann model – one degree of freedom (1962)	m_1 56.8 ± 9.4	c_1 3840.0 ± 1007.0	k_1 75 500.0 ± 28 300.00	• Linear model – one degree of freedom • Total weight 56.8 kg • Excitation: $\ddot{z} = 5\ \sin \omega t$	
Wei and Griffin (1998)	m_1 43.4	c_1 1485.0	k_1 44130.0	• Linear model – one degree of freedom • Total weight 51.2 kg • m_0 in rigid contact with the seat • Excitation: $\ddot{z} = 5\ \sin \omega t$	
	m_1 7.8	c_0 -	k_0 -		
Model with two degrees of freedom Muksian and Nash (1976)	m_2 5.44	c_2 686.0	k_2 0.0	• Non linear model – two degrees of freedom • Total weight 79.83 kg • $c_1' = 17289 f_0^2, f_0 (excitation\ frequency$ $10Hz$ • $0, otherwise$ • m_0 in rigid contact with the seat • Excitation: $\ddot{z} = 5\ \sin \omega t$	
	m_1 47.17	c_1' See note c_1 467.0	k_1 63318.0		
	m_0 27.22	c_0 1780.0	k0 27158.0		
Alken (1978)	m_2 5.5 ± 0.9	c_2 318.0 ± 161.0	k_2 41 000.0 ± 24 100.00	• Linear model – two degrees of freedom • Total weigth 56.8 kg • Excitation: $\ddot{z} = 5\ \sin \omega t$	
Wei and Griffin (1998)	m_1 51.3 ± 8.5	c_1 2807.0 ± 1007.0	k_1 74 300.0 ± 17400.00		

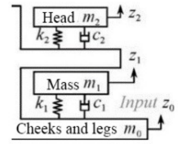
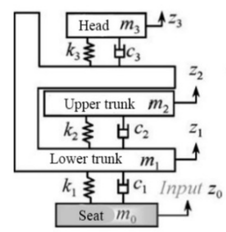
3.15	m_2 10.7 m_1 33.4 m_0 6.7	c_2 458.0 c_1 761.0 c_0 -	k_2 38 374.0 k_1 35 776.0 k_0 -	• Linear model – two degrees of freedom • Total weight 50.8 kg • m_0 in rigid contact with the seat • Excitation: $\ddot{z} = 5\ \sin \omega t$	

Table 2.

Three-degree-of-freedom lumped parameter models of seated human subjects

Author	Biomechanical parameters			Remarks	Schematic of the model
	Mass (kg)	Damping (N-s/m)	Stiffness (N/m)		
Model with three degrees of freedom Suggs, etc. (1969)	m_3 5.5 ± 0.9 m_2 36.0 ± 6.0 m_1 15.3 ± 2.5	c_3 318.0 ± 42.0 c_2 ∞ c_1 2806.0 ± 1000.0	k_3 74 300.0 ± 17 400 k_2 ∞ k_1 40 900 ± 22 700	• Linear model – three degrees of freedom • Total weight 56.8 kg • Masses m_1 and m_2 it connects rigidly because the values of k_2 and c_2 are infinite • Excitation: $\ddot{z} = 5\ \sin \omega t$	

Conclusions

Lumped parameter models from the literature were also analyzed and validated in what by synthesizing different experimental data. The following conclusions can be drawn from the above:

1. Lumped parameter models are limited to univariate analysis. These mathematical models include linear and non-linear systems with varying degrees of complexity depending on the objective of the analysis

2. From the analysis of biomechanical models: with one degree of freedom Dieckmann (1957) (Coermann, 1962), two degrees of freedom (Wei and Griffin, 1998), (Allen, 1978), (Muksian and Nash, 1976), with three degrees of freedom (Suggs et al., 1969), (Allen, 1978), (Cho-Chung Liang, Chi-Feng Chiang, 2006 and Suggs C.W., Abrams C.F., Stikeleather L.F., 1969), (A. Picu 2009), with four degrees of freedom (Wan and Schimmels, 1995), (1998, Liu, Shi), (Boileau and Rakheja,

1998), Wagner and Liu (2000), with six degrees of freedom (Muksian and Nash, 1974), with seven degrees of freedom (Patil et al., 1977), (Cho-Chung Liang, Chi-Feng Chiang, 2005 and Patil, M.K., Palanichamy, M.S., Ghista, D.N., 1977), (Abbas et al., 2010), (Sengkang et al., 2013), with nine two-dimensional degrees of freedom (Harsha et al., 2014), with eleven degrees of freedom (Qassem et al., 1994; Qassem and Othman, 1996), the important frequencies of the body components result human presented in table 18., page 110, [82] namely:

Head - 2.06 Hz; chest - 1.2 Hz; trunk - 1.21 Hz, forearm - 1.17 Hz, arm - 3.39 Hz, thigh - 4.7 Hz, foot - 0.93 Hz.

3. From the analysis of the results of the biodynamic models presented in [100], the conclusion that will be used in the validation of the biodynamic models with the results of experimental measurements is drawn, the important frequencies of the component parts of the human body are those in the table below, table 4.7., [82].

Table 4.3.

The important frequencies of the human body [82]

Name of component part of the human body	Frequency [Hz]
Head	2,06
Chest	1,20
Trunk	1,21
Forearm	1,17
Arm	3,39
Thigh	4,7
Leg	0,93

Selective Bibliography

[1] Bausic Florin, **Toader Daniel**, Bausic Alexandra, Toader Eliza – „Contribuţii privind analiza modelelor biomecanice ale organismului uman supus acţiunii vibraţiilor" – Sinteze de Mecanica Teoretica si Aplicata, Volumul 8 (anul 2017), Numarul 3 – Matrix Rom

[2] Bausic Florin, **Toader Daniel**, Bausic Alexandra – „Metodă şi dispozitiv pentru monitorizarea în timp real a corpului uman supus acţiunii vibraţiilor" – Sinteze de Mecanica Teoretica si Aplicata, Volumul 9 (2018), Numarul 3 – Matrix Rom

[4] Bausic Florin, **Toader Daniel**, Bausic Alexandra, Bacanu Sorana – „Contribuţii privind analiza vibraţiilor induse organismului uman în timpul procesului de lucru" – Sinteze de Mecanica Teoretica si Aplicata, Volumul 10 (anul 2020), Numarul 1, pag , 57-60, ISSN 2068-6331 – Matrix Rom

[5] Toader Daniel, Alexandra BAUŞIC, Florin BAUŞIC - Analiza experimentală a vibraţiilor induse organismului uman- Sinteze de Mecanica Teoretica si Aplicata, Volumul 11 (anul 2020), Nr.l 2,pag 109-112, – ISSN 2068-6331 Matrix Rom

[6] Toader Daniel, Dogaru Marina, Ursache Robert, Bausic Florin – „Partial experimental contributions of the validation of biomechanical models of the human body subjected to the action of mechanichal vibrations – Modelling in Civil and Environmental Engineering, Scientific Journal, Vol. 16 - No.4: 25-33-2021, Doi: 10.2478/mcee-2021-0018, ISSN 2784-1391, Tehnical University of Civil Engineering Bucharest

[7] Legendi, A., Bauşic, F., Pavel, C. - Analiza transmisibilităţii vibraţiilor utilizate în scop terapeutic- metoda de investigaţie a structurii osoase, SIMEC 2007, 31 martie 2007, Editura Conspress Bucureşti, ISBN 973-7797-83-3, pag. 133-136;
[8] Panaitescu-Liess, R. - Modele biomecanice asociate organismului uman. Stadiul actual al cercetărilor – Raport de cercetare, februarie 2012;
[9] Reynolds, D.D. and Soedel W. (1972) Dynamic Response of the hand-arm system to a sinusoidal input. Journal ofSound& Vibration 21,339-353
[10] Miwa, T., Y. Yonekawa Y., Nara A,,.Kanada K., Baba K. (1979) - Industrial Health17,85-122 Vibration isolators for portable vibrating tool . Part-1. Agrinder.
[11] Mishow JW, Suggs C.W., (1977) - Hand-arm vibration part-1, vibration response to the human hand. Jr. of Sound and Vibration 1977,53; 545-58
[12] Meltzer G. (1979) - Proceedings of the International Symposium on Man under Vibration Suffering and Protection, Udine, Italy, 210-221. A vibration model for the human hand-arm system