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Physics of Shock and Physiological Effects on Biological Systems †

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Abstract: Shock vibrations from handheld tools have long since been suspected to cause an increased risk of hand-arm vibration syndrome. This paper gives an introduction to its physical origin and transformation of the hand. Also, the pathophysiological effects on biological systems from shock vibration are shown through in vitro models on fibroblasts and red blood cells. Finally, the results from an in vivo rat tail model are described. The results show that high-amplitude shocks with a high-frequency content have a detrimental effect on biological systems, and thereby presumably also have a negative effect on human hand tissue. This indicates the need for a risk estimation for vibration injuries that includes the frequency range of shock vibrations and can quantify their peak amplitudes.

Keywords: hand-transmitted shock; vibration; shock; isolated shock; continuous shock physiological effects

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1. Introduction

This contribution to the ICHAV 2023 workshop dedicated to shock vibration has the intention to give a background to the term shock and the inevitable relation between its duration and frequency. It will also present some studies on shock vibration carried out on biological systems which, to some extent, can be transferred to humans.

2. Properties of Shock Vibration

Shock vibration is commonly generated in many machines where there is a strong force acting on the machine during a very short time compared to the work duty cycle. The force can originate from several mechanisms, but one of the most common (and the one with the highest acceleration amplitudes) is related to an accelerated mass hitting a work tool and releasing its energy. This can be the piston hitting the drill in a hammer drill, or the impact mechanism hitting the shaft with the socket in an impact wrench. Generally, the force is very high and the duration in which they are in contact is very short, typically 20 µs for a pneumatic drill. In an ideal situation, all the energy would be transferred to the tool, but this is not the case. Instead, part of the impact energy is also transferred to the machine housing, where it creates a vibration that propagates to the hand of the operator. The vibration consists of both the direct impact and the resonances in the machine structures that are excited.

The relation between the pulse duration and the frequency content is given by $f = 1/T$. In ISO 5349-1 [1], only frequencies below 1250 Hz are considered. Therefore, shock pulses with a duration shorter than 0,8 msec are essentially excluded, which applies to most of the shock seen in hand-held machines. An example of this is shown in Figures 1 and 2, which show the time signal and frequency spectrum of the acceleration measured on the handle of a typical 3/4″ pneumatic impact wrench. In Figure 1, the RMS and VPM (vibration peak magnitude [2,3]) are marked in red and green. The red line in Figure 2 is the cumulated energy and, as can be seen, only a fraction of the energy is below 1250 Hz. This underlines the necessity to measure shocks at sufficiently high frequencies to capture the phenomena. The acceleration should therefore be measured at a frequency that is sufficiently high enough to be able to cover the main energy content transferred to the biological system of interest.

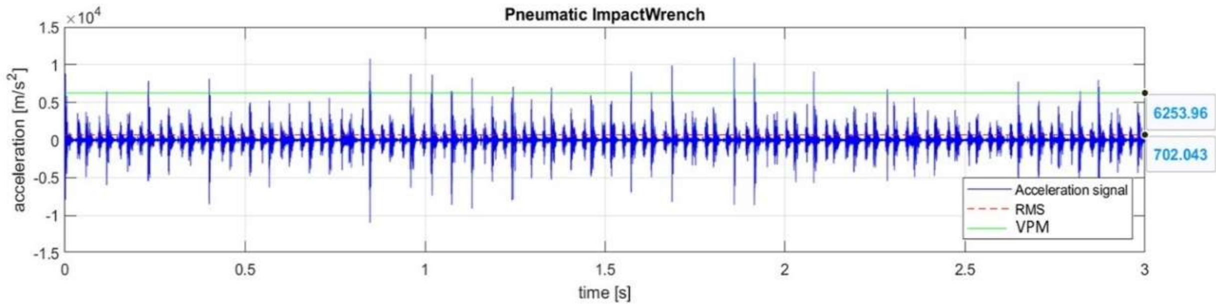

Figure 1. Acceleration of a 3/4″ pneumatic impact wrench.

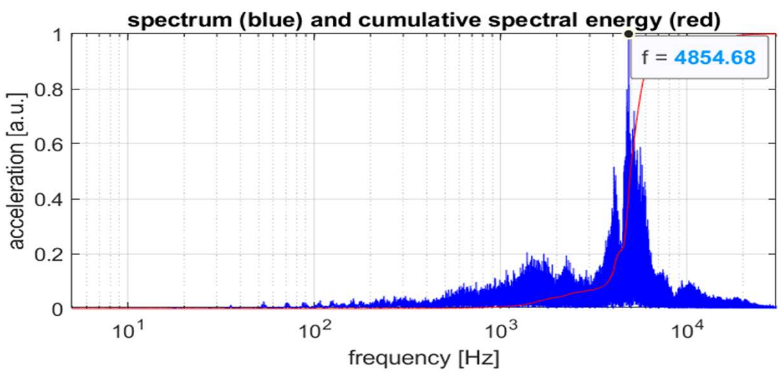

Figure 2. Acceleration frequency of a 3/4″ pneumatic impact wrench.

3. Physiological Effects of Shock

There have been several studies investigating the effects of vibration on physiological systems, using both in vitro and in vivo models. A review article is found in [4].

3.1. Tests on Red Blood Cells

There are two studies that have investigated the effect of high-frequency shock's impacts on red blood cells indicating a correlation to physiological effect. The advantage of using red blood cells is that it is easy to measure the degree of lysis by analysing the haemoglobin colouring of the plasma or counting the viable cells. In the first study [5], elastomer containers of cow blood were attached to a machine surface and subjected to vibration for 15 min. The result indicates that the degree of lysis of the cells was considerably stronger correlated to the high-frequency peak acceleration than to the ISO 5349-1 value. See Table 1.

In the second study on red blood cells [6], the blood was placed in containers and inserted into an impact hammer simulation test rig, creating high-acceleration amplitudes. The results showed a clear correlation between the degree of lysis and the exposure time and amplitude.

Table 1. The degree of lysis on machine surfaces and acceleration amplitudes. Data from [5].

Test	ISO5349-1 acc., One Axis (m/s^2)	Average Peak acc., (m/s^2)	Percentage of Lysis
1: Impact wrench socket	10	>30,000	100%
2: Impact wrench handle	2.2	15,000	0.4%
3: Impact wrench handle with internal dampening mechanism	2.4	2000	0.07%
4: Vertical grinder handle with grinding wheel and grinding	7.1	1000	0.1%
5: Vertical grinder handle with unbalanced wheel	6.5	500	0.1%

3.2. Test on Mouse Fibroblast Cells

This study was recently performed at RISE Research Institutes of Sweden as a pilot study to measure the biological effects of shock vibrations and compare them to low-frequency sinusoidal vibrations. The cells tested were L929 mouse fibroblast cells (NCTC clone 929: CCL-1 American Type Culture Collection). Two test rigs were constructed, one for emitting mainly sinusoidal vibration at 50 Hz and one for shock vibration. Both rigs had essentially the same ISO 5349-1 acceleration and the difference was in the high-frequency shock.

The results show a clear indication that shock vibration has an effect on cell viability. The colorimetric assay result of the cell viability (Table 2) corresponded well with the microscopic observations (Figure 3). A hypothesis is that the detrimental effects of shock are caused by cavitation in the samples.

Table 2. Cell viability after 15 min vibration exposure. Cell viability was measured by colorimetric assay, which is based on the reduction of a yellow tetrazolium salt (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide or MTT) to formazan by metabolically active cells.

Test	ISO5349-1 acc., (m/s^2)	Average Peak acc., VPM (m/s^2) [2]	Relative Viability Compared to Control
Sinus rig	16.5	170	41%
Shock rig	13.9	71,030	1%
Control	0	0	100%

3.3. Test on Rat Tails

This study [7] was conducted on a rat tail model, where the rat tail was exposed to shock vibration from a dedicated test rig, with the intention of having a vibration level similar to that of a bucking bar. The measurements that were made on the test rig after the study was published showed that the ISO 5349-1 vibration was 9 m/s^2 and the peak acceleration was approx. 100,000 m/s^2, measured up to 50 kHz.

The tails were exposed to a single 12 min vibration. Immediately after stopping the vibration, there was damage to the nerve endings in the skin, as well as mast cell degranulation and hypersensitivity to thermal stimulation. Four days after stopping the vibration, the nerve endings had become disrupted, indicating that the single vibration insult triggered a destruction process.

The results from the study are summarized in “Shock-wave vibration causes severe nerve damage. Frequency weighting seriously underestimates the risk of nerve injury with impact tools”.

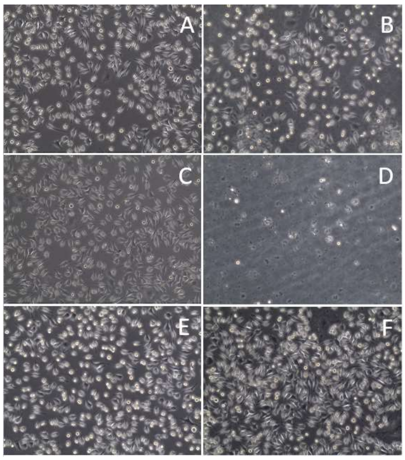

Figure 3. Representative microscope images of L929 mouse fibroblast cells before ((**A**): sinus rig, (**C**): shock rig) and after exposure to 15 min of vibration ((**B**): sinus rig; (**D**): shock rig). Control cells were not exposed to vibration ((**E**): time 0; (**F**): after 15 min).

4. Discussion

High-frequency shock vibration has long since been suspected to cause vibration injuries, and a number of studies have shown the physiological effects, of which a few are described in this abstract. However, in the current standard for risk evaluation, ISO5349-1, only frequencies up to 1250 Hz are considered, and within that bandwidth, the higher frequencies are supressed. This results in the shock vibration being almost eliminated.

To progress the research field of vibration injuries, it is necessary to increase the studied frequency and develop test methods for higher frequencies, as well as metrics for the quantification and definition of shock, together with exposure metrics.

The potential for substantially reducing high-frequency shock at a low cost is huge for machines but, unfortunately, there is no incentive, since shock vibration is not considered for either risk estimation or for vibration declaration.

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References

1. *ISO 5349-1*; Mechanical Vibration–Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration–Part I: General Requirements. International Organization for Standardization (ISO): Geneva, Switzerland, 2002.
2. Lindell, H.; Johannisson, P.; Grétarsson, S.L. Definition and quantification of shock/peak/transient vibration. *Proceedings* **2023**, *86*, 29. [CrossRef]
3. Johannisson, P.; Lindell, H. Definition and Quantification of Shock/Impact/Transient Vibrations. *arXiv* **2022**, arXiv:2211.08999. [CrossRef]
4. Krajnak, K.; Riley, D.A.; Wu, J.; Mcdowell, T.; Welcome, D.E.; Xu, X.S.; Dong, R.G. Frequency-dependent Effects of Vibration on Physiological Systems: Experiments with Animals and other Human Surrogates. *Ind. Health* **2012**, *50*, 343–353. [CrossRef] [PubMed]
5. Lindell, H.; Lönnroth, I.; Ottertun, H. Transient Vibration from Impact Wrenches: Vibration Negative Effect on Blood Cells and Standards for Measurement. In Proceedings of the Eighth International Conference on Hand-Arm Vibration, Umeå, Sweden, 9–12 June 1998.

6. Ando, H.; Nieminen, K.; Toppila, E.; Starck, J.; Ishitake, T. Effect of impulse vibration on red blood cells in vitro. *Scand. J. Work Environ. Health* **2005**, *31*, 286–290. [CrossRef] [PubMed]
7. Govinda Raju, S.; Rogness, O.; Persson, M.; Bain, J.; Riley, D. Vibration from a Riveting Hammer Causes Severe Nerve Damage in the Rat Tail Model. *Muscle Nerve* **2011**, *44*, 795–804. [CrossRef] [PubMed]