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Evaluation and Optimization of Handle Design Parameters of a Grass Trimming Machine

Zulquernain Mallick

School of Mechanical Engineering, Universiti Sains Malaysia, Nibong Tebal, Malaysia

The grass trimming machine is a widely used agricultural machine for cutting grass by the roadside and in other areas in Malaysia. Hand–arm vibration (HAV) syndrome is very common among workers operating power tools and performing similar work for extended periods. Grass trimming involves the use of a motorized cutter spinning at high speed, resulting in high levels of HAV among its operators. The existing D-shape handle causes HAV-related stress and operational load in operators. This research proposes a new design of a handle of the grass trimming machine. When this new design was compared with the old one, it was found that the new handle resulted in 18% lower HAV. To find the lowest HAV, 3 critical parameters of the new handle (length, angle and material of the cap of the handle) were optimized using the Taguchi quality tool. Appropriately selected parameters of the new handle significantly reduced the occurrence of HAV among grass trimmers.

grass trimming machine hand–arm vibration design parameters optimization D-shape handle

1. INTRODUCTION

The risk of developing hand–arm vibration (HAV) syndrome has been reported to depend on the magnitude of vibration transmitted to the tool handle, on the mechanical coupling between the hand and the handle, on the duration of vibration exposure and on user sensitivity to HAV [1, 2, 3]. On the basis of a synthesis of the widely varying reported data sets, the International Organization for Standardization defined the range of free driving-point mechanical impedance of the human hand–arm system under vibration in the 20–500 Hz range along the three translational axes of a basicentric co-ordinate system, namely, X_h, Y_h and Z_h [4].

The Health and Safety Guide set the vibration level to be limited to 5.5 m/s^2 for 8 hrs of daily exposure and action limit of 2.5 m/s^2 [5]. Even a lower level of vibration can produce some numbness under prolonged exposure. Tudor demonstrated that sound design principles when applied to an existing trimmer can be used to reduce the acceleration level. This is done by adopting a design which reduces radial and ulnar deviation as well as palmar flexion, eliminates wrist movements and the operator adopting a more natural stance [6]. The contribution of grip force is considerably larger than that of push force, with a larger diameter of the handle causing a higher level of vibration to be transmitted to the hand–arm system [7]. The effects of machine vibration on the hand–arm of the operators have been studied by many researchers. Giacomin, Shayaa, Dormegnie, et al. [8] studied the effect of steering-wheel rotational vibration on the driver's annoyance and suggested new frequency weighting. Wearing gloves while using a pneumatic screwdriver can

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Correspondence and requests for offprints should be sent to Zulquernain Mallick, School of Mechanical Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Malaysia. E-mail: <zmallick2002@yahoo.co.in>.

reduce hand-transmitted vibration [9]. The most common occupational risk factor cited in the literature is upper extremity posture (wrist, elbow, shoulder) [10, 11, 12, 13]. The actual disease mechanism associated with the development of carpal tunnel syndrome is not fully understood, but it is believed that awkward posture, excessive force and frequent repetitions impose mechanical and physiological stress on the soft tissue of the upper extremity, e.g., wrist deviation (flexion, extension, ulnar and radial deviation) [14]. Tool reaction force and upper limb muscle contraction are related and result in eccentric dynamic muscle contraction [15, 16, 17].

A number of studies have reported that hand–arm posture has a detrimental effect in terms of generating large static forces [18, 19, 20]. In the present D-shape handle design (Figure 1) the hand–arm posture becomes almost straight during a grass trimming operation, which is a source of elevated HAV. Therefore, the objective of this study was to evaluate the performance of a grass trimming machine in terms of HAV by proposing a new handle design. Different values of the design parameters under investigation were adopted by the operators during a trial session and it was difficult to estimate the suitability of a particular value for minimizing HAV. In view of the above, and to determine the levels of parameters that would minimize HAV, a quality tool (the Taguchi method) was adopted.

2. ERGONOMIC DESIGN CONSIDERATION

Ergonomic risk factors were usually found when hand tools were being used. Hand tool design/redesign is, therefore, an essential issue in reducing hand/wrist discomfort and injuries [21, 22, 23, 24, 25]. In the case of the present design of the grass trimming machine, right-handed operators use their right hand for the pistol grip main handle, while the left hand grips a D-shape handle, which can be adjusted along the axis of the drive shaft (Figure 2). Manipulation of the cutter plane results from the rotation of the left wrist, elbow and shoulder joint. The wrist of the left hand is generally bent in palmar flexion and manipulation of the cutting plane generally moves the wrist from ulnar to radial deviation. Palmar flexion is defined as rotation of the hand about the wrist in the direction of the palm, while in ulnar and radial deviation the hand rotates about the wrist to the right or left. From Figure 2 it is clear that to operate the D-shape handle the operators were required to deviate their hands from the neutral position to a larger extent than in the new design. Therefore, one can conclude that the old shape is more stressful especially if used for a long time. For any wrist position other than neutral, grip strength is reduced [26]. The situation becomes more complicated when vibration is also present. Vibration increases grip

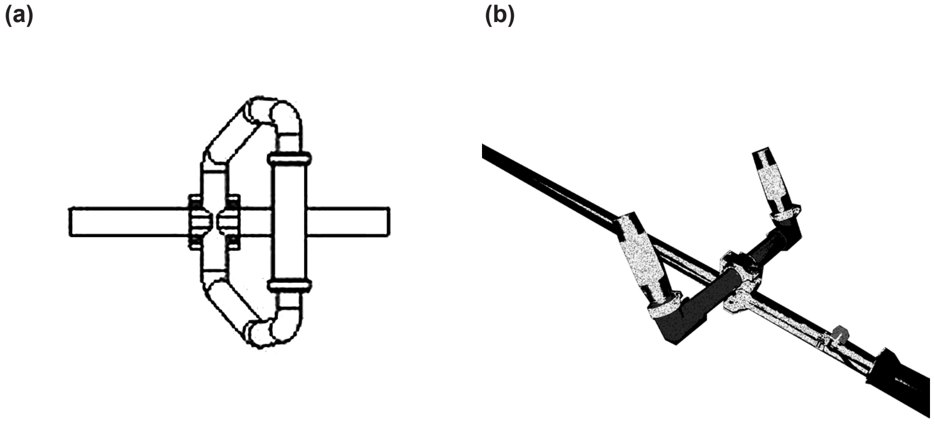

Figure 1. (a) The original D-shape handle, (b) the new design with an acrylonitrile butadiene styrene pipe.

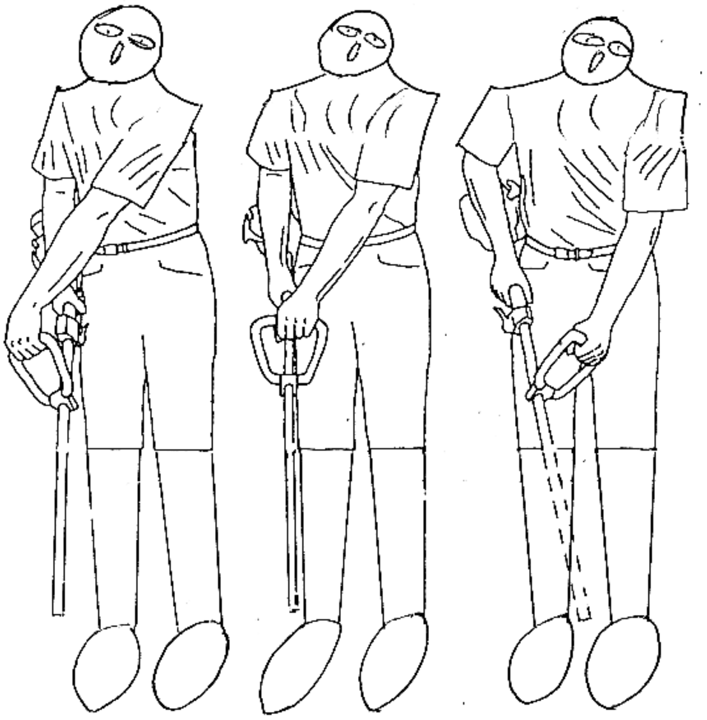

Figure 2. Wrist movement showing deviation of the wrist from ulnar to radial in the D-shape handle.

force [27]. The D-shape handle, therefore, has a nonergonomic design. In the present design, the D-shape handle is made of hard plastic, 2.5 cm in diameter. The new handle design is shown in Figure 1. It is expected that the new design will be effective for both left- and right-hand operators.

3. METHODOLOGY

3.1. Data Collection

The 10 healthy subjects who participated in this study were asked to stabilize the speed of the cutter at a particular throttle setting for one minute. The speed of the rotating head was then noted. A miniature triaxial accelerometer (Brüel & Kjær type 4506, Denmark) was mounted on the back of the palm of the subject holding the D-shape handle. The front end of a Brüel & Kjær type 4506 accelerometer in general has two connection options, whole-body and HAV. In this case the HAV front end was used (Brüel & Kjær type 1700A) and this was connected to a modular sound level meter also used as data storage and display (Brüel & Kjær Observer type 2260) and later downloaded to a personal computer for further analysis. The baseline value of HAV was measured for all three axes of the D-shape handle (Table 1). In a similar way the level of HAV for all nine combinations of parameters (Table 2) was determined using the same grass trimmer speed, i.e., 4000 rpm, span frequency of 156 Hz and centre frequency of 78 Hz with the new handle. The three parameters selected for this study were

TABLE 1. Experimental Layout Using L9 Orthogonal Array

	Parameter Level		
Experiment No.	**A**	**B**	**C**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

Notes. A—length of handle, B—angle of handle, C—material of cap of handle.

TABLE 2. Result of Analysis of Variance (ANOVA) for Vibration

Symbol	Parameter	*df*	*SS*	*MS*	*F*	Contribution (%)
A	length of handle	2	12.0403	6.0202	14.7958	26.2387
B	angle of handle	2	14.0843	7.0422	17.3075	30.6930
C	material of cap of handle	2	18.9493	9.4746	23.2858	41.2949
Error		2	0.8138	0.4069		1.7734
Total		8				100

TABLE 3. Operating Parameters and Their Levels

Symbol	Parameter	Level 1	Level 2	Level 3
A	length of handle (cm)	30	40	50
B	angle of handle (°)	0	45	90
C	material of cap of handle	wood	aluminum	nylon

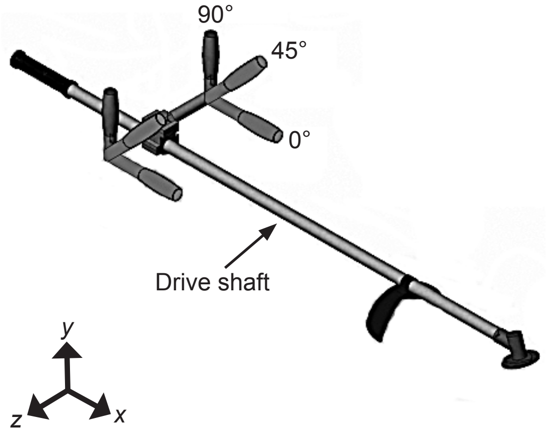

Figure 3. Different values of handle angles in the new handle design (0°, 45° and 90°).

length, material (acrylonitrile butadiene styrene) and angles of the handle. Their levels are shown in Table 3, while the angles explored in this study are shown in Figure 3. The overall result for the new handle is shown in Table 1. Before the experiment the subjects were briefed about the experiment and a trial session was run to ensure that they knew how to use the equipment correctly.

3.2. Determination of Optimal Cutting Parameters

An orthogonal array was used to reduce the number of experiments that were to determine the optimal cutting parameters. The results of the grass cutting experiments were studied with the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA). On the basis of those results, optimal cutting parameters that would minimize HAV were determined. Subsequently a confirmation test was carried out to verify the results. In this study an L9 orthogonal array was used (Table 2).

4. RESULTS AND DISCUSSION

The results were obtained by observing the level of HAV for different combinations of operating parameters of the new handle. All subjects performed the grass trimming operation for all the combination (Table 1). Average values were noted in all three directions, i.e., *X*, *Y* and *Z*.

4.1. Main Effects

To achieve the main effect, average HAV produced by the grass trimming machine, according to the experimental plan of the orthogonal array, at various levels of parameters (Table 1) was calculated; the results are shown in Table 4.

The S/N graph in Figure 4 shows that the best combination of parameters and their levels for optimum HAV-related performance for the new handle design was A1 B1 C3. Therefore, those parameters and their levels will be responsible for minimum HAV affecting operators of grass trimming machines.

TABLE 4. Average Vibration Levels in *X*, *Y* and *Z* Directions When an Acrylonitrile Butadiene Styrene Pipe Holder Was Used

				Results			
Experiment No.	**Length (cm)**	**Angle (°)**	**Material**	X	Y	Z	$(X^2+Y^2+Z^2)^{0.5}$
1	30	0	wood	0.862	0.538	2.117	2.3480
2	30	45	aluminum	2.430	0.989	3.432	4.3500
3	30	90	nylon	0.762	0.738	1.919	2.2080
4	40	0	nylon	0.910	0.816	2.490	2.7290
5	40	45	wood	2.312	1.410	3.404	4.4100
6	40	90	aluminum	2.348	1.604	2.093	3.5310
7	50	0	aluminum	2.410	0.989	3.352	4.2000
8	50	45	nylon	1.766	0.886	2.612	3.2360
9	50	90	wood	2.430	0.989	3.432	4.3451
Initial cutting parameters	—	—	—	1.887	1.430	2.573	3.4970

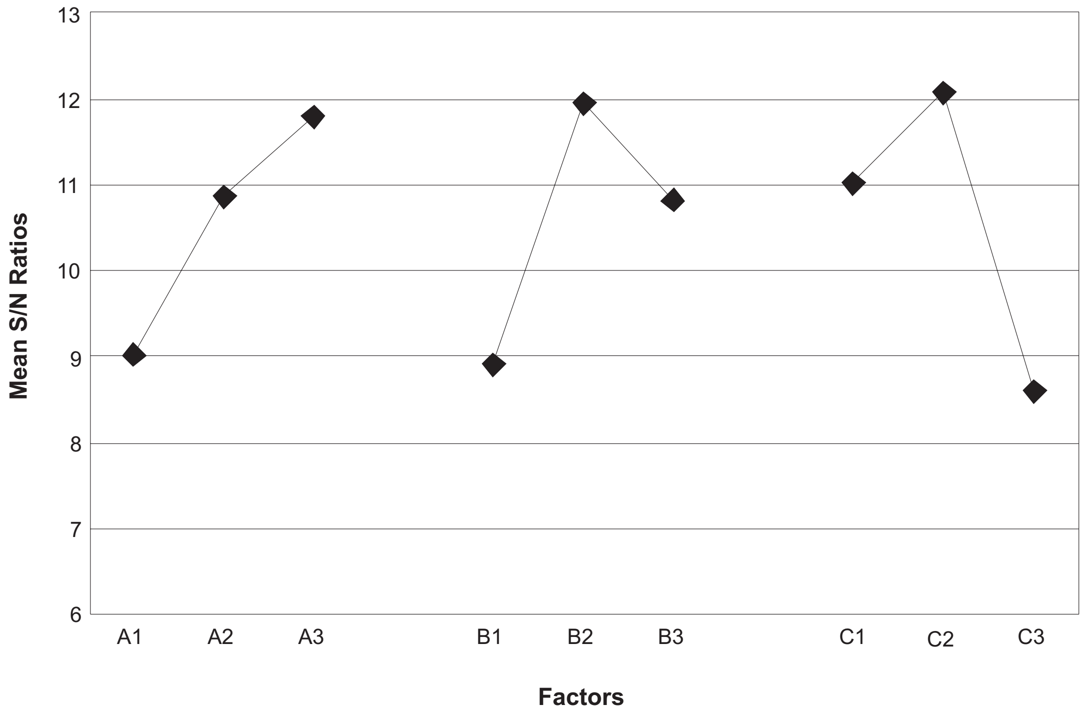

Figure 4. Combined S/N graph for vibration performance for all the design parameters considered in the study. *Notes.* S/N—signal-to-noise.

4.2. ANOVA

Table 2 shows the result of ANOVA for the design parameters of grass trimming machines. All three parameters, i.e., length of handle, angle of handle and material of the cap of the handle, were significant in terms of HAV. From the value for F ratio for different parameters (Table 2), the parameters length of the handle and angle of the handle are statistically significant at the 90% level of confidence, while the parameter material of the handle is significant at the 95% level of confidence. Therefore, on the basis of the main effect and ANOVA, the optimal parameters for achieving minimum vibration from the grass trimming machine were the length of handle at level 1, the angle of the handle at level 1 and the material of the cap of the handle at level 3.

The result indicates that the old and new designs of the handle are not equal in terms of generating HAV. The new design produces reduced hand–arm vibration. It is apparent from the proposed design of the handle that both hands of the operators will be symmetrically used to hold the two ends, which will reduce the level of vibration as compared to the original D-shape handle. On the other hand as the flexion angle has a value greater than 90°, it will have less influence on the hand–arm system in terms of vibration as compared to the original handle, in which the operator's arm is completely stretched. The findings of the present work are supported by many studies. On the basis of the measurements performed with five different elbow angles and exposed to X_h-axis vibration in the 4–1 000 Hz frequency range, Burström and Lundström showed a considerable effect of the elbow angle on the average absorbed power, specifically in the 4–50 Hz frequency range [28]. Another study reported that the flexion of the elbow affected the average absorbed power of the hand–arm system; the highest power absorption was reported for the 180° elbow flexion (extended arm) [29]. Yet another experiment reported that low-frequency apparent mass magnitude of the hand–arm system with an extended forearm was approximately three times that of a system with a flexed forearm [30]. In the proposed design, the shoulder–elbow angle is reduced in comparison to the original handle. Table 5 shows that the difference between the experimental result and the estimated result is only 0.12 m/s^2. Thus the two values are very close and strongly correlated, as the error is only 3.43%.

TABLE 5. Results of Confirmation Test for Vibration

Parameters	Initial Parameter	Optimal Parameters Prediction	Optimal Parameters Experiment
Level		A1 B1 C3	A1 B1 C3
Vibration (m/s^2)	3.49	3.37	2.76
S/N ratio (dB)		10.56	8.84

Notes. Reduction in vibration: 3.49 – 2.76 = 0.73 m/s^2.

5. CONCLUSION

On the basis of the results of this study the following conclusions may be drawn.

- A proper selection of the parameters of a new handle design can attenuate HAV.
- The new handle design resulted in 18% lower HAV.
- Among the three handle design parameters considered in this research, the material of the cap of the handle emerged as the highest contributor to HAV generated in the grass trimmers, followed by the angle and length of the handle.
- The levels of factors that produce lowest HAV are length of the handle (A) at level 1 = 30 cm; angle of the handle (B) at level 1 = 0°; material of the cap of the handle (C) at level 3 = nylon.
- An even better design of the handle may be possible once more parameter levels are explored in future research.

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