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Estimation of effects of type and size of rivet guns on hand–arm vibration by Tukey's Honestly Significant Difference Test

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Systematic Review

Graziella Aghilone[1] Massimo Cavacece[2]

[1] *Pharmacy and Medicine Faculty, University La Sapienza of Rome, Via Regina Margherita n.273, 00198 Rome (RM) Italy, e–mail: graziella.aghilone@uniroma1.it*

[2] *ASME Member, Department of Civil and Mechanical Engineering, University of Cassino and Lazio Meridionale, Via G. Di Biasio n.43, 03043 Cassino (FR) Italy, e–mail: cavacece@unicas.it*

Abstract Operation of hand held power tool results in exposure to hand–arm vibration, which over time lead to many health complications. We propose a methodology to evaluate protective equipment and working techniques for the reduction of vibration exposure. The methodology consists of a statistical approach to investigate the effects of rivet guns on hand–arm vibration. The statistical approach is composed of two parts: the One–Way ANOVA and a pairwise comparison technique, proposed by Tukey under the name of the honestly significant difference (HSD) test. [DOI:10.12866/J.PIVAA.2015.01.02] [1]

Keywords: Exposure reduction, Discomfort, Statistical approach

1 Introduction

Vibration exposure, caused by prolonged and regular work with powered hand–held tools, equipment or processes can have adverse effects on the hands and arms of users [Griffin, 2008]. Effective controls are necessary actions [Aghilone and Cavacece, 2013]. Workers that use such equipment may suffer various forms of damage, known as hand–arm vibration syndrome (HAVS) [Health and Executive, 1997]. Painful condition can provoke effects on blood circulation, damage to the nerves and muscles, and loss of ability to grip properly. The best known form of damage is vibration white finger (VWF), which is a prescribed industrial disease [Milosevic and McConville, 2012].

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Poor design combined with excessive use makes the hand tools a factor for the development of cumulative trauma disorders (CTDs) of the hand, wrist, and arm [Milosevic and McConville, 2012].

According to Griffin, transmission of vibration to the upper arm depends on the angle of elbow [Griffin, 2008]. In our study we consider the experiments, proposed by Kattel and conducted with the elbow flexed at 90 degrees [Kattel and Fernandez, 1999]. We analyze the values of vibrations transmitted at the neutral posture. The conclusion, obtained by [Kattel and Fernandez, 1999], can be related to the finding by Griffin. The results on transmissibility of vibration show that most of the vibrations produced by the rivet guns is absorbed by hand and fingers. This result estimated that vibrations higher than 200 Hz were not permitted to pass through to the wrist and the vibrations were localized to fingers and hand.

There are numerous factors which influence the vibration exposure, such as tool construction, tool condition, attachment used, attachment condition, material of workpiece, direction of operation, operature posture, feed–force and grip force [Rimell et al., 2008].

A concerted effort is introduced to devise methods of preventing CTDs at workplace. The aim of this study is to propose a statistical approach to investigate the effects of rivet guns on hand–arm vibration. The statistical approach develops the One–Way ANOVA and a pairwise comparison technique, proposed by Tukey under the name of the honestly significant difference (HSD) test.

2 Anova: single factor

Suppose that we have k samples or groups in our analysis. We will use the index j to indicate groups. Each group consists of a sample of size n_j. We use the index i to indicate sample element.

Suppose the jth group sample is

$$\left\{x_{1,j}, \ldots, x_{i,j}, \ldots, x_{n_j,j}\right\} \ . \tag{1}$$

The total sample consists of all the elements

$$x_{i,j} : \qquad 1 \leq i \leq n_j,\, 1 \leq j \leq k \ . \tag{2}$$

We will use the abbreviation $\bar{x}_j$ for the mean of the jth group sample; $\bar{x}$ for the mean of the total sample, called the total mean.

Let the sum of squares for the jth group be

$$SS_j = \sum_{i=1}^{N} \left(x_{ij} - \bar{x}_j\right)^2 \ . \tag{3}$$

We define the sum of squares within the groups:

$$SS_W = \sum_{i=1}^{n_j} SS_j = \sum_{j=1}^{k} \sum_{i=1}^{n_j} \left(x_{ij} - \bar{x}_j\right)^2 \ . \tag{4}$$

In addition, we can define the following degrees of freedom

$$df_w = \sum_{j=1}^{k} \left(n_j - 1\right) = n - k \ . \tag{5}$$

We define the mean square

$$MS_W = \frac{SS_W}{df_W}\,, \tag{6}$$

as the sum of the group sample variances.

For each group we define the ratio F:

$$F = \frac{MS_W\ (\text{Between Groups})}{MS_W\ (\text{Within Groups})}\ . \tag{7}$$

We indicate $df_{1,2} \geq 1$ the numbers of degrees for the numerator and denominator or the ratio that is assumed to have an F–distribution. For any particular α, F_{crit} returns the probability p $(0 < p < 1)$ that an F–distributed random variable with df_1 and df_2 degrees of freedom is greater than or equal to α–value.

3 Tukey Honest Significant Difference Test

In order to analyze the pattern of difference between means, the anova is often followed by specific comparisons, and the most commonly used involves comparing two means, called pairwise comparisons. An easy and frequently used pairwise comparison technique was developed by Tukey under the name of the honestly significant difference (HSD) test. The main idea of the HSD is to compute the honestly significant difference between two means using a statistical distribution defined by Student and called the q distribution. This distribution gives the exact sampling distribution of the largest difference between a set of means originating from the same population. All pairwise differences are evaluated using the same sampling distribution used for the largest difference. This makes the HSD approach quite conservative.

We consider two groups A and B. The idea behind this test is to focus on the largest value of the difference $(\bar{x}_{max} - \bar{x}_{min})$ between two groups A and B. The relevant statistic is

$$q = \frac{\bar{x}_{max} - \bar{x}_{min}}{s.e.}\ . \tag{8}$$

with

- $\bar{x}_{min}$ is the smallest average of groups A and B;
- $\bar{x}_{max}$ is the largest average of groups A and B.

The standard error $s.e.$ is obtained by following relation

$$s.e. = \sqrt{\frac{2 \cdot MS_W}{n_j}}\ . \tag{9}$$

The statistic q has a distribution called the studentized range q. Tables of critical values for this distribution can be found in studentized range q Table [Pearson, 2011]. The t–test is equivalent to

$$t_{stat} = \frac{(\bar{x}_{max} - \bar{x}_{min})}{s.e.} = \frac{(\bar{x}_{max} - \bar{x}_{min})}{\sqrt{\dfrac{2 \cdot MS_W}{n_j}}}\ . \tag{10}$$

Activation	Type	Size	Blows/min	Stroke [mm]	Weight [Kg]
Push-to-start	1	**L**	1440	137	1.4
		M	2160	102	1.3
		S	3960	40	1.0
Trigger-start	2	**L**	$*$	$*$	2.0
		M	$*$	$*$	1.3
		S	3960	41.3	0.99
Push-to-start	3	**L**	1725	102	1.35
		M	2000	76.2	1.3
		S	3000	58.8	1.2
Trigger-start	4	**L**	$*$	$*$	1.3
		M	$*$	$*$	1.2
		S	$*$	$*$	1.6

Table 1: Specifications of the rivet guns used in the experiment ($*$ denotes information not supplied by the manufacturer)

Note that the statistic q is related to the usual t statistic by $q = \sqrt{2 \cdot t}$. The critical value for t is given by $t_{crit} = q_{crit}/\sqrt{2}$. The value q_{crit} is function of α–value, k and df and it is obtained by studentized range q Table [Zaiontz, 2015].

If $t > t_{crit}$, there is significant difference in means μ between group A and group B. Then we reject the null hypothesis that would be

$$\begin{cases} H_0 : \mu_A = \mu_B \\ H_1 : \mu_A \neq \mu_B \end{cases} \tag{11}$$

and similarly for other pairs.

From these observations we can calculate confidence intervals, lower and upper values, in the usual way:

$$(\bar{x}_i - \bar{x}_j) \pm t_{crit}\sqrt{\frac{2 \cdot MS_W}{n_j}}\ , \tag{12}$$

or equivalently

$$(\bar{x}_i - \bar{x}_j) \pm q_{crit}\sqrt{\frac{MS_W}{n_j}}\ . \tag{13}$$

We indicate

$$\Delta_{crit} = q_{crit}\sqrt{\frac{MS_W}{n_j}} = t_{crit}\sqrt{\frac{2 \cdot MS_W}{n_j}}\ . \tag{14}$$

the critical difference.

4 Experimental investigation

A combined analysis of data from all the subjects was performed and the results of the combined analysis have been presented. Unweighted root–mean–square (RMS) acceleration in the three basicentric orthogonal axes $\mathbf{X}$, $\mathbf{Y}$ and $\mathbf{Z}$, at the wrist location, were the objective measures used to investigate the effects of rivet guns on hand–arm vibration (Table 1).

Neutral wrist postures and two applied forces (8 and 12 lb) were examined in this study. The rivet guns were categorized into four types 1–4. Each of the types had three different sizes large ($\mathbf{L}$), medium ($\mathbf{M}$) and small ($\mathbf{S}$). Vibration data were collected at neutral posture of the wrist with 8 and 12 lb of applied force for all the rivet gun type (type 1, 2, 3 and 4) and size combinations: $\mathbf{L}$, $\mathbf{M}$ and $\mathbf{S}$.

Types of rivet guns (type 1, 2, and 3) are recoilless types with a built–in mechanism to reduce vibration produced by the tool. Type 4 is a trigger–to–start activated type with no vibration dampening provisions (i.e., it is not a recoilless type).

5 Results

We distinguish the following groups of results:

- Groups $A1$, $A2$, $A3$ and $A4$ indicate the RMS values of accelerations in the case of applied force 8 lb (Table 2);
- Groups $B1$, $B2$, $B3$ and $B4$ denote the RMS values of accelerations in the case of applied force 12 lb (Table 3).

The last columns in Table 2 and in Table 3 indicate the total accelerations A_{tot}. Total accelerations A_{tot} allow us to evaluate the effects of vibrations with reference to types and sizes of rivet guns.

For the experimental investigations, we will use a method called the Analysis of Variance, also known as ANOVA. There are several types of ANOVA. For our purpose, we will be focusing on single–factor (or one–way) ANOVA. We articulate a statistical approach to compare more 2 means at the same time. Anova can be used to test the hypothesis that the means among two or more groups are equal, under the assumption that the sampled populations are normally distributed. The total accelerations A_{tot} represent the factor of ANOVA. Types and sizes of rivet guns are levels of ANOVA.

The factor, total accelerations A_{tot}, is an independent treatment variable whose settings (values) are controlled and varied in the experimental investigations. The total accelerations A_{tot} is the only factor. The analysis of variance that we will be using to analyze the effect of total accelerations is the One Way ANOVA.

Firstly, we propose summary of Anova (Tables 4 and 5). In the Table 6 and 7, $\mathbf{SS}$ is the sum of squared differences of each score from the mean of all the scores. We distinguish sum of squares between groups and sum of squares error, or sum of squares, within groups. The sum of squares error is the sum of the squared differences between the individual scores and their group means. Mean squares MS are evaluations of variance and they are computed by diving the sum of squares by the degrees of freedom $\mathbf{df}$. The $\mathbf{F}$ ratio is computed by dividing the mean square $\mathbf{MS}$ between groups by the mean square $\mathbf{MS}$ within groups. The probability value $\mathbf{p}$–value is the probability of obtaining an $\mathbf{F}$ as large or larger than the one computed in the data assuming that the null hypothesis is true. $\mathbf{F}_{crit}$ is the highest value of $\mathbf{F}$ that can be obtained without rejecting the null

ID	Rivet	RGT	RMS acceleration [g]			
			X-axis	Y-axis	Z-axis	A_{tot}
A1	1	L	2.93	7.31	5.21	9.44
		M	6.24	6.88	5.52	10.80
		S	3.29	7.17	5.50	9.62
A2	2	L	4.47	7.37	7.17	11.21
		M	6.16	7.24	5.46	10.96
		S	2.92	6.06	5.42	8.64
A3	3	L	5.16	6.86	5.63	10.26
		M	5.08	7.01	5.52	10.27
		S	5.19	7.27	5.34	10.41
A4	4	L	16.46	7.39	5.71	18.92
		M	28.61	7.16	5.81	30.06
		S	25.19	7.09	5.48	26.74

Table 2: Descriptive statistics for RMS acceleration value at the three axes at applied force 8 [lb], rivet gun type, and rivet gun size combinations

ID	Rivet	RGT	RMS acceleration [g]			
			X-axis	Y-axis	Z-axis	A_{tot}
B1	1	L	4.26	5.62	4.75	8.48
		M	6.24	6.00	5.79	10.41
		S	4.34	5.68	5.20	8.84
B2	2	L	4.96	6.77	5.06	9.80
		M	5.82	5.34	4.95	9.32
		S	4.53	5.54	4.74	8.58
B3	3	L	4.71	4.23	4.89	8.00
		M	4.96	6.55	5.22	9.73
		S	5.29	6.79	5.24	10.08
B4	4	L	13.74	7.36	4.67	16.27
		M	24.46	6.98	5.44	26.01
		S	27.41	6.67	5.29	28.70

Table 3: Descriptive statistics for RMS acceleration value at the three axes at applied force 12 [lb], rivet gun type, and rivet gun size combinations

Groups	n_j	Sum	Average	Variance	SS
A1	9	50.05	5.56	2.51	20.06
A2	9	52.48	5.83	2.10	16.81
A3	9	53.06	5.89	0.78	6.28
A4	9	108.90	12.1	82.35	658.85

Table 4: Summary of Anova: Single Factor with applied force 8 [lb]

Groups	n_j	Sum	Average	Variance	SS
B1	9	47.88	5.32	0.52	4.17
B2	9	47.71	5.30	0.46	3.69
B3	9	47.88	5.32	0.69	5.56
B4	9	102.02	11.33	76.09	608.70

Table 5: Summary of Anova: Single Factor with applied force 12 [lb]

hypothesis. Using the Table 8, there is an indication of a significant difference in the means of groups.

The critical values q_{crit} are determined from the distribution of the studentised range (Table 9 and Table 10). These Tables illustrate unplanned comparisons by Tukey's HSD in the case of applied force 8 and 12 [lb].

6 Discussion

In this study we develop a statistical approach in the following phases:

- ✓ The One–Way ANOVA describes a continuous response in terms of a single factor composed of two or more levels. It is a generalization of Student's t test for independent samples.
- ✓ The One–Way ANOVA is followed by a specific comparison. We propose a comparison between two mean values. Thus we have developped a pairwise comparison. A pairwise comparison technique was developed by Tukey under the name of the honestly significant difference (HSD) test. HSD computes the honestly significant difference between two means using a statistical distribution defined by Student and called the $\mathbf{q}$ distribution. The $\mathbf{q}$ distribution gives the exact sampling distribution of the largest difference between a set of means, originating from the same population.

Source of Variation	SS	df	MS	F	p–value	F_{crit}
Between Groups	271.66	3	90.55	4.13	0.014	2.90
Within Groups	702.00	32	21.94			
Total	973.66	35				

Table 6: Anova with $\alpha = 0.05$ and applied force 8 [lb]

Source of Variation	SS	df	MS	F	p–value	$\mathbf{F}_{crit}$
Between Groups	244.77	3	81.59	4.20	0.013	2.90
Within Groups	622.13	32	19.44			
Total	866.90	35				

Table 7: Anova with $\alpha = 0.05$ and applied force 12 [lb]

If	Then
$\mathbf{F} > \mathbf{F}_{crit}$	Reject the null hypothesis
$\mathbf{F} < \mathbf{F}_{crit}$	Accept the null hypothesis
$\mathbf{p}$–value $< \alpha$	Reject the null hypothesis
$\mathbf{p}$–value $> \alpha$	Accept the null hypothesis

Table 8: Interpreting the ANOVA One Way test results

Comparison	mean	std error	t_{stat}	q_{crit}	$q_{crit,adj}$	sig	lower	upper
A3-A4	6.20	2.21	2.81	3.83	2.71	yes	0.22	12.19
A2-A3	0.064	2.21	0.03	3.83	2.71	no	-5.92	6.05

Table 9: Unplanned comparisons by Tukey's HSD in the case of applied force 8 [lb]

Comparison	mean	std error	t_{stat}	q_{crit}	$q_{crit,adj}$	sig	lower	upper
B3-B4	6.01	2.08	2.89	3.83	2.71	yes	0.38	11.65
B2-B3	0.02	2.08	$9.09 \cdot 10^{-3}$	3.83	2.71	no	-5.61	5.65

Table 10: Unplanned comparisons by Tukey's HSD in the case of applied force 12 [lb]

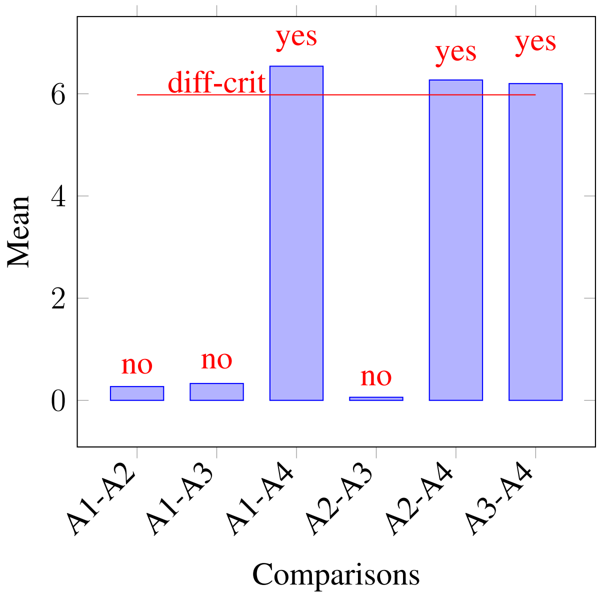

Figure 1: Planned comparisons by Tukey's HSD in the case of applied force 8 [lb]

According to the experimental analysis, in the $\mathbf{X}$–axis, $\mathbf{Y}$–axis and $\mathbf{Z}$–axis, rivet gun type (RGT), rivet gun size (RGS), and the interaction between RGT and RGS offered significant evaluations on unweighted RMS values of accelerations. By comparison of the RMS values of acceleration we can obtain important remarks evaluating the following cases of applied force:

- In the case of 8 lb of applied force, the RMS values of accelerations of type 4 is significantly different from RMS value of acceleration of types 1, 2 and 3 in the three basicentric orthogonal directions. There were no significant differences of accelerations for $\mathbf{L}$, $\mathbf{M}$ and $\mathbf{S}$ sizes in ID $A1$, $A2$ and $A3$ for the $\mathbf{X}$–axis, $\mathbf{Y}$–axis and $\mathbf{Z}$–axis. The values of A_{tot} accelerations of types 1, 2 and 3 are about 8–10 g. The values of A_{tot} accelerations of types 4 are about 18–30 g. The RMS values of acceleration of type 4 are significantly different from RMS values of acceleration of types 1, 2 and 3 in the three basicentric orthogonal directions. Thus, type 4 produces high vibration.

- In the case of 12 lb of applied force, we can confirm the conclusions of the previous case. The values of A_{tot} accelerations of types 1, 2 and 3 are about 8–10 g. The values of A_{tot} accelerations of types 4 are about 16–28 g. We can confirm that type 4 produces high vibration.

Tukey HSD test allows us to elaborate the deviations of average values of groups. Statistical investigations offer the following results:

◦ In the case of 8 lb of applied force, we can obtain the average of each group: $A1$, $A2$, $A3$ and $A4$. Secondly, we can derive the successive differences of average values of pairs: $A1$–$A2$, $A1$–$A3$, $A1$–$A4$, $A2$–$A3$, $A2$–$A4$, $A3$–$A4$. We obtain the following differences:

$$\begin{aligned} &\text{Average}_{A1-A2} = 0.27 \quad \text{Average}_{A1-A3} = 0.33 \quad \text{Average}_{A1-A4} = 6.54 \\ &\text{Average}_{A2-A3} = 0.06 \quad \text{Average}_{A2-A4} = 6.27 \\ &\text{Average}_{A3-A4} = 6.20\,. \end{aligned} \tag{15}$$

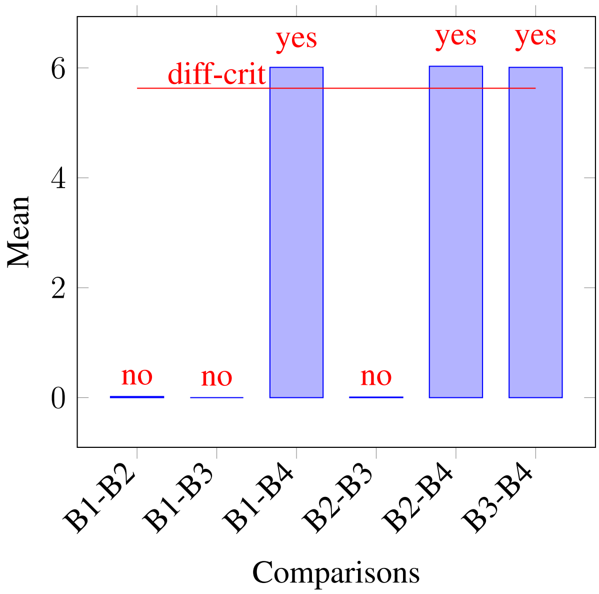

Figure 2: Planned comparisons by Tukey's HSD in the case of applied force 12 [lb]

We can deduce $\Delta_{crit} = 5.98$ by Eq.(14). From Eqs.(15) it follows that

$$\begin{cases} \text{Average}_{A1-A4} = 6.54 > \Delta_{crit} = 5.98 \\ \text{Average}_{A2-A4} = 6.27 > \Delta_{crit} = 5.98 \\ \text{Average}_{A3-A4} = 6.20 > \Delta_{crit} = 5.98\,, \end{cases} \tag{16}$$

differences respect to group 4 are greater than the critical value Δ_{crit}. We can reinforce the proposition that type 4 produces high vibration in the case of 8 lb of applied force (Figure 1).

- In the case of 12 lb of applied force, we can obtain the average of each group: $B1$, $B2$, $B3$ and $B4$. Secondly, we can derive the successive differences of average values of pairs: $B1$–$B2$, $B1$–$B3$, $B1$–$B4$, $B2$–$B3$, $B2$–$B4$, $B3$–$B4$. We obtain the following deviations:

$$\begin{aligned} &\text{Average}_{B1-B2} = 0.02 \quad \text{Average}_{B1-B3} = 0.0 \quad \text{Average}_{B1-B4} = 6.01 \\ &\text{Average}_{B2-B3} = 0.01 \quad \text{Average}_{B2-B4} = 6.03 \\ &\text{Average}_{B3-B4} = 6.01\,. \end{aligned} \tag{17}$$

We can deduce $\Delta_{crit} = 5.63$ by Eq.(14). From Eqs.(15) it follows that

$$\begin{cases} \text{Average}_{B1-B4} = 6.01 > \Delta_{crit} = 5.63 \\ \text{Average}_{B2-B4} = 6.03 > \Delta_{crit} = 5.63 \\ \text{Average}_{B3-B4} = 6.01 > \Delta_{crit} = 5.63\,, \end{cases} \tag{18}$$

deviations respect to group 4 are greater than the critical value Δ_{crit}. We can conclude that type 4 produces high vibration in the case of 12 lb of applied force (Figure 2).

Based on the recommendations of ISO 5349, in terms of exposure times, users should not be exposed to type 4 rivet guns for more than 30 min per day. However, it is safe to use the other types for 4–8 h per day [Kattel and Fernandez, 1999].

7 Conclusion

Rivet guns type 1, 2, and 3 are efficient in cases of force applied 8 lb and 12 lb. Rivet guns type 4 reaches high values in cases of force applied 8 lb and 12 lb.

Size is another factor influencing the accelerations. It is plausible that the large–size produces higher acceleration values than the smaller sizes. Rivet guns type 1, 2, and 3 reduce vibrations with rivet gun sizes **L**, **M** and **S**. Type 4 had the highest acceleration values with rivet gun sizes **L**, **M** and **S**.

When the results of the effects of type and size of rivet guns are combined, statistical methodology emphasizes that the large size of type 4 (conventional) had the largest effect on the hand–arm system with respect to the amplitude of vibration transmitted. Based on this result, it is concluded that the large size of type 4 rivet gun was the worst among all the rivet guns under study. Thus, the users of these types and sizes of rivet guns need appropriate controls to be protected against the risk of developing vibration related musculoskeletal disorders.

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