Assessment of the Effectiveness of Anti-Vibration Gloves. A Comparison of the Conventional and Energy Method. Analysis and Interpretation of Results – Part Two

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Abstract

The article is the second part of the article entitled "*Assessment of the effectiveness of anti-vibration gloves. A comparison of the conventional and energy method. Introduction – part one"* [4], which presents the assumptions and the construction of models of the biodynamic system consisting of the human operator, the anti-vibration glove and the hand-held power tool. The second part is devoted to a comparative analysis and interpretation of results obtained by means of the two methods. The analysis reveals a positive effect of the anti-vibration glove as a personal protective equipment, which reduces the operator's exposure to vibrations generated by the angle grinder. However, the effectiveness of the glove was assessed differently by the conventional or the energy method. It was also found that the energy method was a better tool for analyzing the impact of vibrations at different phases of the tool's operation.

Keywords: biomechanical system, local vibrations, energy assessment method

1. Introduction

There are a number of factors that need to be taken into account when conducting studies of the effectiveness of vibration reduction of anti-vibration gloves. One of them is the type of hand-held power tool [5]. In this particular case, the effectiveness of vibration reduction by means of an anti-vibration glove depends, among other things, on the grip force and the pressure exerted by the operator on the tool handle, the vibration acceleration signal generated by the tool, frequency characteristics of the glove's transmissibility, operating conditions, the mode of operation, the technological process and dynamic properties of an individual operator [3, 5, 6].

Safety requirements for anti-vibration gloves are specified in relevant industrial standard [8]. However, the effectiveness of anti-vibration gloves is assessed in two frequency ranges: mean values of corrected transmissibility for the glove must not exceed 0.9 for the lower frequency range (25 ÷ 200 Hz) and 0.6 for the higher frequency range (200 ÷ 1250 Hz). Only when transmissibility values are lower than or equal to the minimum values can a glove be regarded as an anti-vibration glove [8]. The anti-vibration gloves tested in the study satisfied the safety requirements specified for this kind of personal protective equipment.

The purpose of the study was to determine the difference in the assessment of the effectiveness of vibration reduction depending on the method used, i.e. the conventional and energy method. The methods rely on different assessment criteria: the first case only accounts for vibration accelerations; the second takes into considerations values of energy inputs absorbed by the human body. As a result of the analysis, it was possible to determine the factor change in the assessment of the glove's effectiveness depending on the method used. Based on these values, the two methods were compared in order to identify differences in their assessments.

2. Results of the conventional analysis

Tables 1 and 2 present theoretical and experimental RMS values of vibration accelerations obtained for the condition of working with and without the anti-vibration glove. Results of numerical simulations were obtained by solving mathematical models (2) and (3), presented in the first part of the article [4].

It should be noted that theoretical values of RMS values of vibration accelerations obtained for both conditions were very similar to the mean experimental value – a difference of less than 1%. The results obtained for a new model of the glove (Table 2 in article [4]) represent the first attempt of using dynamic parameters which were determined experimentally. The high degree of similarity is thanks to the new model of the glove, which was adjusted to specific laboratory conditions in which the performance test was conducted.

Table 1. RMS values of vibration accelerations in the case of working without the glove and the difference relative to the mean measured value

Reduction point	**Simulated RMS value of vibration accelerations [m/s^2]**	**Experimental RMS value of vibration accelerations [m/s^2]**	**Difference relative to the mean experimental value[%]**
j = 4, mass m_3 and m_4	101.20	101.00 ± 2.82	0.20
j = 3, mass m_2	92.46	–	–
j = 2, mass m_1	8.99	–	–
j = 1, mass m_0	0.12	–	–

Table 2. RMS values of vibration accelerations in the case of working with the glove and the difference relative to the mean measured value

Reduction point	**Simulated RMS value of vibration accelerations [m/s^2]**	**Experimental RMS value of vibration accelerations [m/s^2]**	**Difference relative to the mean experimental value[%]**
j = 6, mass m_{G3}, m_{G4} and m_T	117.80	117.00 ± 6.79	0.68
j = 5, mass m_4 and m_{G2}	26.76	–	–
j = 4, mass m_3 and m_{G1}	26.59	26.55 ± 0.83	0.15
j = 3, mass m_2	26.88	–	–
j = 2, mass m_1	2.72	–	–
j = 1, mass m_0	0.04	–	–

The effectiveness of the anti-vibration glove can be assessed conventionally on the basis of experimental results. In this case, effectiveness is assessed in terms of a dimensionless index, defined as a ratio of the RMS value of vibration accelerations measured at the grinder handle (equivalent to the RMS value experienced by the operator at the palm of the hand without a glove) to the RMS value of vibration accelerations experienced by the operator at the palm of the hand with the glove. The relationship is given by the following formula:

$$I_{\mathrm{E}} = \frac{a_{\mathrm{RMS,\,H}}}{a_{\mathrm{RMS,\,P}}} \tag{1}$$

where:

$a_{\mathrm{RMS,\,H}}$ – mean RMS value of vibration accelerations at the grinder handle, without the glove, i.e. for $j = 4$, and equal to 101.00 m/s^2, (Tab. 1),

$a_{\mathrm{RMS,\,P}}$ – mean RMS value of vibration accelerations at the palm of the hand, with the glove, i.e. for $j = 4$, and equal to 26.55 m/s^2 (Tab. 2).

By applying this index, the effectiveness of the anti-vibration glove can be expressed as a factor change, which was equal to 3.80. This means that the tested glove reduces the RMS value of vibration accelerations relative to the value obtained when the glove is not used. In this case, the glove reduces the transmission of vibrations, i.e. reduces accelerations of vibrations by a factor of 3.80.

The high factor change in the effectiveness of protection is mainly due to the measurement of RMS values of vibration accelerations, which were measured under the linear weighting setting, i.e. without any filters and for the measurement frequency range between 10 and 10,000 Hz. This setting was necessitated by the requirements concerning input data for energy analysis. Additional series of measurements were performed using the H/A filter under the same laboratory conditions (Table 3)

Table 3. RMS values of vibration accelerations measured with the H/A filter and linear weighting – laboratory measurements

Measurement condition	**Value**		**Unit**
	with H/A filter	**with filters**	
at the handle (without the glove)	4.15 ± 0.13	101.00 ± 2.82	m/s^2
at the handle (with the glove)	3.75 ± 0.15	117.00 ± 6.79	
at the palm of the hand (with the glove)	2.20 ± 0.03	26.55 ± 0.83	

It should be noted that measurements performed with the H/A filter and without filters (with linear weighting) differ considerably. The results indicate two important facts. First of all, the application of the filter affects the RMS values of vibrations accelerations measured at the tool handle: the RMS value of vibrations accelerations at the handle increases, but only when measured without filters in the linear range between 10 and 10,000 Hz. This means that the anti-vibration glove amplifies vibrations accelerations, but mostly those that are not included in the frequency range specified in the standard, i.e. above 1250 Hz. In the second frequency range, i.e. with the H/A filter, a significant reduction in vibrations accelerations at the handle was recorded, and this is precisely the value that is relevant in assessing the impact of vibrations generated by tools on the human body.

The second fact that can be concluded from the measurement results is the lower effectiveness of the glove when the H/A filter is used. In this case, the factor change, calculated according to formula (1), is equal to 1.89. The tested glove reduces the RMS of vibrations accelerations in the H/A range, but the reduction of vibrations in the range which is relevant for the human body is lower than the factor change for the wider frequency band.

In summary, the conventional method indicates a positive effect of using the anti-vibration glove for both kinds of measurements. However, the conventional (amplitude-based) method can only be used to compare two conditions: when the operator is working without and with the glove. More information about the effect of vibrations on the human body can be obtained by applying the energy method, which described in the following section.

3. Results of the energy method

Given known dynamic parameters of the model of the human body [7] and measured and simulated RMS values of vibration accelerations obtained by applying the model of the combined H – G – T system, it is possible to conduct energy analysis [1, 2]. The following method can be used to determine the energy input absorbed by a specific subsystem of the H – G – T system, taking into account the impact of the other subsystems. This can be done by identifying the energy component associated with the human body subsystem, which is part of the combined model.

In order to determine the energy input absorbed by the human body, it is necessary to identify energy components (energy inputs) of three kinds of forces, according to formulas (4)–(9), presented in the first part of the article [4]. This task was accomplished by performing numerical simulations of accelerations, velocity and displacements of vibration associated with structural forces during the operation of the H – G – T system. Results of these simulations are the input for the energy method. Tables 4 and 5 present the results of energy analysis for the condition without and with the anti-vibration glove.

Table 4. Values of energy components of forces (energy inputs) for the model of the operator working without the glove at time t_1 = 5 and t_2 = 30 seconds

Energy component of forces	**Time t_1 = 5 seconds [J]**	**Time t_2 = 30 seconds [J]**	**Difference $E_{C\text{-}X,t2} - E_{C\text{-}X,t1}$ [J]**
inertial $E_{H\text{-}INE,t}$	2.58	15.32	12.74
dissipative $E_{H\text{-}DIS,t}$	9.66	57.61	47.95
elastic $E_{H\text{-}ELA,t}$	11.77	43.36	31.59
Σ	24.01	116.29	92.28

Table 5. Values of energy components of forces (energy inputs) for the model of the operator working with the glove at time t_1 = 5 and t_2 = 30 seconds

Energy component of forces	**Time t_1 = 5 seconds [J]**	**Time t_2 = 30 seconds [J]**	**Difference $E_{C+R\text{-}X,t2} - E_{C+R\text{-}X,t1}$ [J]**
inertial $E_{H+G\text{-}INE,t}$	0.22	1.27	1.05
dissipative $E_{H+G\text{-}DIS,t}$	0.92	5.23	4.31
elastic $E_{H+G\text{-}ELA,t}$	3.32	6.29	2.97
Σ	4.46	12.79	8.33

Figure 1 shows a comparison of the sum of three energy components associated with 3 kinds of forces – inertial, dissipative and elastic – for the model of the operator working without and with the glove. The numbers represent energy values after two periods: t_1 = 5 seconds and t_2 = 30 seconds. The third section of the chart shows the difference between the two values in order to exclude the energy input absorbed by the human body during the unsteady motion in the startup of the system.

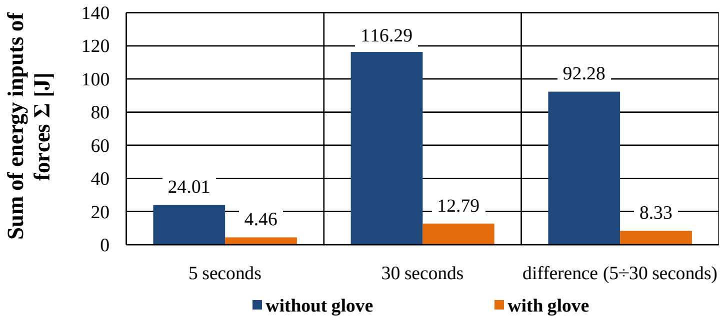

Figure 1. Sums of energy components of forces for the model of the operator working without and with the glove after time t_1 = 5 seconds and t_2 = 30 seconds and in the interval between t_2 and t_1, i.e. during the steady motion phase ($E_{X,\,t2} - E_{X,\,t1}$)

The results presented in Figure 1 indicate that the anti-vibration glove reduces the energy input absorbed by the human body. Under this approach, the effectiveness of the glove is also measured in terms of a dimensionless index, which is defined as a ratio of the sum of three energy components of forces for the model of the operator working without the glove to the corresponding sum calculated for the case with the glove. The index is expressed by the following formula:

$$E_C = \frac{E_{H\text{-}INE,t} + E_{H\text{-}DIS,\,t} + E_{H\text{-}ELA,t}}{E_{H+G\text{-}INE,t} + E_{H+G\text{-}DIS,\,t} + E_{H+G\text{-}ELA,t}} \tag{2}$$

where:

$E_{H\text{-}X,\,t}$ – energy components associated with inertial, dissipative and elastic forces for the case without the glove and calculated using formulas (4)–(6) presented in the first part of the article [4],

$E_{\text{H+G-X},\,t}$ – energy components associated with inertial, dissipative and elastic forces for the case with the glove, calculated using formulas (7)–(9) presented in the first part of the article [4].

It is worth noting that the effectiveness of the glove is different for each of the three situations. After calculating the value of the effectiveness index, the following order was obtained:

- after t_1 = 5 seconds – a factor change of 5.38,
- after t_2 = 30 seconds – a factor change of 9.09,
- in the interval between 5 and 30 seconds, during the steady motion – a factor change of 11.08.

It should be emphasized that the effectiveness of the glove increases as the time of operation increases. The startup phase is particularly critical: after t_1 = 5 seconds the index of effectiveness of is the lowest and is equal to 5.38. One practical recommendation that can be derived from this fact is that the tool should not be restarted repeatedly within a short interval of time.

After a longer period of time (t_2 = 30 seconds), the input of vibration energy absorbed by the operator working with the glove is considerably lower. This is because the flow of vibration energy absorbed by the body is lower by a factor of more than 9. This means that the most optimal phase for using the tool is the period of steady motion. This is also confirmed by the value of the effectiveness index calculated for the interval between 5 and 30 seconds: in this case the vibration energy input is reduced by a factor of over 11.

Figure 2 presents a structural distribution of energy inputs in the human body associated with the three kinds of forces. The percentage share of each energy component was calculated by relating the energy input associated with the specific force to the total energy input absorbed by the human body. Once again, the resulting values are shown for three situations: after time t_1 = 5 and t_2 = 30 seconds and in the interval between 5 and 30 seconds (for the steady motion). The structural distribution is calculated using the following formula:

$$P_{\text{S}} = \frac{E_{\text{X},t}}{E_{\text{X-INE},t} + E_{\text{X-DIS},\,t} + E_{\text{X-ELA},t}} \cdot 100\% \tag{3}$$

where:

$E_{\text{X},\,t}$ – values of energy components (energy inputs) of inertial, dissipative and elastic forces for each of the three situations (values from Tables 4 and 5).

The results shown in Figure 2 indicate that the percentage share of structural energy inputs associated with the three forces for the operator working without and with the glove depends on the period of time. This is an important conclusion since the structural energy inputs can be linked with specific changes in the human body [1, 2].

When the tool is used for a short period of time, the percentage share of energy input due to elastic forces for both conditions is the highest – Fig. 2a. For this reason, this energy component will mainly affect the elastic parts of the human body, which include muscles, tendons and joint capsules. As a result, repeated restarts of the grinder within a short period of time will increase the likelihood of pathological changes in these body parts.

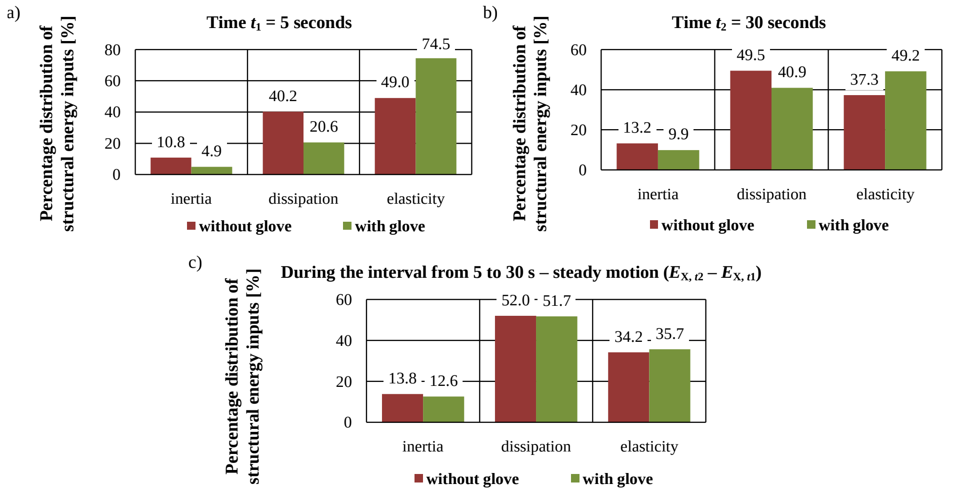

Figure 2. Percentage share of structural energy components for the model of the operator working with and without the glove: a) after t_1 = 5 seconds; b) after t_2 = 30 seconds c) during the interval from 5 to 30 seconds – steady motion ($E_{X, t2} – E_{X, t1}$)

The distribution changes for the longer period t_2 = 30 seconds. In this case, for the case of working without the tool, the dominant energy component is associated with dissipative forces, while for the case with the glove, the energy input from elastic forces – Fig. 2b. However, this conclusion is somewhat misleading because the contributions are affected by the energy inputs generated during the unsteady motion, shown in Fig.1. When one analyses the structural distribution of energy inputs in the interval of steady motion, shown in Figure 2c, one can see that for both conditions the dominant energy input is associated with dissipative forces, which can be linked to an increase in body temperature caused by the dissipation of energy.

4. Comparison of the conventional and the energy method

The two methods should be compared on the basis of linear measurements obtained for the frequency range of 10 to 10000 Hz. For this frequency range, the effectiveness of the glove, according to the conventional (amplitude-based) method is equal to 3.80. When the effectiveness is assessed in terms of energy, it should be based on value obtained for the steady motion, which is 11.08. This choice is motivated by the fact that the measurements of RMS values of vibration accelerations were made during the steady motion of the tool.

5. Summary

The main outcome of the study is that, regardless of the method used, the anti-vibration glove was found to be effective in reducing the impact of vibrations generated by the tool. However, a different degree of effectiveness was obtained for each method: in the case of the conventional method (based on amplitude values), it was 3.80, while for the energy method, it was 11.08. As can be seen from the data, the assessment of effectiveness is evidently different.

The study has also shown the energy method to be a more holistic approach to analyzing the effect of vibrations on the human body. In particular, the energy analysis has revealed the significant contribution of vibration energy absorbed by the human body during the startup phase – Fig. 1. It was also possible to notice that the impact of vibrations changes depended on the time of using the tool – Fig. 2 – from the startup of the biomechanical system to the steady motion phase. Based on energy simulations, it can be concluded that exposure to vibrations generated by angle grinders can, first of all, lead to pathological changes in the elastic elements of the operator or to overheating, and only to a lesser degree can disrupt blood flow.

Comparative studies in this areas will be continued. The analysis described in the article is also the first attempt at building a medium-sized discrete model of an anti-vibration glove specially designed for use with an angle grinder. Dynamic parameters of the glove will be determined along the three directions of vibrations, i.e. along the x, y and z axes.

Acknowledgements

The study was financed from a grant awarded by the Ministry of Science and Higher Education for the research project no. 02/21/DSPB/3494.

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