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Whole body vibration in mountain-rescue operations

E. Alberti[a], D. Chiappa[b], G. Moschioni[a], B. Saggin[a,*], M. Tarabini[a]

[a]*Dipartimento di Meccanica, Politecnico di Milano-Polo Regionale di Lecco, Via M. d'Oggiono 18/A, 23900, Lecco, Italy*
[b]*CNSAS Corpo Nazionale per il Soccorso Alpino e Speleologico, Italy*

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Abstract

In mountain-rescue operations injured people are generally exposed to vibrations and shocks that can be potential causes of physical conditions worsening. Such vibrations can derive both from patient's body manipulations (e.g. when it is being loaded and immobilized on a stretcher) and from forces coming from the transport devices and vehicles. Despite the general feeling that during this kind of operations the levels of transmitted vibrations to the injured can be quite large and potentially dangerous, there is practically no study in literature providing reliable parameters (i.e. measurements) to support or dismiss these beliefs. This paper reports the results of a measurement campaign carried-out in order to outline, identify and quantify the excitations a human body is exposed to, during typical transportation phases related to mountain-rescue operations. The work mainly presents and discusses the experimental setup with the aim of focusing on the problems related to this kind of measurements; the results of the experimental campaign carried-out for the measurement of the vibrations undergone by a human body during a simulated rescue operation are presented and discussed as well. Such simulation includes three phases of transportation: on a hand-held stretcher, on an ambulance and on a helicopter. The work is not intended to supply a complete characterization and analysis of vibrations transmission during any rescue operation but just to provide a preliminary overview and to define a measurement method that can be applied for a more comprehensive characterization. With such aims measurements were carried out in on-field situations stated as "typical" by rescue experts and data then analyzed both with standard procedures and algorithms (e.g. ISO 2631s weighting curves) and with the commonly used statistical indexes; in the analysis it is important to be aware that standardized measurement procedures and indexes, created to verify comfort or health-risks of workers, might not fit the case of a generic patient who experienced a serious mountain accident. The work includes also a laboratory activity mainly related to mechanical characterization of the stretcher used in the field tests. The most interesting result of the study is the comparison of the vibration levels in the various rescue phases that, even when using different indicators, shows that the most critical issue is due to hand transportation despite the bad judgment usually expressed for helicopter flight.

1. Introduction

Mountain hiking and climbing, due to their nature, include relevant elements of risk and every year thousands of people are involved in rescue operations related to mountain accidents. Nonetheless similar rescue operations are carried out also in other environments during, for example, natural disasters such as

*Corresponding author. Tel.: +390341488702; fax: +390341488751.
E-mail address: bortolino.saggin@polimi.it (B. Saggin).

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earthquakes and floods. Traumatic pathology represents a large part of the overall cases and, among the trauma victims, about 20% is in serious state or severely injured [1]. Although rescuers deserve the maximum care to the patients during the transportations, vibrations and shocks are frequent. The necessity of patient isolation from vibrations is evidenced by the existence of large number of safety devices (such as pneumatic anti-shock garments–also known as PASG–, collars and spine-immobilization boards) commonly used in rescue operations. Under this perspective literature shows a lack of knowledge in the evaluation of vibration magnitude in different rescuing conditions although information about shocks can be a key factor in safe transportation of the patient [2]. Studies currently available in literature focus on whole-body-vibrations (WBV) exposure measurements for people (considered as "workers") sitting on ambulances and helicopters [3,4] according to BS 6841 [5] and ISO 2631 [6]. Some studies take into account the improvement of medical conditions of the injured when cared by a trained team [7,8] or the correlation between the transport device [9,10] and the clinical evolution of patients. Unfortunately, such studies do not include measurements of the vibration transmitted to the patients and therefore a correlation analysis cannot be performed. The design of suspended stretchers [11,12] and the reduction of vibration level on helicopters [13,14] are the object of other research works. Literature can be summarized as follows, with regards to the present problems: few studies consider the effect of vibrations on injured people [10]; most of them do not include measurements of the transmitted vibration and are based on subjective assessment of the vibration level. This paper intends to provide a measurement method and the results of a preliminary experimental campaign whose targets are:

- providing an overview of acceleration parameters in various rescue conditions with regards to different frequency-weighting methods;
- the characterization of vibration level due to different means of transport;
- the evaluation of importance of each transportation phase (hand-stretcher, ambulance and helicopter) on the exposure to vibrations of a patient; and
- the assessment of stretchers efficiency in vibration reduction, since a stretcher is present in most cases independently on transportation vehicle.

2. Tests description

In order to gather significant data about phenomena, tests were carried out by means of simulations of typical transportation conditions following patient recovering and immobilization: with a hand-held stretcher, on an ambulance and on a helicopter.

Recovery and immobilization phases, although very critical for patients' health, are not part of this work for two main reasons. The first reason comes from spectral considerations: risks of injuries do not depend on "vibrations" but mostly on very slow excitations during lifting and moving maneuvers. The second from a repeatability approach: in these phases stresses mostly depend on peculiar factors, such as the type of trauma as well as patients' position after the traumatic event.

Experiments were carried out with one kind of stretcher, ambulance and helicopter; the patient was replaced by a healthy person of 78 kg mass (Body Mass Index—BMI—26 kg/m^2). Tests are comprehensive of most typical events, from lifting of stretcher from the ground to load–unload operations on vehicles. The simulated operations are carried out with the patient already immobilized.

During on-board phases, on ambulance and helicopter, the patient was immobilized on the same stretcher used for ground transportation. Such a choice limits somehow the overview on different stretchers (e.g. ambulance-native devices) but is more representative of a real-world condition, since the patient is kept as long as possible on the same stretcher from the rescue point to the hospital in order to avoid movement-bound risks. On the other hand the effects related to the peculiar stretcher have been analyzed through a mechanical characterization of the stretcher itself. In this way it is possible to give a certain generality to results, as later shown.

2.1. Hand stretcher transportation

This scenario is typical of first aid situation in severe mountain environment, when it is not possible to recover the patient directly on the event location (i.e. the place is not safely reachable with an ambulance or with an helicopter). Two rescuers transport the stretcher on their shoulders along mountain trails, generally and possibly in downhill conditions, with the help and direction of one or more other persons, for safety reasons; paths are usually characterized by crushed stones, uneven trail, rocks and pits. The patient is therefore exposed to vibrations induced on the stretcher by the movements and shocks generated by rescuers. The random components in such situations are noteworthy and mostly depend on the characteristics of the trail as well as the rescuers' ability.

In our simulations (Fig. 1a) two rescuers raise the stretcher on their shoulders and transport the patient downhill. A rope passing through a shackle linked to the ground is held by another rescuer and relieves the carriers from the weight component parallel to the ground, preventing carriers from slip risks. The path where rescue simulations were carried out is a low-difficulty downhill track, chosen in order to allow tests also with non-trained persons as carriers.

Tests, consisting in:

- stretcher load on shoulders,
- transport (approximately 200 m, about 150 s duration), and
- stretcher unload onto the ground,

were carried out by four couples of transporters (both skilled and novices) and each test was repeated twice.

2.2. Ambulance transportation

In this phase the stretcher containing the patient is tied onto the standard ambulance trolley stretcher (Fig. 1b), loaded inside the ambulance with the head toward the front of the vehicle. This phase simulates the transportation to the nearest hospital or helicopter-reachable area. During the transportation important factors that may have an influence on vibrations suffered by the patients are:

- road type (e.g. mountain road with close turns, standard urban road with normal traffic activity, highways); and
- road specific conditions (e.g. off-road terrain, asphalt with presence of pit holes, etc.).
  Our simulation consists in three off-road terrain-paths and five urban paths. All tests were carried out on the same ambulance (based on Fiat Ducato frame) with the same driver with long-term experience. Each simulation lasts from 120 to 350 s.

2.3. Helicopter transportation

Very different recover approaches are used in rescue missions, depending on the geo-morphological characteristics of the place of operation, weather conditions and even rescue techniques that vary from

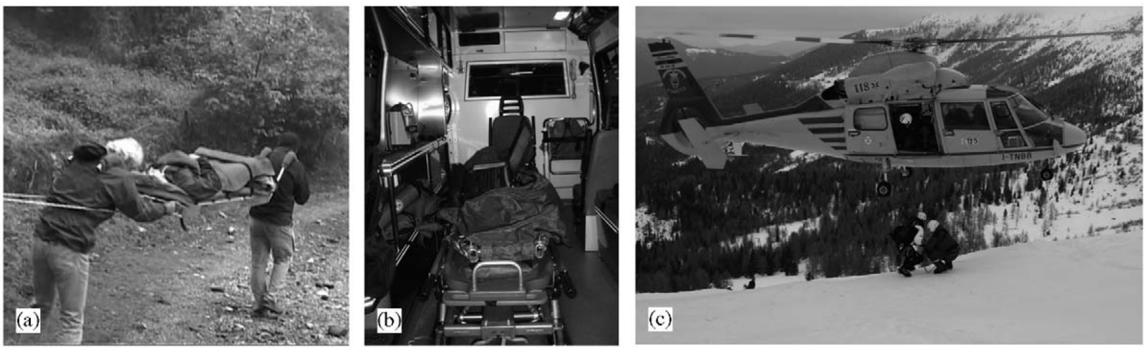

Fig. 1. Hand stretcher transportation (a), the instrumented stretcher inside the ambulance (b) and the helicopter during hovering rescue (c).

country to country. A group of tests was studied in order to simulate the most common operations: the patient, immobilized on the stretcher, can be loaded on the helicopter in different ways summarized as follows:

- stretcher hand-lifted and deposed on the deck of the landed helicopter;
- as above but with helicopter hovering at few centimeters from the ground, with the deck at approximately 1 m from ground;
- stretcher lifted on the helicopter by means of a winch mounted aside of the helicopter as shown in Fig. 1c; (in this case the helicopter stands still at about 5–25 m from ground, depending on environmental conditions) and
- cruise (approximately 6 min).

The stretcher is simply leaned on the helicopter cabin deck, usually covered by a rigid plastic mat. Helicopter characteristics and, mostly, its mechanical design (especially the nature of the links between the blades and the rotor, as well as the number of blades) have great influence on on-structure vibrations [13,14]. Hence depending on the rotor typology (rigid, semi-rigid or flexible) significant differences in vibration magnitude and spectrum are expected. The helicopter used in our tests (Aerospatiale Dauphin AS 365 N3) is equipped with flexible rotor. In this case, due to obvious safety reasons, all operations were carried out by trained personnel.

3. Measurement chain

Due to severe rescue conditions, measurement chain quality is crucial. Not only every element of the measurement chain must match the requirements of current standards [6,15,16] but also every part must be as small and light as possible in order to minimize the influence of measurement systems on phenomena. On a stretcher-tied body the vibration path is hardly predictable (stretchers' structures and links are complex and not always repeatable, due also to the fact that they're assembled in harsh environments during rescue operations); therefore the choice of number, type and position of accelerometers in this kind of tests is a key factor with respect to the data significance. On the other hand each measurement point (i.e. an accelerometer with its conditioning and filtering unit) has relevant costs not only from an economical point of view, but also since it increases physical dimensions and masses of the measurement system. For current experiments the optimal compromise was for an eight-channels custom-made system.

Measurement chain is composed by:

- a seat pad with a triaxial accelerometer, placed between the stretcher and the patient, according to ISO standards [6];
- a biaxial accelerometer on the forehead of the patient;
- three mono-axial accelerometers placed in different points of the stretcher-structure (Fig. 2a);
- two four-channels conditioning amplifiers with antialias filtering; and
- a laptop computer equipped with a 16 bits, 250 kHz sampling rate, data acquisition board with Misure5® data acquisition and analysis software.

Antialiasing filter cutoff frequency was set to 1 kHz; scan rate to 2.5 kHz.

Accelerometers are five monoaxial B&K 4508 type and one triaxial PCB 356A22, with nominal sensitivity of $10\,\mathrm{mV/(m/s^2)}$, and frequency range ($\pm 10\%$) of 0.4 Hz–5 kHz. They underwent metrological confirmation before tests with a B&K 4294 calibrator. Measurement uncertainty is mainly due to accelerometers nonlinearity, as usual in the case with this kind of setup [17]. The combined standard uncertainty, according to ISO GUM [18] is 2.3%.

Data from seat-pad accelerometer are collected in accordance with the standard [6]. Due to the position of the seat pad accelerometer, its data are representative of the vibrations that reach the patient body and thus have been considered as a reference for all analyses. Data of accelerometers on the stretcher-structure are used in order to have additional information about the kinematics during the transport.

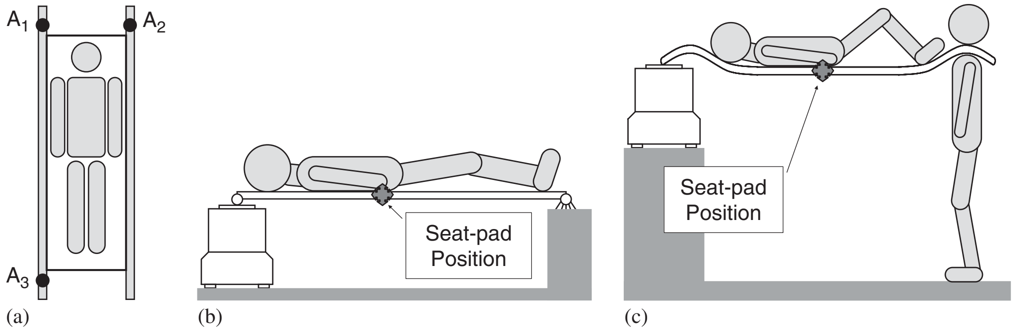

Fig. 2. Accelerometers position (a) and experimental setup (b, c) for stretcher dynamic characterization.

With regards to the methods for head-vibrations measurements, the interposition of a transducer at the interface between head and the supporting structure is critical, since the head is laterally supported with a compliant foam; hence, the use of a pan as suggested by ISO 2631 [6] is not feasible. In our setup measurements were made at the patient forehead, with accelerometers glued on a belt tight around the head. This kind of mounting has been characterized in the lab by comparison with the measurements of a laser vibrometer pointing directly on the head. Such comparison shows that measurements are reliable only in a band up to about 7 Hz. Nevertheless measurements were carried-out with this limitation so as to have preliminary data about the head vibration that can be quite relevant for the common trauma cases. In any case this kind of measurements deserves a deeper investigation and it was decided not to include them in this paper.

4. Experimental results

Data acquired were analyzed under different perspectives in order to outline peculiarities and mostly to compare the outcomes with different indexes. The use of the weighting functions and indexes of the ISO 2631 is still a questionable issue [4] when the task is the evaluation of vibrations effects on health or comfort of healthy people although that is the purpose for which they were setup. In the present case, when dealing with injured subjects, it becomes totally arbitrary. It was anyway decided to perform these kind of analysis for tree main reasons:

- a vibration that can cause discomfort to a healthy person will at least give the same annoyance to an injured one;
- the use of the common parameters allows a direct comparison between these conditions and other normal (work) activities;
- the typology of injury can be so different that the attempt to define a single parameter applicable for any situation is probably a nonsense; the disturbance generated to the healthy is, anyway, a common parameter that needs to be integrated with a specific one dependant on the type of injury. The study of such specific parameters is not part of this research and should be carried out in association with clinical studies like [10].

ISO standards [6,15] suggest analysis, methods and parameters, which can be summarized as follows:

- frequency-weighting of acceleration according to proposed weighting functions;
- calculations of acceleration-levels (both along one axis and as vectorial combination of the three axes) with appropriate time-constants;
- evaluations of the following parameters:

(a) a_w: the weighted root-mean square (rms) value of the acceleration history, that can be considered as an indicator of the average incoming vibration power, defined as $a_w = \sqrt{(1/T)\int_0^T a_w^2(t)\,\mathrm{d}t}$;

(b) MTVV: the Maximum Transient Vibration Value defined as the maximum value achieved by the weighted running rms acceleration (with 1 s time-constant);

(c) VDV: the fourth power Vibration Dose Value, defined as $\mathrm{VDV} = \sqrt[4]{\int_0^T a_w^4(t)\,\mathrm{d}t}$.

a_w is the basic index for evaluation of vibration exposure and summarizes the vibrations reaching the body as a general, averaged, amount of mechanical excitation. In addition the ISO standard proposes the evaluation of the MTVV/a_w and VDV/($a_wT^{0.25}$) ratios (said T the duration of the test) as indicators of applicability of the a_w alone for the characterization of the received vibration.

The MTVV/a_w ratio is an indicator of the presence of shocks or short-term events (large ratio values indicate that short-time, high acceleration level events occur in a generally low level history).

The VDV is a cumulated value that strongly depends on the duration of the measurement session. The intrinsic characteristics of simulated rescue operations do not allow a constant duration. Thus the direct comparison of VDV values achieved in different phases can be misleading. The VDV/($a_wT^{0.25}$) ratio is an index that describes the ratio between the 4th power acceleration and its rms. Similarly to MTVV/a_w this index outlines the presence of acceleration peaks in the time history; on the other hand it's anyway an average, less sensitive to single events.

When vibration is measured along more than one axis, ISO 2631 [6] suggests to evaluate the Vibration Total Value determined from orthogonal acceleration values as $a_v = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2}$. As already mentioned, application of the standard is questionable: calculations are therefore performed both with frequency weighting and without. For a better description of the vibration characteristics and sources, frequency domain analysis is presented in terms of overall-spectra. In some cases, in order to point out the evolution of harmonic content of signals in time, a time–frequency analysis based on a short time Fourier transform (STFT) algorithm is also presented.

4.1. Hand stretcher transportation

Weighted and unweighted combined acceleration levels at the seat pad are summarized in the first row of Table 1. Due to the relevant dispersion typical of this kind of measurements, data are summarized as the mean and the standard deviation of weighted and unweighted acceleration levels, averaged on eight tests, carried out by four different couples of transporters. Data dispersion during the transport phases can be figured out by ratios between the means and the standard deviations (either weighted or unweighted); such values are in the order of 25% and indicate that tests differ significantly from each other. This is an expected result, though, since real test conditions do not allow better repeatability (Figs. 3 and 4).

Table 2 shows that the factor MTVV/a_w is greater than 2 along the three measurement axes. In Fig. 5a and b spectra deriving from measurements with different couples of transporters (experienced rescuers and novices) are depicted. Experienced rescuers grant a "softer" transportation than novices and naturally tend to avoid excitation of natural vibrations of the stretcher, compensating and damping them with their body and walking approach. It is also to be noticed that experienced rescuers tend to walk out of synchronization. This provides a less evident influence of excitation given by the walk of transporters (whose components in our experiments are between 1.5 and 2 Hz Fig. 5a and b) and a good stability, evidenced also by a STFT analysis (Fig. 4a). The analysis of the accelerations measured at the stretcher frame does not provide any additional information since

Table 1
Seat-pad vibration total values on different means of transport: summary

Test	Seat-pad vibration total values [m/s^2]					
	Unweighted			Weighted		
	Mean	SD	SD/Mean	Mean	SD	SD/Mean
Hand transport	1.46	0.29	0.20	1.06	0.25	0.24
Ambulance off-road	1.87	0.18	0.10	1.21	0.12	0.10
Ambulance urban	1.03	0.15	0.15	0.64	0.08	0.13
Helicopter cruise	1.02	0.05	0.05	0.27	0.02	0.07

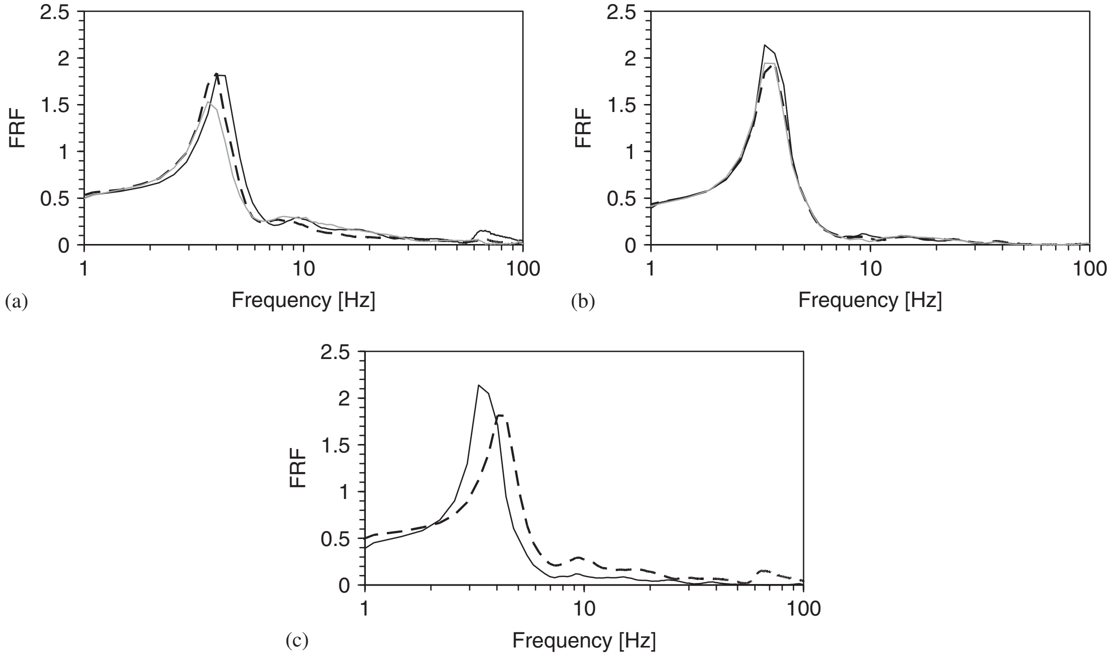

Fig. 3. Changes in FRF due to: (a) patient's body mass (—— 70 kg, - - - - 80 kg, ——— 90 kg); (b) nonlinearities (—— 4.5 m/s^2, - - - - 5.4 m/s^2, ——— 6.3 m/s^2); (c) use of shafts (—— with shafts, - - - - without shafts).

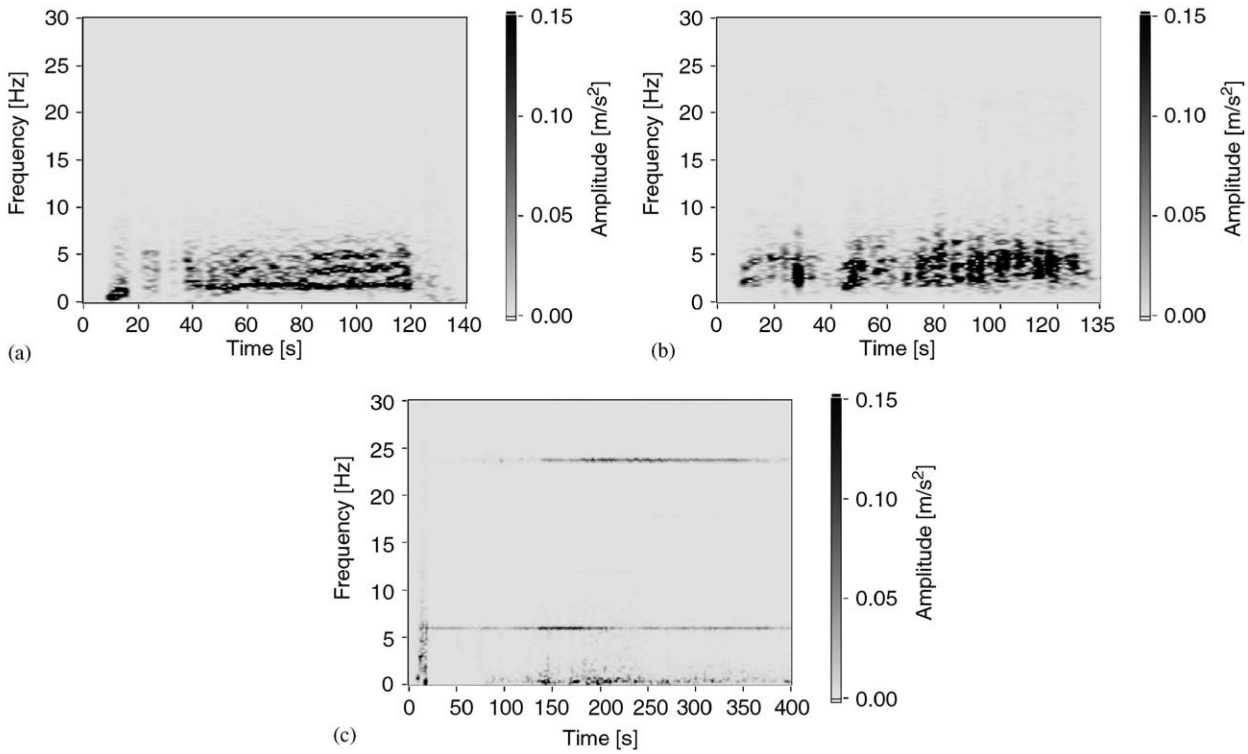

Fig. 4. Short time Fourier transform of the seat-pad X accelerations in different transport conditions: (a) hand transport, skilled operators, (b) ambulance transport on off-road terrain, and (c) helicopter: stretcher-loading and cruise. *X*-axis time [s], *Y*-axis frequency [Hz], Color scale acceleration values [m/s^2 rms].

Table 2
Crest factors, MTVV, MTVV/a_w and VDV/(a_wT$^{0.25}$) ratios on different means of transport

Test	Crest factors			MTVV [m/s^2]			MTVV/a_w			VDV/($a_w T^{0.25}$)		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Hand transport	12.0	46.6	28.2	1.8	1.0	0.8	2.0	2.4	2.1	1.6	1.5	1.5
Ambulance off-road	11.4	15.5	13.0	3.7	0.9	0.6	3.3	2.7	2.8	1.9	1.9	1.7
Ambulance urban	12.3	10.2	12.8	2.7	0.5	0.5	4.1	3.1	3.0	2.0	1.7	1.8
Helicopter cruise	11.5	25.9	7.13	0.6	0.3	0.1	2.2	4.0	2.5	1.4	1.7	1.5

the differences, with respect to seat-pad data, are explained by test repeatability and stretcher frequency response function (FRF).

4.2. Ambulance transportation

The simulations of ambulance transportation were carried out on three off-road paths and in five different urban conditions. Synthetic results are presented in Tables 1 and 2: accelerations measured at the injured-stretcher interface in off-road paths are the most severe among all tested conditions, while in urban conditions the transportation is less critical. It can be observed that the MTVV/a_w ratios are systematically greater than 2 along the three axes. With a VDV/($a_w T^{0.25}$) ratio constantly over 1.7, the ambulance transportation is the most critical under this point of view. Acceleration spectra during ambulance transportation (Fig. 5c and d) and STFT (Fig. 4b) are significantly different than shoulder stretcher transportation, although the natural frequency of the stretcher (between 3 and 4 Hz) is obviously present in both tests.

Fig. 6 shows the analysis of vibration levels on different point of the stretcher that are:

- on the stretcher frame close to the feet;
- on the stretcher frame close to the head; and
- near the center of gravity at the stretcher–patient interface (measured with seat-pad).

From data analysis it is evident that exposure of the patient' feet to vertical vibrations is higher than the exposure suffered by the head. Since feet are above the rear vehicle axis and the head is near the ambulance center of mass, these differences are probably related to vehicle pitch. Such a fact outlines that the characterization of WBV using the seat-pad measurements alone can be misleading: at least a second point, reasonably the head, must be included.

4.3. Helicopter transportation

Acceleration values (Tables 1 and 2) show that the helicopter cruise is the least critical transportation phase. Both STFT and vibration spectra (Figs. 4c and 5e) show differences between spectra on the helicopter (narrow frequency components) and the ones measured in the previous conditions (broad-band spectra). Harmonics at 6 and 24 Hz, originated by the four-blades rotor, are particularly evident. Since the stretcher excitation spectrum (due to helicopter vibrations) does not contain harmonics close to the stretcher natural frequency, the resonance is not excited and frequency components between 3 and 4 Hz are absent. Predominance of high frequency components during the cruise is outlined both by acceleration spectra (Fig. 4) and by the large difference between weighted and unweighted acceleration values (Table 1). Accelerations measured on the stretcher frame are representative of the helicopter deck vibrations, but due to the stretcher FRF are not representative of patient vibration exposure.

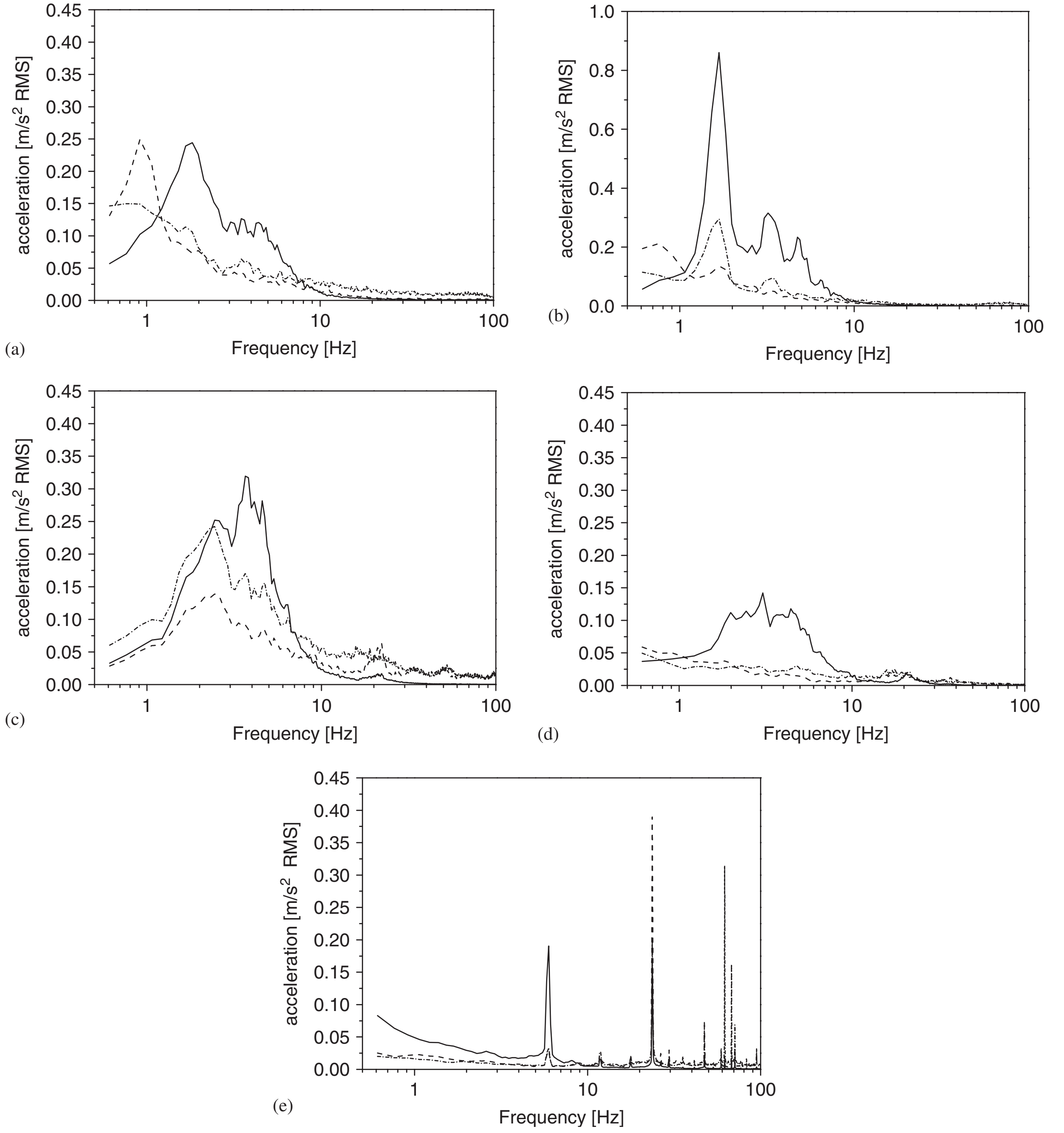

Fig. 5. Acceleration spectra at the injured–stretcher interface in different conditions: (a) hand transport, skilled operators, (b) hand transport, novices, (c) ambulance, off-road, (d) ambulance, urban, and (e) helicopter loading and cruise; ——— seat-pad *X*-axis, - - - - seat-pad *Y*-axis, ⋯⋯ seat-pad *Z*-axis.

4.4. Load– unload operations

The comparison between acceleration values in different stretcher load and unload operations is shown in Fig. 7b, and Tables 3 and 4. Such operations are supposed to be the ones where the occurrence of shocks is highest. Among the tested conditions the ones producing the most severe shocks are load operations on the

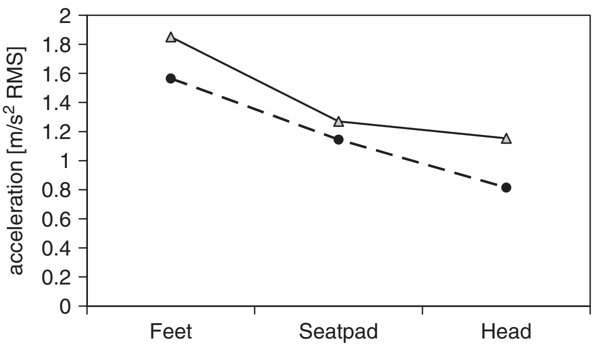

Fig. 6. Acceleration measured on the stretcher at feet, center of gravity and head position. Head is toward the front of the vehicle. ——Δ—— unweighted acceleration values, —●— Weighted acceleration values.

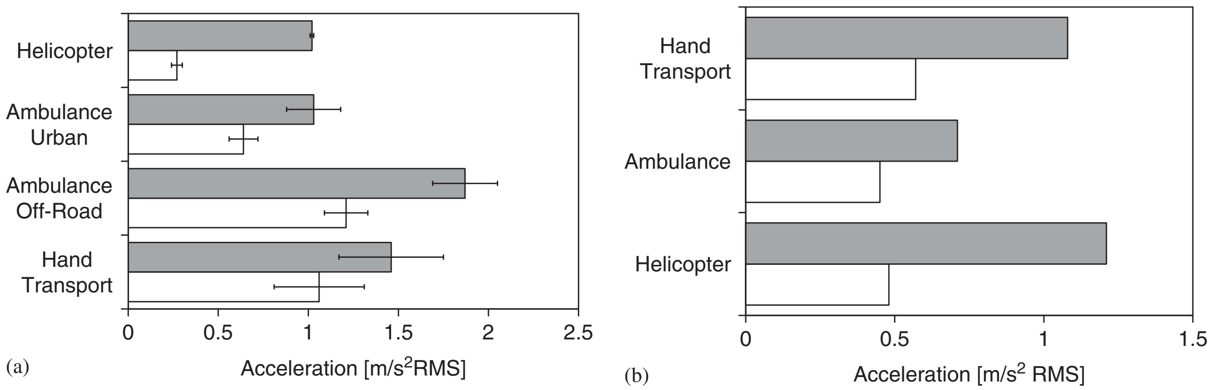

Fig. 7. Comparison of vibration total values at the stretcher–injured interface with different means of transportation (a) and in different load–unload operations (b).

helicopter and unload in the hand transportation. In these situations high MTVV values are due to shocks on the stretcher frame and rigid parts (due to collisions with the helicopter frame or the ground). An important reduction in shock magnitude could be simply achieved, for example, by adding shock absorber to the stretcher or with an accurate choice of unload position on the ground (for example grass). It is to be noted that the final part of unloading operations (that is when the stretcher is in the lowest position before touching the ground) is the most uncomfortable and critical for the rescuers. This probably leads to bumps in the operations. All indexes, instead, show that the use of the standard trolley stretcher as mean of loading on the ambulance significantly decreases the vibrations reaching the injured with respect to the other means of transport.

4.5. Stretcher characterization

Before the on-field experiments the identification of the stretcher FRF in different conditions was considered fundamental both for a proper interpretation of data and in order to unbind them from the peculiarity of the single device adopted. Stretchers used in mountain-rescue operations must be light, easily transportable and quickly mountable. Such necessities hardly match with requirements of comfort and isolation from vibrations. The stretcher chosen for our tests (Kong model 870.00) is one of most used for such purpose. It consists of an aluminum frame with a nylon cloth suspended with interwoven fastening belts. The stretcher can be used either with shafts (for shoulder transportation) or without (on the ambulance or

Table 3
Seat-pad vibration total values in different load/unload operations

Test	Seat-pad vibration total values [m/s^2]	
	Unweighted	Weighted
Hand transport	1.08	0.57
Ambulance	0.71	0.45
Helicopter (landed)	1.21	0.48
Helicopter (hovering)	1.71	0.49
Helicopter (winch lifting)	1.60	0.48

Table 4
Crest factors, MTVV, MTVV/a_w and VDV/($a_wT^{0.25}$) ratios in different load/unload operations

Test	Crest factors			MTVV [m/s^2]			MTVV/a_w			VDV/($a_wT^{0.25}$)		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Hand transport	8.3	12.4	10.6	3.7	0.6	0.5	9.7	1.7	2.2	1.7	1.5	1.6
Ambulance	18.9	46.7	36.6	1.0	0.5	0.7	3.2	2.6	2.8	2.1	1.8	2.0
Helicopter (landed)	39.6	42.5	56.3	1.1	0.6	0.9	2.6	2.5	3.1	2.0	1.9	2.3
Helicopter (hovering)	18.7	38.5	46.5	1.8	0.6	0.8	4.6	2.8	3.7	2.7	1.8	2.1
Helicopter (winch lifting)	31.8	83.9	40.5	2.1	0.5	0.4	4.8	3.0	2.9	3.0	1.9	1.7

helicopter). Because of dry friction between belt fibers and between belts and frame, a nonlinear behavior, already observed in woven elements [19] is expected. Characterization tests were therefore carried out with different vibration magnitudes. Laboratory experiments have been carried out with and without shoulder shafts, with the experimental setup shown in Fig. 2b and c. Excitation (white noise acceleration with rms magnitude levels between 3 and 7 m/s^2) is generated with an electro-dynamic shaker placed at one end of the stretcher. The opposite side has been leaned upon the shoulders of a standing person (to simulate the transportation over mountain paths) or connected to the ground, reproducing the condition when it is lying on a rigid floor. Shaker's dynamic performances do not grant constant Power Spectral Density levels of the excitation at frequencies below 3 Hz. Since FRFs are calculated relying on a reference accelerometer (measuring the actual shaker excitation) and since amplitude-related nonlinearity in this frequency range seems to be negligible (Fig. 3b), data are reported also below 3 Hz. Presented FRF is the average of three tests repeated in the same nominal conditions; it is calculated as the ratio between spectra of acceleration measured behind the bottom of a laying person and at the shaker–stretcher interface. Spectra are obtained with the average of 500 measurements of 2.7 s. Due to the geometrical test configuration (seat pad with accelerometers roughly in the middle of the stretcher length, between the shaker and the rotating joint), FRF at low frequencies, when the stretcher behaves as a rigid body, is about 0.5. Tests were carried out with three different healthy people simulating the patients (respectively with a body mass of 73 kg (BMI 23 kg/m^2), 78 kg (BMI 26 kg/m^2) and 95 kg (BMI 26 kg/m^2).

Results of tests are shown in Fig. 3a–c: one can notice differences in FRFs due to patient body mass (a) and levels of vibration (b). Differences due to the use of the shoulder's shafts are shown in Fig. 3(c). The first natural frequency of the patient–stretcher system is close to 4 Hz; there the modal shape corresponds to an oscillation of the patient in the vertical plane, mainly due to the belts compliance; the frame, instead, is approximately rigid at those frequencies. Vibrations with frequencies above 5 Hz are damped because of this mode. When used with shafts, due to the contributions of the structure compliance to modal displacements, the stretcher natural frequency is slightly lower and FRF has a larger amplification with respect to the other condition.

5. Discussion

5.1. Parameters

An analysis compliant to ISO 2631 [6] has been performed although at the moment there is no evidence of similarities between long-term WBV exposure and short-lasting vibration exposure of injured subjects. Such analysis is presented in order to assess values comparable with existing literature. It is important, anyhow, to outline that the present work aims to provide an overview of the situation in this field.

The limits of ISO 2631-1 methods, if applied to present case, mainly consist in the fact that the standards are intended to set general parameters for long or even short term exposure of healthy people. In the case of traumatic patients other factors, not included in ISO 2631-1, can be more important. For example, the consciousness of the patient may dramatically change the muscular reaction to excitations, therefore changing the mechanical response of the whole system and thus the measured level of vibration. Other limits in the use of ISO 2631 [6] may arise in the evaluation of the worsening of a bone or spinal trauma where the position of the body on the stretcher is fundamental, since the evolution of the trauma depends not only on vibration amplitude, but also from its direction. When applying ISO 2631-1 criteria, vibration direction is only partially taken into account. As previously pointed out, the study of these and other specific parameters should be carried out in association with clinical studies. However, the analysis with ISO 2631-1 parameters is considered important both as a starting base and because frequency weighting summarizes also the mechanical response of the body [6], thus undertaking significance of the real stress the body undergoes to.

As already pointed out in Ref. [4], "extremely large differences are possible even when using alternative methods presented in the same standard"; hence divergences between the different evaluation criteria are expected. Among tested conditions differences arise in the ambulance urban path, where vibration levels a_w are generally minimal—due also to the presence of the trolley—while rare peaks due to road imperfections raise MTVV to high values. Vibrations and shocks have different effects depending on patient pathology: traumatic patients will not suffer for relatively high a_w values, which instead can be critical for aneurisms or vascular pathologies. On the other side traumas can dramatically worsen with just one high level shock event.

The parameters of ISO 2631 [6] already provide useful indications: the ratio MTVV/a_w, always greater than 2, points out that "single events" are relevant if compared to average levels. Such index does not depend on the transportation mean, since it has similar values both for helicopter and shoulder transportations. The VDV/($a_w T^{0.25}$) ratio leads to the same conclusions for the ambulance transportation although it is not clear for the other two cases. It is important to notice, anyhow, that the use of both ISO 2631 parameters and the commonly used statistical indexes give similar information when used for the comparison of one operation with respect to the others.

This leads to the conclusion that ISO 2631 can be used for analysis of patients' vibrations, taking great care to the choice of the parameter (e.g. a_w or MTVV) with regards to the type of injury.

5.2. Measurement points

The analysis of acceleration in different points of the stretcher frame outlines that vibrations reaching the injured body are not uniformly distributed at the stretcher–patient interface. A single measurement point, like the seat-pad measurement near the body center-of-gravity for example, can be meaningful in presence of low spine injuries, but is less important in case of head or legs injuries. The definition of a procedure for head acceleration measurements seems a necessary improvement to the research in this field.

5.3. Comparison between transportation means and phases

The comparative analysis of means of transportation type is summarized in the histogram of Fig. 7a, and Tables 1 and 2. Both weighted and unweighted acceleration at the stretcher–patient interface show that the most critical phases, among the described experiments, are the ambulance off-road trip and the hand stretcher transportation, both characterized by high vibration levels and large data dispersion. High values of Crest Factor and MTVV/a_w (systematically greater than 1.5) show the presence of impulsive events, confirmed by the ratio VDV/($a_w T^{0.25}$) that in most cases exceeds 1.7. The conclusion according to ISO 2631 [6] is that a_w cannot be used as the only index for characterization of WBV.

The stretcher load–unload phases of the stretcher from the carriers' shoulders generate the highest accelerations (a_w) among tested conditions. Both MTVV and VDV evidence that shock type events characterize this kind of operations and therefore these two indexes should be included in the evaluation.

The least critical among the tested conditions seems to be the helicopter transportation, where low levels could even be significantly reduced with the use of simple mechanical dampers.

6. Conclusions

Results of a measurement campaign on WBV exposure in mountain-rescue operation have been presented and discussed. Although the analysis presents relevant limitations mainly due to the small number of tested conditions, some meaningful results have been outlined. The analysis of acceleration on different point of the stretcher frame show that the vibration measurement with the seat pad may underestimate the maximum vibration level that reaches the patients. The most severe condition was discovered as the transportation of the stretcher on rescuers' shoulders, that generates the largest accelerations during both the walking and the load/unload phases. It was evidenced that the stretcher natural frequency is close to the walking frequency and therefore improvements could be achieved with a different stretcher design. Data analysis has demonstrated that in all phases and with any transportation device the weighted rms acceleration level (a_w) is not a sufficient indicator and other indexes are needed to characterize the acceleration peaks. Further analyses are required in order to validate results on different kind of ambulances, helicopters and mountain paths and to correlate vibration exposure indexes with the evolution of the injured clinical conditions.

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