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Computer Based Welding Training System

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A computer-based welding training system to be used in welding shops has been developed to facilitate and to substantially enhance the basic skills in shielded metal arc welding. The process is begun by creating a tool that captures the skill performance from the intermediates group into coded knowledge. Afterwards a software tool shows how to transfer knowledge by using the principles of learning feedback. Sixty novices were assigned to use the training system with the T-weld welding position. The results show that novices could significantly increase their welding skills after using the feedback in arc length, work angle and travel angle, while the performance of welding speed is unimproved, all the three inspectors rated the quality of welding in feedback group higher than non-feedback group.

Keywords: Welding skill, Training System, Shield Metal Arc Welding, Training software, Hardware sensors.

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1. INTRODUCTION

Welding is a highly skilled operation that requires precision in order to achieve its tasks. Learning, memorizing rules and instructions is necessary; however, this idea is insufficient when carrying out the task of welding effectively. To become an expert welder, one must go through a lengthy apprenticeship. This enables novices to acquire the fine precisions that expert welders possess. Throughout their training, novices are required to learn about the precise ways in which each task component interacts with one another in order to achieve a flawless joint. A number of welding training systems have been developed to assist and to speed up this process. None, however, have incorporated real-time instant capturing and assessed all of the key components for good welding.

The welding skill has four key parameters: arc length, welding speed, travel angle and work angle. The arc length is the distance from the electrode tip to the part to be welded. A welding engineer's objective is to keep the electrode at a constant distance from the part's surface with a sufficient gap to avoid stubbing out the flame. The welding speed is the speed of travel of the torch over the part and is controlled by hand. The travel angle is the angle of the electrode as it travels along the weld path. For most welding applications, the travel angle is 15 – 30 degrees. The work angle is the angle in which the electrode is pointing at the weld joint. Basic positions of welding such as bead-on-plate (welding on one piece of metal) and T-welds (joining two pieces of metal at right angle) require a work angle of 90 and 45 degrees respectively. All parameters are substantially controlled by hand.

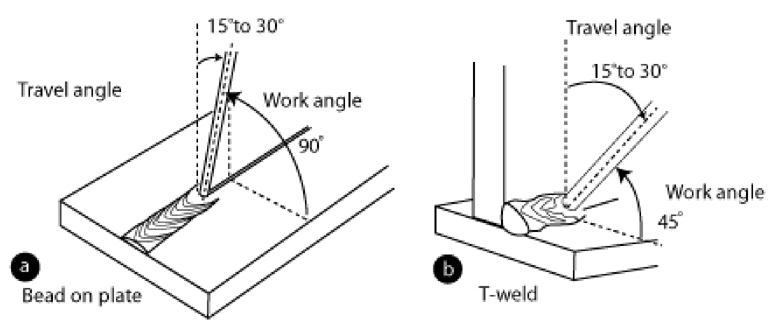

Figure 1. A Diagram Illustrating the Two Welding Positions a) Bead-on-Plate and b) T-Weld

Problems that novices tend to encounter in welding can be roughly divided into three areas. Arc length is too long or too short resulting in arc chokes and spattering. Also, welding speed is too fast or too slow, the outcome is in incompletion of the fusion and slag inclusion. For the travel angle or work angle of electrode which is too wide or too narrow, it results into irregular control and poor penetration along edges (Kitpipak, 1998).

For the past decade, a number of training devices have been invented in order to hand down the knowledge and skill to novices. Two types of learning tools have been developed: virtual training (Aiteanu, 2003), (Donald et al., 1990), (Fast, 2004) and computer-assisted training device (Koji et al., 2004). One of the disadvantages of training device is that the factors such as heat, brightness of the arc and welding speed reduce the performance of welding skills. Conventionally, trainee performance can be assessed by considering the four key parameters together with the quality of the outcome. Yet, only two parameters, namely work and travel angles, have widely accepted recommended guidelines. There are no recommended guidelines for arc length and welding speed. By being able to define ranges of acceptable limits of performance for four key skills parameters, one would be able to approach the training process systematically.

The aim of this research is to design and develop a computer-based hands-on experience welding training system with real-time voice feedback that can provide guideline for all of the four key parameters. The study is divided into two phases with the following objectives:

Device development process

- Capture relevant data pool from the expert's performance
- Determine tolerance limits as a benchmark for novice's training
- Develop voice feedback mechanism for trainees
- Develop the visual interface of the system for instructors

Device evaluation trials

- Whether the training system is usable in a real-time environment
- Whether there is a significant difference in skill improvement with the use of the developed training system
- Whether the outcome of the welding is acceptable.

2. DEVICE DEVELOPMENT PROCESS

The device can be divided into four components: data logger of experts' performance, database of experts' performance, voice feedback mechanism and visual interface. The interaction of these four components is illustrated in Figure 2.

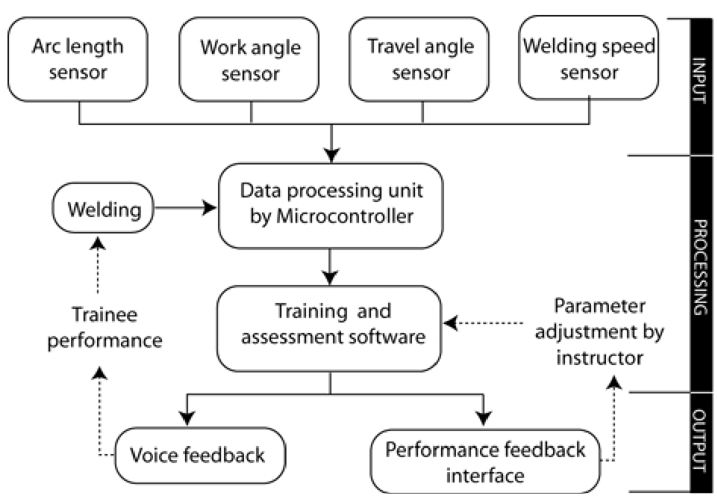

Figure 2. An Overview of the Training System

2.1 Data logger of experts' performance

The purpose of building a data logger was to decode and record the four key parameters from experts' performance using sensors to form the performance database used as a benchmark for novice training (see Figure 3). The sampling rate of data logger is 11.5 Hz.

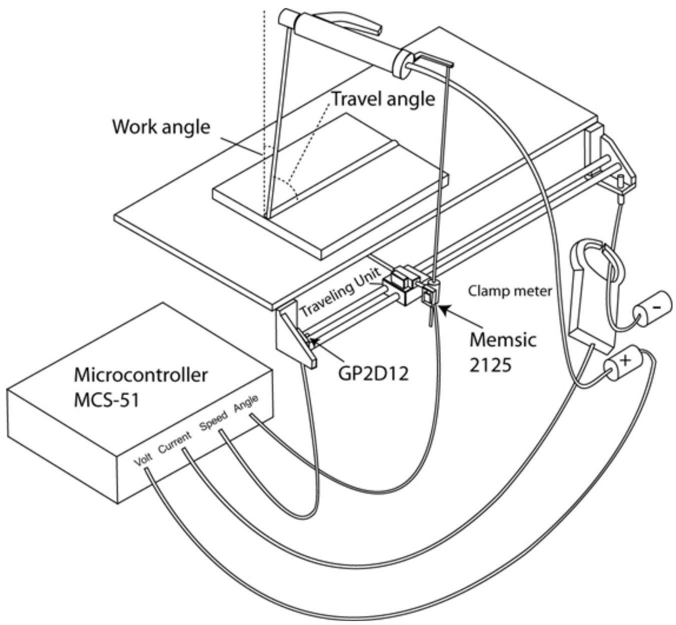

Figure 3. Data Logger for Capturing the Four Welding Parameters Showing Bead-on-Plate Welding Position

Parameters such as welding speed, voltage, amperage and angle were decoded using electronic sensors. As seen in Figure 3, an infrared sensor (GP2D12) was used to measure welding speed. The sensor was placed on the traveling unit used to detect the movement of the electrode holder. A voltage sensor (clamp meter) was used to measure arc length. An angle sensor (accelerometer sensor– Memsic 2125) measured work and travel angles. Whenever an electrode holder was rotated by hand, the accelerometer sensor detected both angles. All of the data detected from the sensors were sent to the Microcontroller *(*MCS-51*)* via a serial port to be processed using C programming on a personal computer.

2.2 Development of the performance database

The data from the data logger presented the experts' performance of four parameters. For demonstration purposes, performances of six Thai expert and six Thai intermediate welders were decoded using the data logger designed for this purpose. The expert welders were Thai gold medalists from Welding Olympics. All of the intermediate welders were qualified welders with more than three years experience. Each of the welders was requested to perform four sets of welding. Each set had three welding sessions. There were altogether twelve welding sessions. The average was taken from both intermediate and expert groups shown in Figure 4. The average of arc length from experts and novices was nearly the same (26 – 32 volts). Travel angle from the expert was considerably stable, however, it is high at 40 degrees. On the other hand, intermediates' performance seemed to control well the angle at the level of 25-30 degrees after 80 seconds. This value was associated with the recommendation guidelines (15 – 30 degree). In the same way, work angle from intermediate was followed the guidelines at 45 degrees while experts' were higher to 55 degrees. The average welding speed of expert was more stable than the intermediate but the value was approximately 20 – 40 cm/min.

Table 1. Results from both experts and intermediates

	Parameters for T-Weld Position			
	Average arc length	Average work angle	Average travel angle	Average welding speed
Expert	25.6 volts STD = 1.4875	54.39° STD = 0.64	40.33° STD = 0.77	27.74 cm/min STD = 7.17
Intermediate	30.4 volts STD = 1.44	47.39° STD = 1.44	29.91° STD = 2.55	34.89 cm/min STD = 2.55
Recommended guidelines	N/A	45°	15-30°	N/A

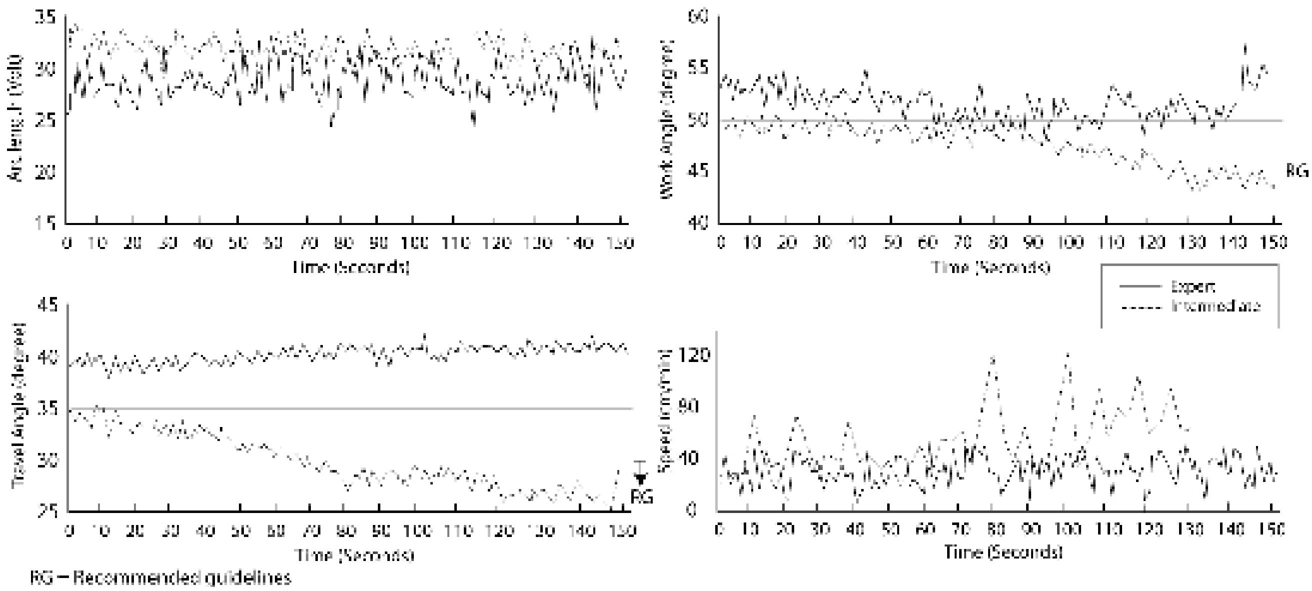

Figure 4. Expert and Intermediate performance of T-weld

In conclusion, the values obtained from the intermediate group were closer to the recommended guidelines for the travel and work angles (29.91°and 47.39°, respectively). Expert group's standard deviation is consistent in term of work angle and travel angle (see Table 1). They used wider angle than the recommended guidelines since they have special technique of welding. The recorded values gained from expert's group were difficult for the novice to practice at the first time. Therefore, the data from the intermediate group were used instead of an expert group to calculate the control chart (Edward, 1987).

To maintain quality control and screen out unacceptable mistakes, upper and lower tolerance limits were defined. These are referred to as control charts (Edward, 1987). The control chart or tolerance limits of the welding performance database created in this study were calculated by using the mean, plus or minus, three standard deviations (a standard method of calculating tolerance limits for novice level). The values are presented below in Table 2. The welding standard of work angle was used. The margin of error was plus or minus five degrees.

Table 2. Parameters and tolerance limits used for training system

	Parameters for T-Weld Position			
	Arc length	Work angle	Travel angle	Welding speed
Value	30.4 volts	45°	15-30°	34.89 cm/min
STD	1.44 volts	-	-	2.55 cm/min
3STD	4.2 volts	-	-	7.65 cm/min
Tolerance	29-34.6 volts	40°-50°	15-30°	32.34-42.54 cm/min

2.3 Voice feedback mechanism

Feedback is critical for any form of learning or skill acquisition (Wicken et al., 1999). Voice feedback provided human-like verbal feedbacks on novice's performance. These verbal feedbacks were modeled on actual feedbacks from instructors. The flowchart in Figure 5 presents the mechanism of voice feedbacks for the four parameters.

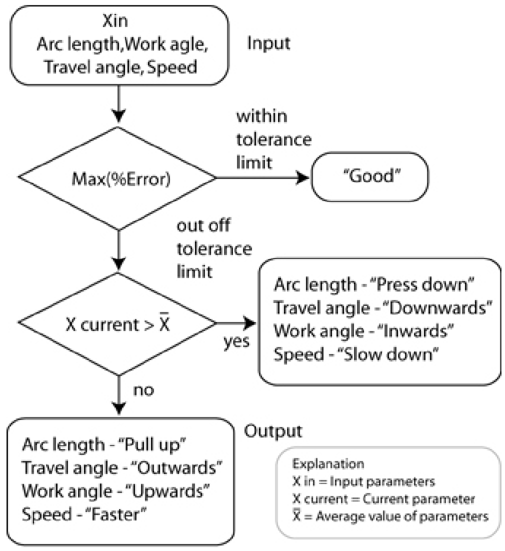

Figure 5. Flowchart of voice command mechanism

A trainee's performance on each of the four parameters compared with the range within the corresponding tolerance limits. If the actual performance value was higher than the upper tolerance limit, then voice feedbacks such as 'Slow down', 'Downward', 'Inward', and 'Press down' would be given. On the other hand, if the actual performance value was too low (lower than the lower tolerance limit), then the following voice feedbacks would be given, depending on which parameter was being violated: 'Faster', 'Upward', 'Outward', and 'Pull up'. If the recorded parameters were within the range of tolerance, the voice command given would be 'Good'. In order to prioritize feedbacks from the training device, a percentage error was used. Algorithm 1 shows the calculation of this percentage error.

$$\% \text{ Error} = \frac{\text{QUOTE} - Xin}{2KS} \qquad \text{... (1)}$$

EQ\x\to (X)

Where QUOTE = An average value of arc length, travel angle, and welding speed from intermediates,
Xin = Input parameter from novice's performance, *K* = Tolerance factor i.e. K = 3, S= Standard deviation

2.4. Performance feedback software interface

The software interface provided two sections: theory and practical sessions. It was designed for trainees to learn both theory and practice and for instructors to monitor and evaluate their students' performance.

2.4.1. Theory Session

For the lecture portion, the device was designed to incorporate a pre-training lesson equipped with a video demonstration and virtual training. During training simulation, trainees could simulate the movement of welding without turning on the welding machine as shown in Figure 6a.

2.4.2 Practical Session

For the practical session, both instructors and trainees could see the trainee's performance index and a summary of performance by looking at gauges and bar graphs displayed on the interface as illustrated in Figure 6b. The gauges were designed to provide instructors with tools to monitor and evaluate trainee's performance on all parameters in real-time. The feedback delay performed in three seconds. Instructors set the tolerance limits to adjust the degree of difficulty of training.

The bottom half of the interface provided a real-time evaluation of the performance. In the bar graph, the software informed trainees whether their performance was within or outside the tolerance limits. If trainees were out of the range, a voice command would be activated. When the session was ended, the final evaluation would be presented showing the total percentage achieved.

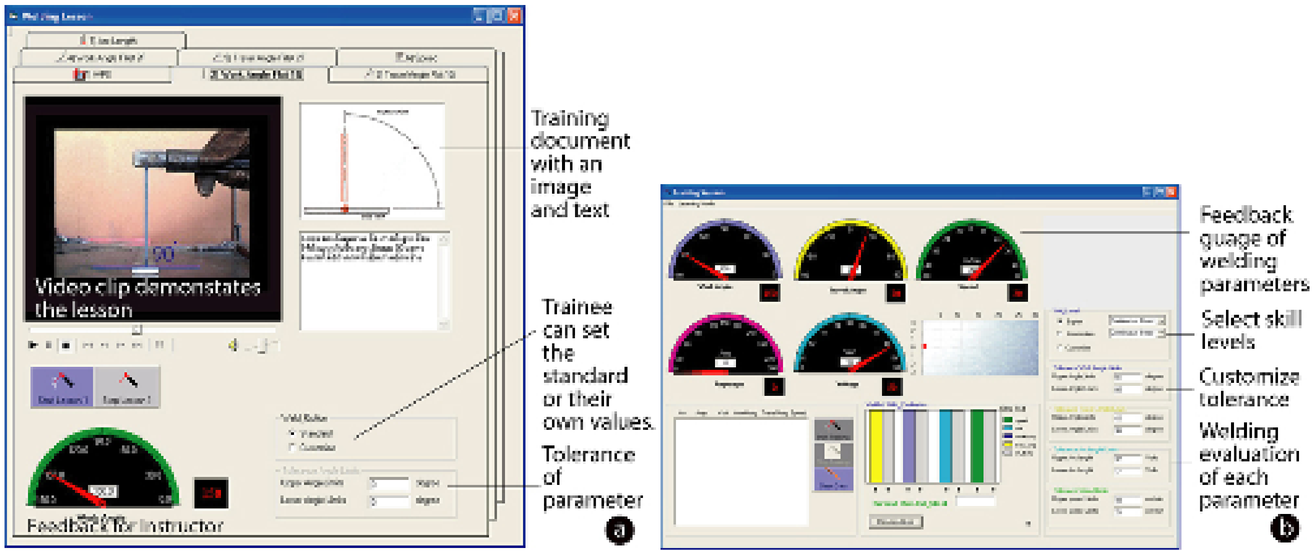

Figure 6. **a)** the interface for the theory and training simulation session **b)** The performance feedback interface

3. DEVICE EVALUATION TRIALS

3.1 Hypothesis

Null-Hypothesis (H01): There is no significant difference between non-feedback group and feedback group in terms of performance.

Null-Hypothesis (H02): There is no significant difference between non-feedback group and feedback group in terms of welding quality.

3.2 Method

3.2.1 Experimental Design

In order to test the hypotheses stated above, an experiment with independent samples design (H01: performance) and an expert assessment (H02: welding quality) were carried out. There were two conditions in the experiment: a control group where subjects performed the welding task without voice feedback (non-feedback group) and a test group where real-time voice feedback mechanism was activated (feedback group). Each subject was asked to perform four test sets of T-weld welding position. Every test set consisted of three welding sessions. There were 12 welding sessions in total. The four parameters were recorded using the training system. During expert assessment, three welding instructors performed visual inspections on all 60 welded metals from the final round and assessed the quality using a five-point rating scale.

3.2.2 Subjects

A total of sixty subjects volunteered to participate in the trial with age range between eighteen and twenty one years old and an average age of twenty one years old. The subjects were freshmen in the field of Industrial Education and Industrial Engineering at King Mongkut's University of Technology Thonburi (KMUTT), Thailand. All subjects had no welding experience and they were randomly allocated into two groups of thirty subjects each.

3.2.3 Material and Equipment

A welding tool and 4,200 pieces of welding metals size 8 x 15 x 1 cm. were used by the subjects to perform the tasks. The data logger was used to record subject's performance for both conditions, and the training system was involved to train the subjects and display the values of the four parameters recorded. The recorded values were compared to the corresponding range of acceptable limit. The real-time voice feedback mechanism was deactivated for the control group and activated for the test group. A five-point rating scale (1 = Fail and 5 = Excellent) was used by the welding instructors to carry out an expert assessment of the finished product.

3.2.4 Procedure

The trials were carried out at KMUTT welding laboratory. The training system was used as a teaching tool in a real setting to evaluate its performance. Each subject was provided with verbal instructions on the test being carried out before the test commenced. The subjects were not informed of the testing conditions and were tested independently. After each test set, they were allowed twenty minutes break before the next test set commenced. The score for each test set was the average of the three welding attempts. After the completion of the trials, three welding instructors inspected all sixty welded metals from the final round. The inspectors were required to mark each piece using the five-point rating scale.

3.2.5. Data Analysis

Data was statistically analyzed using the Statistical Package for the Social Sciences (SPSS) software. The means and standard deviations for each parameter were calculated for each group. Independent sample *t*-test was performed to test for differences among the means of the corresponding parameters. The percentages of skill improvement for each group were also calculated using the frequency of performance within the tolerant limits for each parameter.

4. RESULT

4.1. Welding Performance

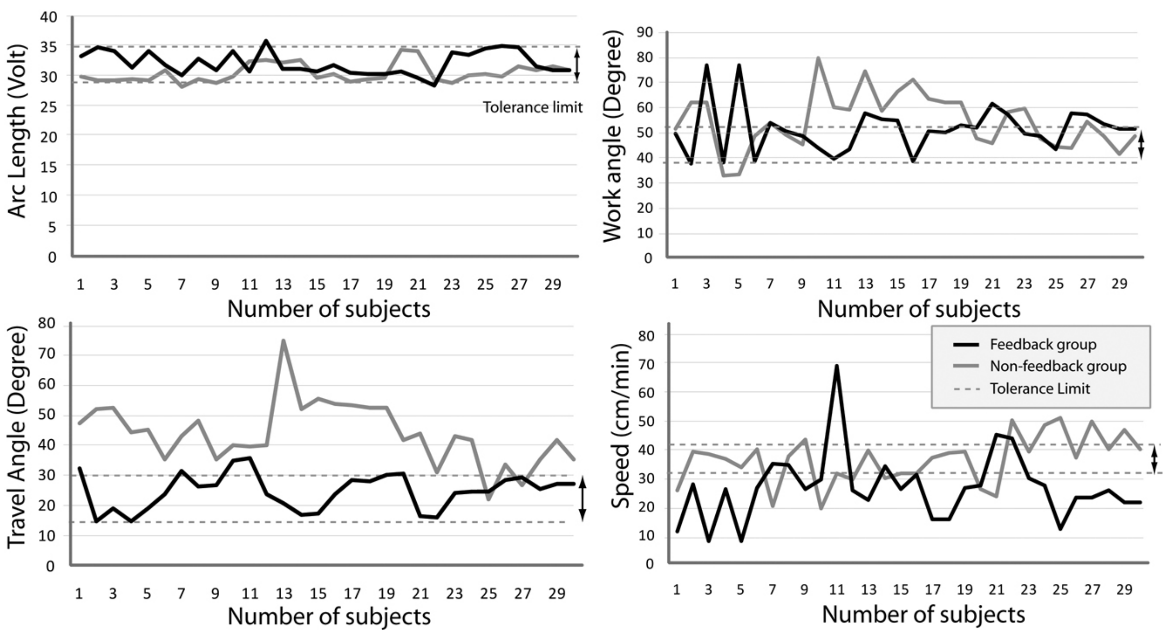

Figure 7. Comparison of performance of thirty subjects

Figure 7 is a comparison of feedback and non-feedback group with the upper and lower tolerance limit. When comparing thirty subjects in each parameter, the arc length is in the tolerant limit (30 – 35 volts) for both feedback and non-feedback group. The travel angle from feedback group is within tolerance limit (15 – 30 degrees) while non-feedback group is above the dash line. For work angle, both groups are above and within the tolerance limit (40 – 50 degrees). The subjects of both groups demonstrated a high variant speed. The value is upper and lower the tolerance limit (32.34 – 42.54 cm/min).

The percentage of skill improvement increased when subjects' performances were within the tolerant limit (see Figure 8). The percentage is calculated according to the average of value in each session. For t-weld position, the percentages of skill improvement in the non-feedback group were lower than the feedback group for all parameters. Feedback group increasingly improved the skills of work angle, travel angle and arc length of more than 26%. On the other hand, the non-feedback group did not improve much after the fourth session. For the welding speed, the performance was low.

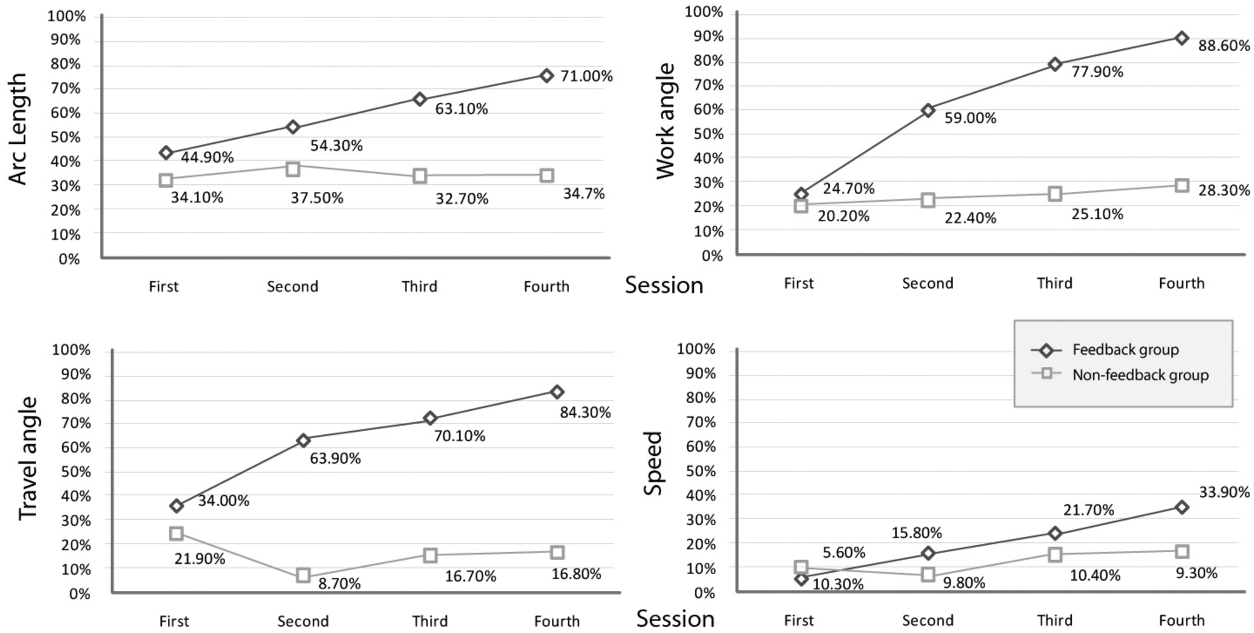

Figure 8. The percent development of skill improvement of four rounds

Table 3. Testing hypothesis for T-weld

	Groups	Mean	Std. Deviation	Sig. (2 tailed)
Arc length	Non-feedback	30.50 volts	1.63	0.004*
	Feedback	32.07 volts	1.97	
Work angle	Non-feedback	54.53°	11.32	0.158
	Feedback	50.06°	8.58	
Travel angle	Non-feedback	43.90°	10.25	0.00*
	Feedback	24.40°	5.95	
Welding speed	Non-feedback	36.19 cm/min	8.83	0.002*
	Feedback	26.58 cm/min	9.6	

* Significant at 0.01% level ($p < 0.01$)

The *t*-test analysis showed that there was a significant difference between the non-feedback and feedback group in terms of performance at 0.01% level ($p<0.01$) for two parameters: arc length and travel angle (Table 3). There was a significant difference in welding speed but the non-feedback group quite performed better than the feedback group. The mean values showed that both groups performed within the tolerance limits for arc length (29-34.6 volts); however, only the feedback group performed within the tolerance limits for travel angle (15-30°).

There were no significant differences between the performances of both groups in work angle. Yet, the work angle means value of 50.06° from the feedback group was much closer to the tolerant limits (40°-50°) than that from the non-feedback group (54.53°) with a smaller standard deviation (8.58 compare to 11.32). The average performance for welding speed in non-feedback group (36.19 cm/min) was within the tolerance limit (32.34-42.54 cm/min). In contrast, the feedback group presented lower performance than non-feedback group. The result shows that verbal feedback has little effect on welding speed.

4.2. Welding Quality

In the final round, three welding instructors conducted visual inspection of every piece of welding. By using a five-point scale, they rated the quality of welding outcome. The inspectors were unrevealed to the testing groups.

Table 4. Statistical description of expert rating for each group

Groups	Score range	Mean	Std. Deviation	Sig. (2 tailed)
Non-feedback	1.4-2.6	2.12	0.38	0.00*
Feedback	2.7-3.6	3.11	0.2	

* Significant at 0.01% level ($p < 0.01$)

Table 4 presents the difference in the welding quality. It can be seen that the quality of welding from the feedback group (score range 2.7 – 3.6) is constantly higher and more consistent than that of the non-feedback group (score range 1.4 – 2.6). The average score welding quality of the finished pieces from the feedback group was better than those from the non-feedback group ($\mu = 3.11$ and 2.12, respectively). T-test had found that there was a significant difference in welding qualities between the two groups at 0.01% level ($p < 0.01$).

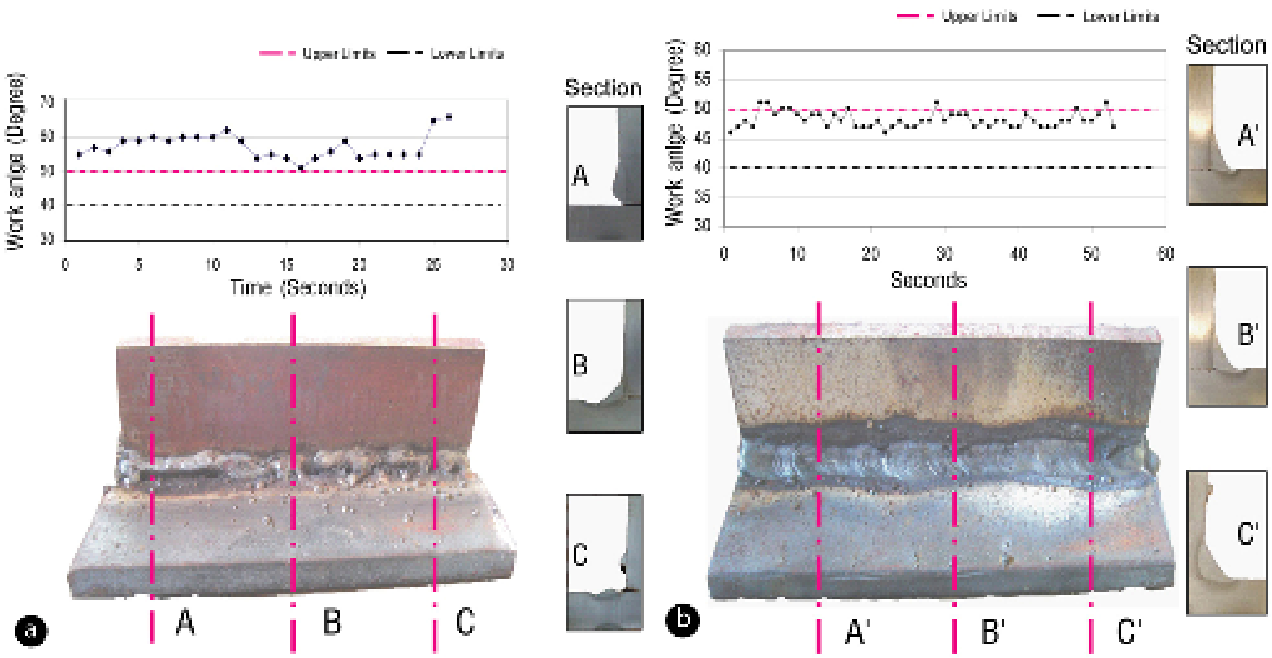

Figure 9. The differences in work quality between the two groups (a. Non-feedback group and b. Feedback group) with an example of the performance on work angle as an illustration.

Figure 9 is the best example of using the training system especially for the work angle. Welding works from the non-feedback group tend to have work angles that were higher than the tolerance limits (graph in Figure 9a) with unstable and uneven welding lines. Failure to join the two pieces of metal together was found more in the non-feedback group (cross-section A and C in Figure 9a) than in the feedback group.

The welding works from the feedback group were of better quality with more even and stable welding lines than those of the non-feedback group (Figure 9b). The molten pools of the welds were found to join the two metal pieces more frequent than those of the non-feedback group. Moreover, the work angles were found to be mostly within the tolerance limits (graph in Figure 9b).

5. DISCUSSION AND CONCLUSION

The use of the new training system, particularly the verbal feedback, demonstrated that it could significantly improve the progression of welding of novices in two parameters: arc length and travel angle. The coded welding speeds do not reflect the subject's true speed whereas a result of the subjects' behavior once voice feedback is heard. Subjects tend to stop and then speed up resulting in the coding machine recording fluctuation speed occurrences. The lack of considerable difference in subjects' performance in terms of welding speed could be partly due to unstable performance of the welding speed. This action might also indicate that speed improvement requires practice and is less affected by instructions. Experts' performance in terms of travel and work angle, even though a small sample size, is consistent with very small standard deviations (0.77 and 0.64, respectively) and means of ~ 40° and ~ 55°, respectively. It is interesting that experts consistently perform at higher angles than the recommended guidelines. A larger amount of data is required to investigate further into the discrepancies between the guidelines and experts' performance.

The experiment has shown that the new training system can be used in real training environments to aid the teaching and training of the skills of welding. It has demonstrated that it can assist in a significant improvement on two of the four key parameters. The subjects could easily develop skills in terms of arc length and travel angle after listening to the voice feedback. With this tool, instructors can accelerate and motivate the welding skills of their learners.

5.1 Industry Application

The tool can be implicated as an assessment for welders' certification. It can be a guideline on the qualification of welding procedure and the performance testing of welders. In addition, the device shows how to capture knowledge of an intermediate group and transfer into a form of a training device. The human knowledge can be applied in conjunction with welding robots in the future.

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BIOGRAPHICAL SKETCH

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