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IMPROVING TRANSPORTATION SAFETY OF INJURED PERSONS BY TAKING INTO ACCOUNT THE BIOMECHANICAL CHARACTERISTICS OF THE HUMAN BODY

Summary. Ambulance vehicles play a vital role in sustaining the life of injured persons and should a provide safe transportation route to the medical institution. Transportation of injured patients in severe/critical conditions should be carried out with high caution, as there is no guarantee that patients' health will not be harmed. The goal of this study is to minimize exposure to the external factors such as random shocks, sharp jumps, vibrations caused by irregular roads, speed breakers, weather, etc., that could influence the tasking ability of the medical team and further threaten the life of the already injured patient. This topic has not been widely researched and still requires implementation of novel standards that should improve the safety of the patient. This article aims to define the biomechanics of cabin occupant safety, introduce ways of collecting live data and develop new mechanisms that would allow safer transportation of patients without any meaningful health deterioration causing by the above-mentioned external factors. This study will identify safety hazards in the ambulance environment and determine the effectiveness of suggested countermeasures to mitigate any further injury or deterioration of the patient's health.

1. INTRODUCTION

Transportation of critically injured patients is in itself a health-deteriorating or potentially destabilizing factor; therefore, decisions should be made quickly on determining the transportation conditions based on the analysis of the potential risks for patients. Selection of the proper position of body placed on the stretcher, usage of body restraints based on the type and severity of injury, personnel awareness in specific situations and road conditions, the shortest transportation route, and effective management of the high-tech transportation processes should enable minimization of extreme deterioration of the patient's health on the way [1, 2].

This study was conducted to evaluate and improve the biomechanical safety of patients in an ambulance environment. Vibration and shock protection standards, mitigating countermeasures and the degree of deterioration of health during transportation for these unique machines still require further clarification.

The following topics are detailed in this study: (1) consideration of the human body both as a mechanical and as a biological entity in an ambulance environment, (2) how much of an impact shocks and vibrations have on this entity during transportation (degree of deterioration of health) and (3) the mitigating countermeasures under numerous conditions of vibration exposure and the mechanisms by which a high level of protection can be attained.

From the mechanical point of view, the human person is a very complex creature and its mechanical properties are almost always changing, especially in damaged condition. There is little tangible information about the immensity of the forces required to produce additional injury to the patient's body during ambulance transportation. To prevent further injuries to patients while gathering data, it is essential to use computer-based simulations for the baseline results. Nonetheless, the data obtained this way must be carefully re-evaluated so that they correspond to the field conditions occurring in real life. Occasionally, there is a possibility to obtain useful information from situations that involve accidental injuries to patients, but while the damage produced can be definitely evaluated, the forces generating additional injury normally cannot. As we know, a person has both physical and emotional qualities, which makes it far more complex to obtain reliable information about the influence of mechanical forces on their functioning. Some mechanical properties of patients can be more easily measured than others, since only micro scale forces are required for such experiments. The difficulty here is the responsibility of a system and variability of the external factors in particular situations [3-5].

The aim of our study is to assess the risks to the safety of patients in the ambulance environment and the effectiveness of countermeasures for reducing such risks, thus minimizing the likelihood of additional injuries. All this requires the adoption of flexible dynamic standards that will be tailored to the specific cases based on their severity.

The chapter below establishes the usage of vibrobench KDXG, which is utilized for mechanical vibration and shock experiments on weights. Later chapters describe the mechanical properties of the human body, the influence of shock and vibration exposure on the patient during the ambulance ride, the mechanisms and procedures required for suppressing these forces and their safety criteria.

2. ESSENCE OF THE PROBLEM - CASE STUDY

Transportation of critically ill patients very often takes place in various road (traffic, road irregularities, rough road surfaces, sharp acceleration/braking) and meteorological conditions (rain, snow, wind, etc.), altogether resulting in unpleasant or even dangerous shocks and vibrations on the patient's body. The resulting side effects for already injured patients are not that uncommon (additional injuries, pain). Monitoring such incidents provides a better assessment of such events and enables the development of mitigating countermeasures.

Statistically, some of these extreme cases can be avoided. These data are from the West Georgia Medical Center (WGMC) emergency department during the span of a1-month period. It considers patient entries by ambulance and is based on the survey results from the ambulance medical brigade (these data are probably subjective, but they provide a general picture of the situation).Table.1 shows the causes of injury for these patients (167 cases).

In more than 30% of these cases, according to the medical brigade, the patients' health deteriorated further during the ambulance ride. The chart below (Fig. 1) describes the essential categories of possible incidents and their nature for more recurring ones. Through research, the issues corresponding to preparation problems and mission planning mostly arise at the retrieval base. Patient retrieval tasking problems involve improper vehicle choice and inaccurate retrieval of the patient himself or herself. Some of the medical equipment problems involve breathing circuit disconnection from the ventilator, or failure of electrical and/or gas supply to medical devices. Other powered medical device problems include battery drainage and the lack of an alternative power supply. Transport operation problems involve vehicle engine malfunction or lack of gasoline fuel, stretcher mechanism problems, and malfunction or unavailability of a lifting device.

Table 1

Cases by cause of injury

Cause of injury	Cases
Physical injury	18
Car accident	97
Neurological disorder	27
Heart problem	22
Other (uncertain)	3

External factors, caused by road and/or meteorological conditions, can subsequently involve intense shocks and exposures various vibrations. The lack of standardized countermeasures or failure to properly assess the effects of these shocks and vibrations can lead to further deterioration of the patient's health. It is not the fault of the medical brigade that it had failed to take appropriate action in these situations, because there are no guidelines or monitoring devices to act accordingly.
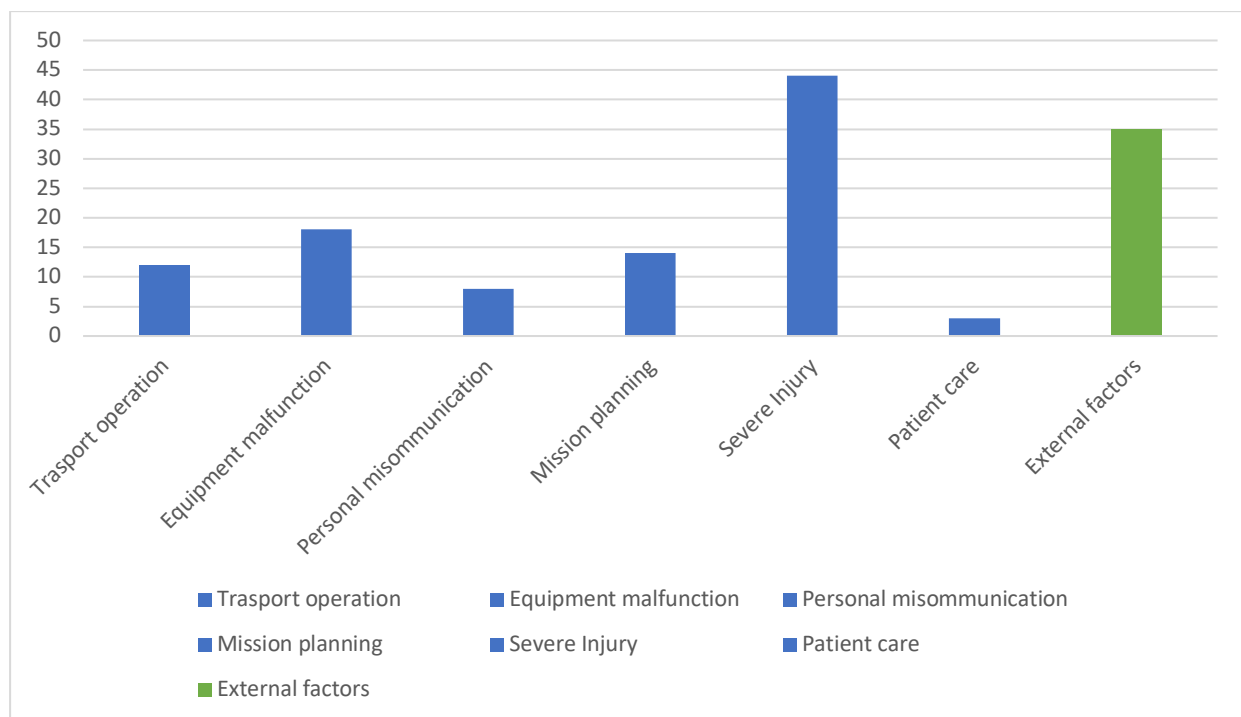

Fig. 1. Incident categories and frequency

These specific factors, highlighted on the chart, will be evaluated further in depth, with the following end goal in mind: maximally reduce the possible complications in transport operations and decrease the influence of external problematic factors (vibration protection and suppression, experienced driver, efficient vehicle routing).Improvements in these factors are progressively increasing a patient's chances to reach the hospital by an ambulance without deterioration of the health situation.

3. FORCES: DEFINITION AND DESCRIPTION

Description of forces. The transmission of forces can occur through solid, liquid and gas. These forces can be spread out or concentrate over a compact zone. Their variation can range from tangential to normal. The formation and structure of a solid frame impinging on the human body surface areas vital as the shape and/or position of the human body itself. This is especially true in an ambulance environment, where a change in body composition can relieve the pressure of the applying forces. It

should also be highlighted that in an injured state, the magnitude of these forces is multiplied, thus causing pain and increase in the tension and stress levels in the body. All of the points listed above must be considered when examining the injuries that occur in various circumstances: in car crashes, during uncontrolled vibrations, sharp shocks/blows, explosions, etc. Experimental studies in laboratory environments often allow us to accurately apply the desired forces, but field conditions are markedly different and random like different external constraints. On this basis, it is often quite difficult to determine in advance how a specific situation will turn out based on laboratory experiments. It is similarly difficult to interpret observations in the field without the advantage of laboratory studies.

Definition of shock. This article uses the definition of shock in its engineering sense: non-periodic excitation characterized by severity and suddenness. A shock wave represents a discontinuous pressure change propagated through a medium at a velocity greater than that of sound in the medium. Generally, forces hitting the peak values in less than a few tenths of a second may be considered as shock forces relative to the human system. In the case of vehicles, a shock can be experienced when a vehicle crosses a pothole or speed breaker at a relatively high speed, causing shocks of various magnitudes to transfer to the wheels, then the vehicle frame and lastly the cabin itself. In an ambulance environment, such shocks can cause severe pain in already injured patients, even causing them to lose consciousness, which in itself represents a destabilizing factor. In the case of internal injuries, such shocks can cause widening of ruptured organs and general deterioration in health, leaves less time to patient to be delivered to the hospital.

Definition of vibration. Any biological organism can be exposed to vibrations at various frequencies if the amplitude of these vibrations is very high. The short definition of vibration is as follows: an object that swings to and from around a rest position. This motion can be described as having the following characteristics:

- oscillation size (amplitude);
- oscillation number per second (frequency);
- oscillation type; and
- oscillation duration.

Our focus is primarily on oscillations ranging from 1 Hz to 100 Hz, with a duration range of 5-15 minutes.

Almost every type of vibration can have some type of psychological effects on humans. Studies show that even short-term exposure to vibration can be a cause of greater muscle tension, elevated blood pressure, increased heart rate, nausea, etc. All of the above make it more difficult for the medical staff to carry out all the necessary procedures for managing the injured patient.

On the road, vehicle movement is always accompanied by random shocks and vibrations. Most of these forces are low impact, and have little significance relative to the humans in the vehicle's cabin. Our focus is on medium- and large-size vibrations that influence the comfort level of cabin members and can occur in specific circumstances: overcoming irregular/rough road surface, speed breakers, large potholes, etc. Such obstacles generate shocks on the wheels of the vehicle, which are then converted into low-frequency oscillations and, through the vehicle frame, are transferred into the cabin.

In such circumstances, complications arise related to the rolling resistance force on the wheels' rotation, which occurs between the moment of tire/ surface contact and movement time. All this creates various vibrations with different amplitude levels. The wheel displacement speed can vary based on the angle of inclination and road surface type, and is also relative to the current weather conditions. In such situations, use of lower gears is recommended to maintain the dynamic factor to overcome hard portions of the road. This conditions forced operating regime of the vehicle engine and transmission system, which in itself contributes to the increasing level of vibrations, subsequently increasing the degree of discomfort for the cabin members.

In the case of ambulance vehicles, in almost every situation, medical procedures should be carried out promptly and efficiently without outside interference. To achieve this, it is very important to minimize the effects of external factors that can hinder proper execution of medical procedures and lead to further deterioration of the health of the patient.

4. A NEW CONCEPT AND A MATHEMATICAL MODEL

To determine the effects of shock and exposure to vibration, experiments should be carried out in a laboratory environment. Relevant results can be obtained from such studies only if the calculation methods and instruments are highly adapted to the specific characteristics of the biological system under research.

All living organisms are diverse in form, size, sensitivity, pain response, type of injury and so on. To develop a new model, all differences must be taken into account. This diversity always requires a lot of experimentation and the thoroughly organized monitoring instruments.

To determine the effects of shock and vibration son injured persons during ambulance transportation, the force values affecting the patient's body should be distinctly defined. In the ambulance environment, the amplitudes for different parts of the body can vary in size, so they all should be specifically defined. This novel concept promotes the usage of vibration pickups in the ambulance cabin, with live acceleration data graph on display indicating the most affected body parts exposed to vibration. With this information and prior knowledge about the patient's injury, medical personnel can make proper decisions to adapt/change the patient's position, use additional cushions, separate restraints for body parts or remove the existing ones.

In terms of vibration pickups in contact with the human body, their size must be quite compact so that they do not distort the existing vibrational load. Subsequently, the weight of vibration pickups should be limited to a few grams, based on the frequency range of interest and the different body parts to which these pickups are attached. In our case, 6 main vibration pickups are used (Back of the head (1), Shoulder (2), Tailbone (1), Heels (2)) plus optional 2 (Elbow (2)), which are placed under common pressure points of the human body in the supine position. Figure 2 illustrates the placement of vibration pickups, which are attached to a subject's body surface over the soft tissue affected by vibrations. The human body is not that rigid, consequently making it more suitable to measure acceleration than displacement or velocity. The mechanical impedance of a human body in the supine position is highly advantageous for evaluating the vibrational energy transmitted to the body through the vibrating system.

Figure 3 shows the accelerometers' response based on their size and weight. The amplitudes are distorted because of the different sizes of the accelerometers attached to a subject's body surface over the soft tissue affected by vibrations. This graph shows the ratio A_L/A_F of the response of the loaded to the unloaded surface with three individual radii r.

In terms of Medical Aspects, various design factors that influence patient care have been explored and discussed. Vibration in ambulances appears to be of clinical significance to the well-being and condition of patients, and it questions some of the elements that influence the modern ambulance design: (1) Dual role with a wide range of weights carried, which affects the suspension design; (2) converting a commercial van into a designated ambulance vehicle; (3) not fully implementing ambulance standards for heat, noise, lighting and vibration suppression; and (4) lack of ergonomic standards required to perform life-sustaining procedures inside the cabin [6-9].

Novel studies have developed experimental methods for improving existing ambulance designs. The ride on the stretcher can be improved by isolating the stretcher on a special secondary suspension system. This chapter presents a mathematical modeling of the vibration process of the vehicle's sprung and unsprung weights while diagnosing its suspension on a vibration table. The calculation results demonstrate the effect of the change in the unsprung and sprung weights on the vehicle's active safety under exploitation.
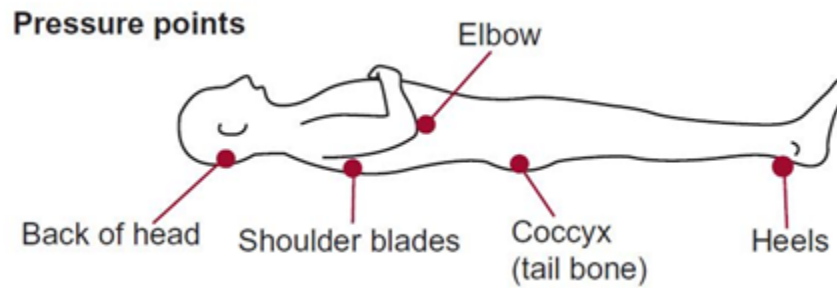
Pressure points

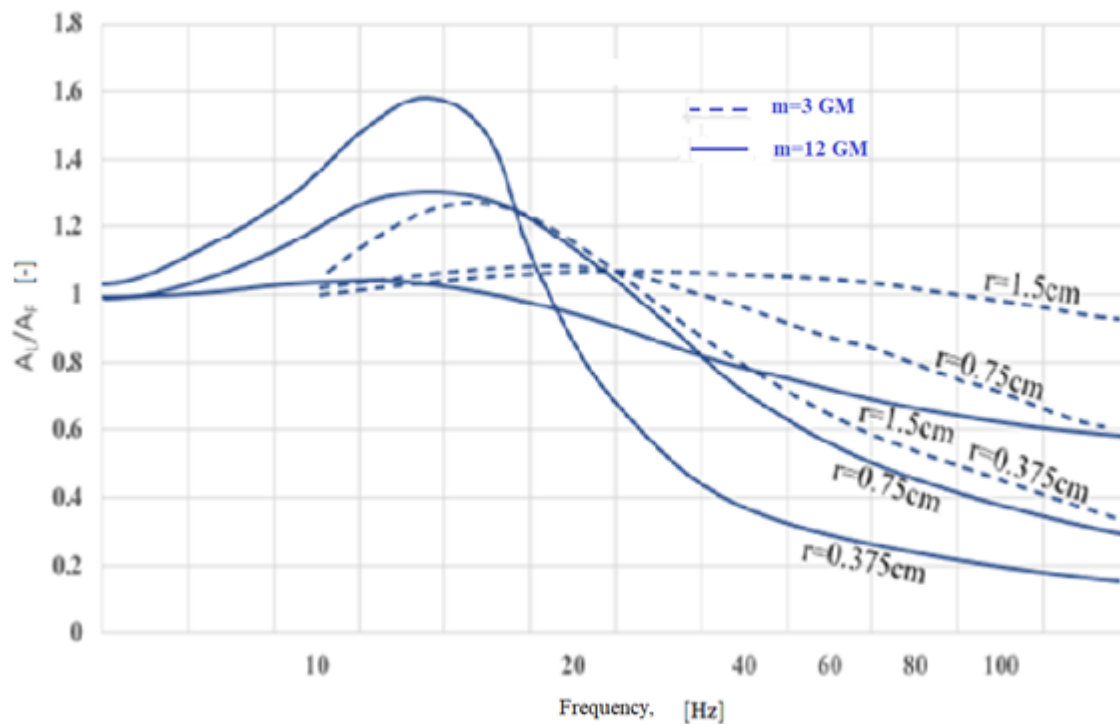Fig. 2. Common pressure points of the human body in the supine position

Fig. 3. Distortion of amplitude because of accelerometers of different weights (m) and sizes

This chapter considers a vibrating system that includes a vehicle placed on a support platform of the KDXG vibrobench (Fig. 4). Partof the car is presented in the form of sprung (M) and unsprung (m) weights, interconnected by an elastic element and a damper. The elastic tire of the wheel is also modeled with an elastic element and a damper, describing the radial stiffness of the tire (C_t) and the degree of its damping (K_t), respectively.
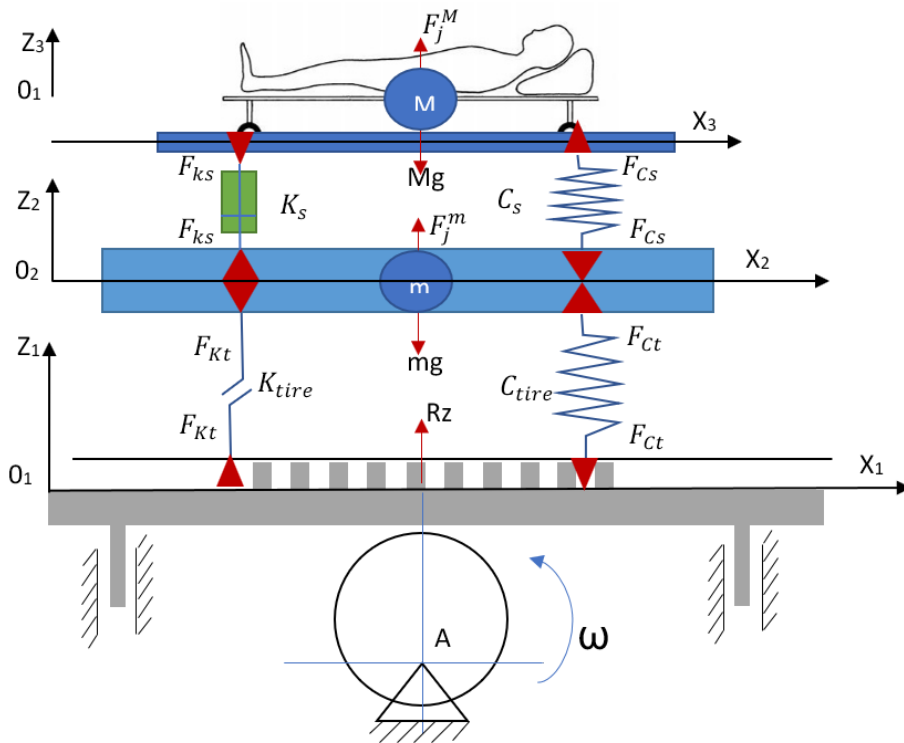
Fig. 4. Calculation scheme of the vibration process on the support vibrobench platform "KDXG"

The design diagram (Fig. 4) shows all forces, external and internal, acting on the system. A countdown of the movements of the sprung and unsprung weights is made from the static equilibrium.

Coordinate systems $Z_1 0_1 X_1$, $Z_2 0_2 X_2$ and $Z_3 0_3 X_3$ (Fig. 4) are fixed and define a static position equilibrium of each of the weights of the described system. To simplify and optimize the mathematical model, the following assumptions were made:
1. In the process of calculations, the whole vehicle is not considered, but only one wheel.
2. The points of application of reactions from the supporting surface of the vibrobench to the tire are at the point of contact with the supporting surface.
3. The vehicle's sprung weight can only move along the OZ_3 axis.
4. The car body is a solid weight, part of which acts on the wheel.
5. The suspension stiffness C_s is constant.
6. The coefficient of resistance of the shock absorber K_s takes on a value during compression K_{scomp} and at decompression $K_{sdecomp}$.
7. Only vertical forces are acting on the vehicle [10-13].

Initially, it is necessary to determine the static deflections of the elastic elements of the suspension system and the wheel tire. (Fig. 5), which are calculated relative to the static equilibrium state of the vehicle weights using the following formulas:

$$\Delta l_s = \frac{Mg}{C_s}; \quad \Delta l_k = \frac{(M+m)g}{C_t} \quad . \tag{1}$$

Then, from the design scheme (see Fig. 5), according to Newton's third law, a system of equations was obtained for equilibrium of M and m:

$$\begin{cases} F_j^M - F_{ks} + F_{Cs} - G_M = 0 \\ F_j^m + F_{Ks} + F_{Ct} - F_{Cs} - F_{kt} - G_m = 0 \end{cases}, \tag{2}$$

where F_j^M and F_j^m represent the forces of inertia, respectively, for sprung (M) and unsprung (m) weights (N); F_{Ks}; F_{Cs} are the forces of the shock absorber and suspension springs (N); F_{Kt}; F_{Ct} are the forces of tire stiffness and its dampening (N); and G_M; G_m are the weights of the sprung (M) and unsprung (m) weights, respectively (N).
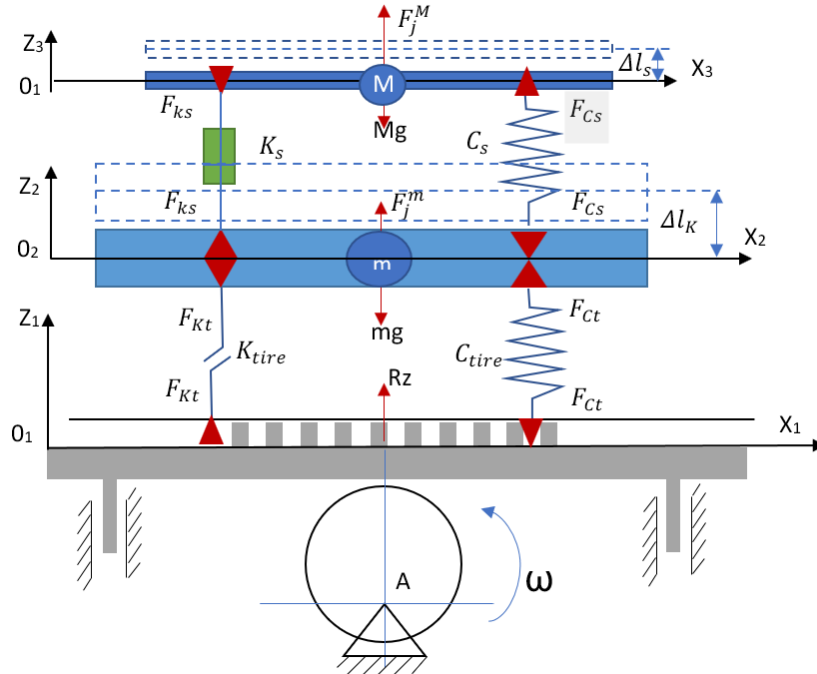

Fig. 5. Static deflections of elastic elements of the suspension and wheel tires

Using the design scheme (see Fig. 4), the following equations were derived (2):

$$F_j^M = M\ddot{z}_3; \; F_j^m = M\ddot{z}_2; \; F_{cs} = C_s(\Delta l_n + z_3 - z_2); \; F_{Ct} = C_t(\Delta l_k + z_2 - z_1);$$

$$F_{ks} = K_s(\dot{z}_2 - \dot{z}_3); \; F_{kt} = K_t(\dot{z}_1 - \dot{z}_2); G_M = Mg; \; G_m = mg; \tag{3}$$

From equations (1), (2) and (3), the system of equation (4) was obtained, which describes the law of oscillations of the sprung M and unsprung weights of the car on the vibration stand:

$$\begin{cases} M\ddot{z}_3 = Mg - C_s \cdot (\Delta l_n - z_2 + z_3) + k_s \cdot (\dot{z}_2 - \dot{z}_3), \\ M\ddot{z}_2 = mg + C_s \cdot (\Delta l_n - z_2 + z_3) + k_s \cdot (\dot{z}_2 - \dot{z}_3) - C_t \cdot (\Delta l_k - z_1 + z_2) + k_t \cdot (\dot{z}_1 - \dot{z}_2); \end{cases} \tag{4}$$

$$\Longleftrightarrow \begin{cases} \ddot{z}_3 = \dfrac{1}{M} \cdot (-K_s \cdot \dot{z}_3 - C_s \cdot z_3 + K_s \cdot \dot{z}_2 + C_s \cdot z_2), \\ \ddot{z}_2 = \dfrac{1}{m} \cdot [-(K_s + K_t) \cdot \dot{z}_2 - (C_s + C_t) \cdot z_2 + K_s \cdot \dot{z}_3 + C_s \cdot z_3 + K_t \cdot \dot{z}_1 + C_t \cdot z_1]. \end{cases}$$

Vibrations of the vibrobench support platform are described using the equation

$$z_1 = f(\omega t) = \sqrt{r_0^2 + R_0^2 - 2 \cdot r_0 \cdot R_0 \cdot \cos(\omega t) - r_0^2 \cdot \sin^2(\omega t)} - R_{min} \quad . \tag{5}$$

This completes the construction of the general system of equations describing the process of oscillations of the sprung M and unsprung weights of the car and also the vibrations of the vibrobench support platform:

$$\begin{cases} \ddot{z}_3 = \frac{1}{M} \cdot (-K_s \cdot \dot{z}_3 - C_s \cdot z_3 + K_s \cdot \dot{z}_2 + C_s \cdot z_2), \\ \ddot{z}_2 = \frac{1}{m} \cdot [-(K_s + K_t) \cdot \dot{z}_2 - (C_s + C_t) \cdot z_2 + K_s \cdot \dot{z}_3 + C_s \cdot z_3 + K_t \cdot \dot{z}_1 + C_t \cdot z_1] \\ z_1 = \sqrt{r_0^2 + R_0^2 - 2 \cdot r_0 \cdot R_0 \cdot \cos(\omega t) - r_0^2 \cdot \sin^2(\omega t)} - R_{min} \end{cases} \quad (6)$$

Using the MatLab application package, graphs of displacements of the car's weights were obtained for a variety of conditions (Fig. 6-8).
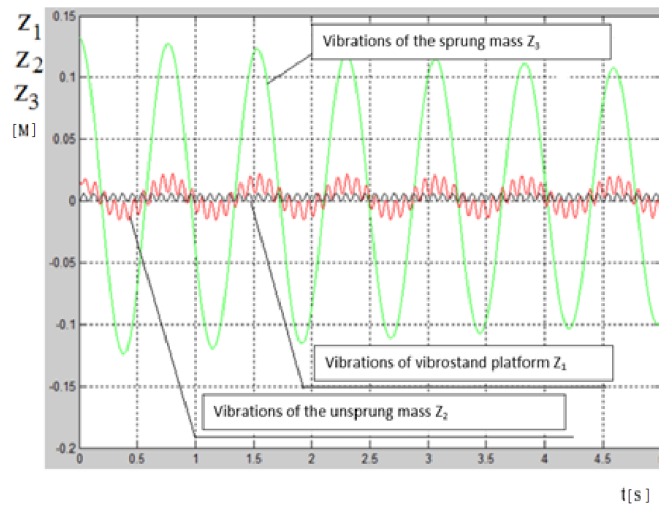

Fig. 6. Characteristics of displacement of the sprung M and unsprung weights of the vehicle
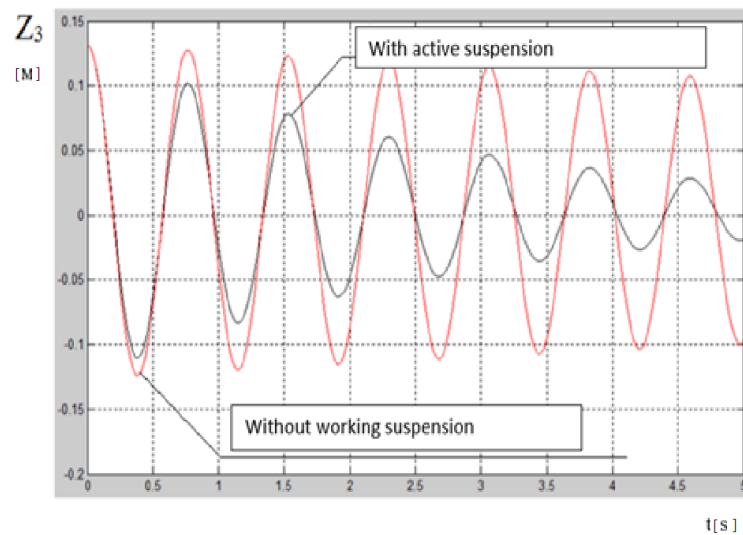

Fig. 7. Characteristics of displacement of the sprung weight of the vehicle with and without an active suspension
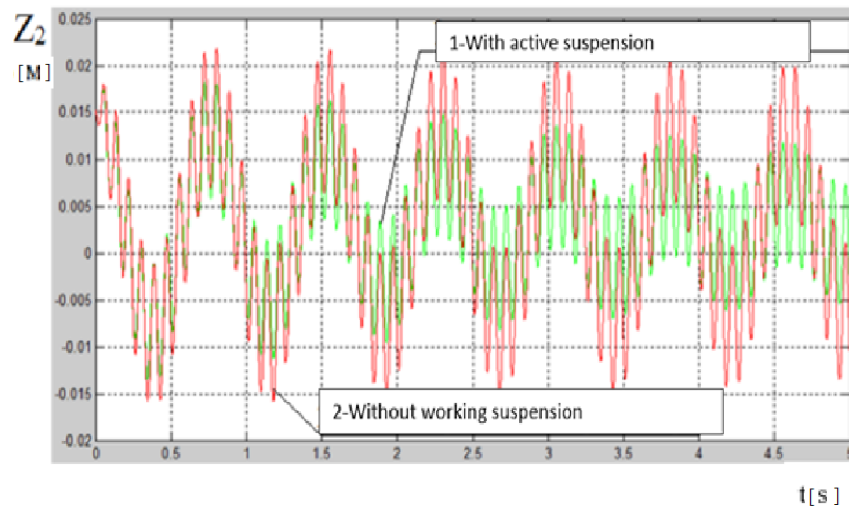
Fig. 8. Characteristics of displacement of the unsprung weight of the vehicle with (1) and without (2) an active suspension

In Fig. 9, the amplitude–frequency characteristic obtained in the course of mathematical modeling clearly yields the following:
1. When diagnosing a vehicle on vibration stands, vibrations occur mainly with the resonant frequencies of the sprung weights ($n_s \sim 1$ Hz) and unsprung weights ($n_{ns} \sim 12$ Hz).
2. When the car's suspension is operating with an active suspension system (position 1, Fig. 9), the vibration amplitude is considerably lower; therefore, the quality of the ride is superior. If the suspension is inactive/defective (position 2, Fig. 9), then the vibration amplitudes (A) increase considerably. The ride quality deteriorates, and can lead to an unpleasant or even a painful ride for injured cabin occupants.
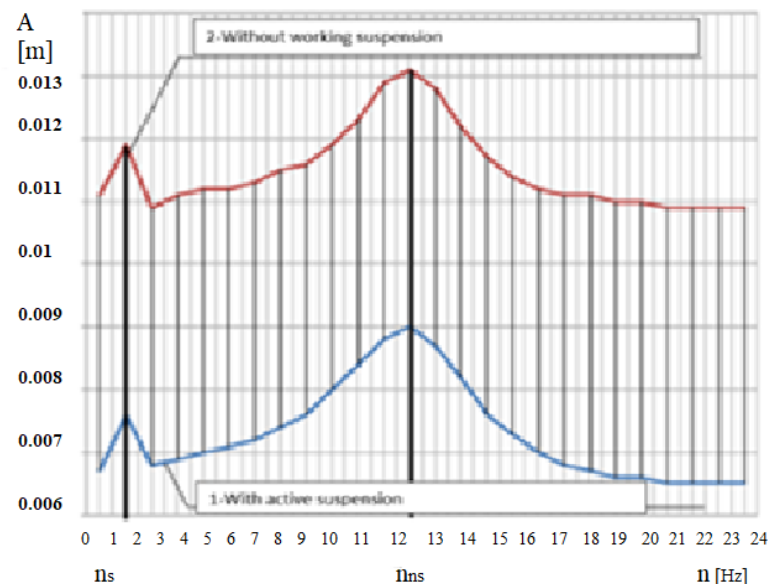

Fig. 9. Amplitude–frequency characteristic of the car with an active (1) and an inactive/defective (2) suspension system
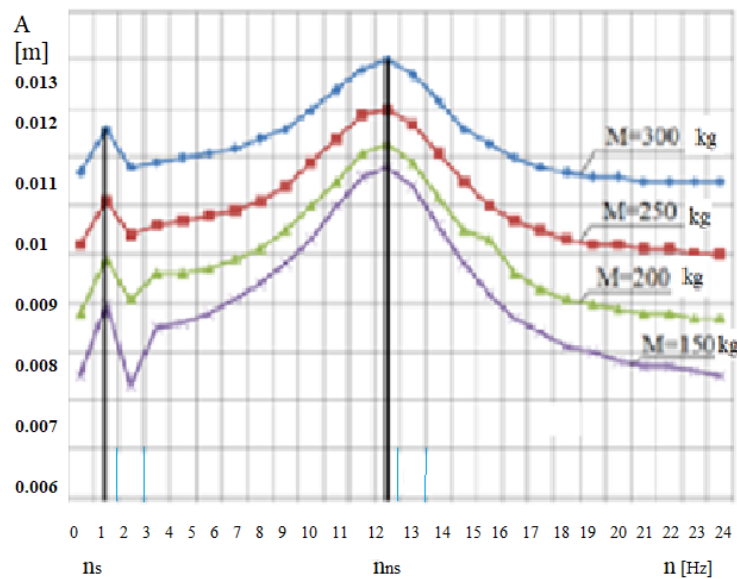
Fig. 10. Influence of the vehicle sprung weight on the frequency response of the suspension

Based on the latest figure (Fig. 10), it is obvious that with a decrease in the sprung weight of the car, the amplitude of oscillations steadily decreases; therefore, the ride quality is improved. Oscillations occur mainly with the resonant frequencies of the sprung weights ($n_s \sim 1$ Hz) and unsprung weights ($n_{ns} \sim 12$ Hz), which do not depend on the change in the sprung weight of the vehicle.

5. RESEARCH ANALYSIS

1. Analysis of the deterioration of the patient's condition caused by vibration loads during the process of transportation by special medical vehicles, and quantitative and qualitative assessments of the vibration loads on the patient's body were performed [14-15].
- Data need to be collected on the degree of deterioration of the patient's health caused by vibration loads during transportation in ambulance and conduct their statistical analysis.
- Assessment and systematization of the effects of vibration load exposure on the body of the patient should be performed according to the type of injury and the degree of its severity.
- Research on the transmission mechanisms of vibrational loads from the vehicle to the patient's body during the transportation process and experimental studies to determine the vibration levels at the patient's location in the vehicle should be carried out.
- Innovative approaches and principles should be developed for reducing vibration loads on body surface of the patient based on the assessment of the research results.
2. A theoretical research methodology should be developed for reducing the vibrational load on the body of the patient during the process of transportation by ambulances.
- A calculation model of the road-vehicle–patient system should be developed;
- The kinematic and dynamic parameters of the calculation model "Road-car-patient" should be determined;
- A computer-aided model should be created;
- Theoretical studies should be planned and conducted;
- The results of theoretical studies should be processed and analyzed.
3. The construction scheme to be installed in the car to suppress the damaging vibrational loads on the patient should be chosen. Methodological and technical recommendations should be made.
- Virtual design schemes should be developed for specialized vibration-suppressing devices in the ambulance cabin;

- The optimal model should be selected according to the results of theoretical studies;
- Mathematical planning and experiments should be conducted;
- Experimental research results should be processed and analyzed.

To achieve the best results in the project implementation process, close cooperation should be established with local medical service establishments.

The goal of this study was to define the biomechanics of ambulance occupant safety and assess how much of an influence vibrations have on an injured patient's health and tasking ability of medical personnel. Through our analysis, the following statements can be made:

- As the road surface varies from rough to smooth, the acceleration level decreases markedly.
- An increase in ambulance speed causes an increase in the acceleration level up to a certain point (i.e., from 40 to 60km/h) and then the level of acceleration declines (from 60 to 80 km/h).
- For rough road surfaces, the level of acceleration and subsequently the vibration levels are larger, making it more likely to further endanger the health of the patient.
- In the case of rough road surfaces, the likelihood of deterioration of the patient's health is quite high if exposure to vibration lasts more than 20minutes (depending on injury type and its severity).
- Even for smooth roads, exposure to mild vibrations for more than 60-80 minutes causes an uncomfortable feeling in patients.

In the ambulance environment, the patient's body is subject to random shocks and vibrations, which do have harmful effects on patients whose health has already been harmed, leading to the occurrence of fatigue, discomfort, excess pain and, in certain cases, loss of consciousness. All this also depends on the sensitivity of each individual as it is one of the most important factors.

Our goal is to research this topic when the movement speed of the vehicle is relatively high, because in the case of ambulances, time is the most valuable resource that many injured patients may not have. Knowing that the driver is approaching a rough road surface at a slower speed, a lower speed, while time is an absolutely valuable resource for the injured patient, may not be the best solution in all cases. This still remains the real issue and requires further study.

Preliminary calculations show that by reducing the unsprung mass of the vehicle, the oscillation amplitude is reduced, thus improving transportation conditions. Resonant oscillations occur mainly at frequencies that depend on the change in the unsprung mass of the vehicle. On reducing the unsprung mass by 25, 50 and 75%, the resonant frequency changes to 13.5 Hz, 16 Hz and19 Hz, respectively. The results clearly show that the mathematical model adequately describes the oscillation processes during a vehicle ride.

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