Development and Implementation of a Skill Transfer System for a Self-Tapping Screw-Tightening Operation

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Abstract. Self-tapping screws have some operational peculiarities. In spite of their economical advantage that requires no prior tapping operation, a weakness of self-tapping screw-tightening operations is that screws can easily be tightened at a non-right angle, thus resulting in an improper tightening strength. Increases in outsourced workers have reduced labor costs, but the accompanying high worker fluidity means that new workers are more frequently introduced into factories. It is necessary to train new workers for self-tapping screw-tightening operations, which occupies a considerable portion of ordinary assembly works. The purpose of this study is to develop and implement a skill transfer system for the operation. This study (1) proposes a set of characteristic values for evaluating the quality of the operation and develops a device that can measure these values; (2) proposes criteria for evaluating the resultant quality of the tightening; and (3) develops a skill training system for better work performance. Firstly, sets of characteristic values for evaluating the quality of the operation, namely, torque, vertical pressure forces and horizontal vibration forces, are proposed. A device that can measure these values is developed. Secondly, criteria for evaluating the resultant quality of the tightening are identified, involving tightening torque, maximum vertical pressure and timing, vibration area during the processing and tightening period, and work angle. By using such parameters, workers with the proper aptitude can be identified. Thirdly, a skill training system for the operation is developed. It consists of screwdriver operation training and screw-tightening training with feedback information about the results of the operation. Finally, the validity of the training system is experimentally verified using new operators and actual workers.

Keywords: Skill Transfer System, Screw-tightening Operation, Measuring Performance, Evaluation Profile, Training System

1. INTRODUCTION

Self-tapping screws are widely utilized in manufacturing, especially in metal component assembly including steel plates, due to their economic efficiency in that they form female threads by themselves with their
torque when used to tighten objects. Despite such an advantage, self-tapping screws also possess disadvantages in that they can form tilted threads or cause extra strain on workers if a worker’s posture or application of strength is inappropriate when using a screwdriver; this is a particular concern when workers are unskilled. These disadvantages may lead to quality control problems when unskilled workers take charge of screw-tightening, which may well arise due to the increasing mobility of the working population and factories’ dependence on low-wage workers. In order to avoid these problems, a training system for imparting skills and knowledge from skilled workers must be designed.

Studies on tool design in the field of ergonomics (Drury, 1980; Joshi et al., 2008; Marras et al., 1991; Mukhopadhyay et al., 2007; Xu et al., 2009), studies on work designs of simple tools (Andrews et al., 2008; Brookham et al., 2010), studies on screw-tightening operations using powered screwdrivers (Johnson, 1988a, 1988b; Lin et al., 2010), and studies on screws that consist of bolts and nuts in the field of mechanical engineering (Morozumi, 1990; Yamamoto, 1992) have been presented. However, studies from actual assembly factories on methods to improve the operations involving either self-tapping screw-tightening or training methods that can enable the transfer and the acquisition of these skills from skilled workers have not been reported.

Studies on training (Hatamura, 2006; Yamada and Kato, 2007; Yamamoto and Mori, 2002) have been presented, suggesting that knowledge and motion should be taught separately. However, it is difficult to acquire the necessary knowledge and apply it to the motion of a self-tapping screw-tightening operation.

This study thus aims to devise a method for gaining characteristic values of self-tapping screw-tightening operations in order to quantitatively evaluate the task and to develop a device for measuring these values. The study also aims to create evaluation profiles covering the skills required to complete satisfactory work and to develop a training system to systematically transfer these skills. Moreover, the also study aims to provide outline of a skill transfer system by compiling the authors’ preceding studies (Matsumoto et al., 1993, 1999, 2000a, 2000b, 2000c, 2001, 2002a, 2002b, 2002c, 2003, 2007; Shida et al., 2001) into a single paper.

2. DEVISING EVALUATION METHODS FOR SELF-TAPPING SCREW-TIGHTENING OPERATIONS

2.1 Obtaining Characteristic Values for Self-Tapping Screw-Tightening Operations

The object of the study here is a self-tapping screw-tightening operation using an electric-powered screwdriver, as powered screwdrivers are commonly used in operations at actual assembly factories. The operational instructions are as follows: First, put a self-tapping screw on the end of the bit of a powered screwdriver. Move the screwdriver and the screw close to the clamped component and the part in which a female thread is to be formed, and position and attach the screwdriver and the screw to the two parts’ center axis line. Push the screwdriver down toward the center axis line, drive in the bit of the screwdriver and begin screw tapping. The screw proceeds to form a female thread in the part and continues even after it completes forming the necessary female thread and the screw head reaches the female thread member. The screwdriver stops turning when it achieves the necessary tightening torque and finally runs idle when the clutch is engaged. A screw-tightening operation is complete when the bit of the screwdriver is removed from the screw.

When operations are conducted by unskilled workers, defect formations are often observed, which may result in the three types of problems described below.

![Figure 1. Characteristic values of the operation.](image-url)
(1) Screwdrivers may not achieve the necessary tightening torque due to inappropriate operations that are high or too close to the body work position, which causes obstacles.
(2) Operations may cause an extra strain on the workers, resulting from the application of excessive pressure upon the screwdrivers.
(3) Vibrations may arise due to tilting of the screwdrivers.

Considering the force applied to a screwdriver while implementing the self-tapping screw-tightening operation, three parameters must be obtained in order to elicit a characteristic value of the operation, as shown in Figure 1. The first is the torque of a screw sticking into the female thread member, $F_t$. The second is the vertical pressure of a self-tapping screw pressing against the female thread member, indicated $F_z$. The last is the unnecessary horizontal force generated by the vibration of the female thread member, mainly due to tilting of the screwdriver from the center axis line as indicated by $F_{xy}$ (hereafter referred to as 'vibration'). These forces $F_t$, $F_z$, and $F_{xy}$ are determined by the torque $f_t$, the manual strength $f_p$, and the angle of the object from the center axis line, theta.

2.2 Developing a Device for Measuring Performance of Self-Tapping Screw-Tightening Operations

Screw-tightening operations are conducted for the purpose of binding clamped parts and female thread members with screws. In a previous study (Matsumoto et al., 1993), the authors created a test piece to measure the characteristic values of a self-tapping screw-tightening operation, hereafter named the "sample plate." In the experiment, the sample plate acts as both a clamped part and a female thread member. The authors also developed a device for measuring the performance of self-tapping screw-tightening operations, utilizing the sample plate for various experiments, as shown in Figure 2. Examples of performance measurements of self-tapping screw-tightening operations using the device are shown in Figure 3, which shows a good case with a 0-degree work angle and a bad case with a 14-degree work angle, which affects the tightening quality. The device roughly consists of three kinds of detectors as follows.

2.2.1 Detector 1: Measurement of torque

This part measures the torque generated while scre-
wing a self-tapping screw into the sample holder. The torque is transferred from the ‘sample holder’, which functions as a holder of the sample plate, through the diaphragm and reaches the torque meter (AIKOH ENGINEERING CO., QF-05K, Accuracy: 0.0015 Nm, Range: -4.9 Nm to +4.9 Nm, Sampling rate: 1 ms), which detects and measures the torque.

2.2.2 Detector 2: Measurement of pressure

This part measures the vertical pressure applied during the self-tapping screw-tightening operation. A loadcell (AIKOH ENGINEERING CO., CM-50K, Accuracy: 0.015 N, Range: 0-490 N, Sampling rate: 1 ms) detects and measures the vertically applied force transferred from the sample plate through the shaft.

2.2.3 Detector 3: Measurement of vibration

This part measures the distance between the center axis line and the screwdriver’s axis, namely, the vibration of the screwdriver. Four loadcells (AIKOH ENGINEERING CO., CM-5K, Accuracy: 0.015 N, Range: 0-49 N, Sampling rate: 1 ms) are arranged in a concentric pattern and are then placed on the sample holder, forming right angles (90 degrees) from the center. The four loadcells detect and measure the horizontally applied force on the sample holder.

3. DEVISING AN EVALUATION PROFILE OF SELF-TAPPING SCREW-TIGHTENING OPERATIONS

3.1 Designing an Evaluation Profile of Self-Tapping Screw-Tightening Operations

Regarding the three problems mentioned in section 2.1, the keys to a solution lie in the evaluation criteria, as follows: For (1), the key parameter is the screw-turning torque, the tightening torque. For (2), regarding the vertical pressing force that presses down the screwdriver, the maximum pressure and its applied timing are selected as key parameters. For (3), the force that prevents the screwdriver from proceeding straight, determined by measuring vibrations in terms of the monitored area during the processing and tightening periods of the screwdriver, and the work angle, which causes tilting in the screwdriver, are selected as key factors (Matsumoto et al., 1999, 2000a, 2000b, 2001, 2002a, 2002b, 2003).
By integrating the six evaluation criteria as indices, considering ideal values, feasible and realistic performance ranges, and an allowable limit, below which the performance affects the quality of the products, an evaluation profile is designed for quantitatively evaluating the performance of self-tapping screw-tightening operations, as shown in Figure 4. The allowable limit of the tightening torque is defined by the product quality specifications in the design process. In the target factory, an M4-size screw should be tightened to 1.8 Nm, so that the allowance range is -10% to +10% (e.g., 1.62-1.98 Nm). The upper limit was determined 0.2 Nm by the lowest level worker in the previous experiments (Matsumoto et al., 2000b). The allowable limits of pressure and vibration were determined in the experiments by five skilled workers who had over 13 months of assembly work experience in the target factory. The average values from the results of the experiments were adopted 30.0 N, threading timing, 1.00 Ns and 0.50 Ns. The upper limits were determined 120 N, ending timing, 6.00 Ns and 3.00 Ns by the lowest level worker in the experiments. The allowable limit of the work angle was determined by previous tightening experiments (Matsumoto and Kanazawa, 1999). The allowable limit for the work angle was 10 degrees. If the work angle exceeds 10 degrees, the tightening quality of the holding strength and loosening strength decreases significantly. The upper limit was determined 20 degrees by the biggest feasible operation in the experiments.

In the evaluation profile, which is represented as a radar chart, each evaluation index line indicates the ideal value as 100 and the lowest performance range as 0 (starting point). The outer line thus shows the ideal performance, and the inner dotted line is the tolerance limit line, which shows the allowable limit of work performance, and the area enclosed by the two lines represents the allowable range of work performance.

Once a figure is obtained using the device for measuring the performance of a self-tapping screw-tightening operation, the figure is plotted on the evaluation index axes, and the resulting average value is specified as the work performance index (WPI). The average value is adopted simply even though tightening torque is the most important criterion for quality and is affected from the rest criteria (Matsumoto et al., 1999, 2000b). Taking the tolerance limit line in Figure 4 as an example in the case of an M4x8-size self-tapping screw, the value for the tightening torque is 1.62 Nm (79.8), the maximum pressure is 30.0 N (90.0), the maximum pressure applied timing, which equals the ending point of the female thread-forming period, is (80.0), the vibration area [processing period] is 1.00 Ns (83.3), the vibration area [tightening period] is 0.50 Ns (83.3), the work angle is 10 degrees (50.0), and the average value is 77.7, thus representing the work performance index of this operation. Necessary condition is that tightening torque should be greater than 1.62 Nm, and then the tolerance limit

![Figure 4. Evaluation profile of a self-tapping screw-tightening operation.](image-url)
number 77.7 is target for better quality of operation.

3.2 Investigating Self-Tapping Screw-Tightening Operation Skills of Actual Workers

The data of 62 workers in an actual assembly factory were collected using the above-mentioned device and the evaluation profile of self-tapping screw-tightening operations (Matsumoto et al., 2000c). As the average for all of the workers, the tightening torque is 1.85 Nm, the maximum pressure is 58.8 N, the maximum pressure occurs during the tightening period, the vibration area [processing period] is 1.65 Ns, the vibration area [tightening period] is 0.81 Ns, the work angle is 1.57 degrees, and the average WPI is 69.7, as shown in Figure 5. Most workers were not within the tolerance limits for pressure and vibration.

Evaluation profiles of the poorest work and the best work and the corresponding characteristics of operations are shown in Figure 6. The WPI of the poorest work is 49.3, and that of the best is 91.2.

According to the data, tips for an ideal performance are described below.

(1) The worker should apply minimum pressure on the screwdriver during the female thread-forming period and maintain the same pressure once the screwdriver begins operating.

(2) The worker should hold the screwdriver straight along the center axis lines and should not apply pressure on the screwdriver to avoid vibration during the threading period.

(3) The worker should twist his wrist in the direction of

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<table>
<thead>
<tr>
<th>Evaluation index</th>
<th>Characteristics of the worst work</th>
<th>Characteristics of the best work</th>
<th>Know-how of operations</th>
</tr>
</thead>
<tbody>
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<td>[1] Tightening torque</td>
<td>Ideal value</td>
<td>Ideal value</td>
<td>Turning wrist in the tightening direction when screw tightening</td>
</tr>
<tr>
<td>[2] Maximum pressure</td>
<td>Larger pressure</td>
<td>Smaller pressure</td>
<td>Applying minimum necessary pressure</td>
</tr>
<tr>
<td>[3] Appearance timing</td>
<td>In tightening period</td>
<td>In threading period</td>
<td>Keeping smaller pressure after starting of operation</td>
</tr>
<tr>
<td>[4] Vibration area [Processing]</td>
<td>Larger vibration</td>
<td>Smaller vibration</td>
<td>Keeping the driver straight</td>
</tr>
<tr>
<td>[6] Work angle</td>
<td>Larger tilt of a driver</td>
<td>Smaller tilt of a driver</td>
<td>Keeping the driver straight</td>
</tr>
</tbody>
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Figure 5. Evaluation profiles of 62 actual workers.

Figure 6. Evaluation profile of the poorest work and the best work.
the screw’s rotation at the moment of completion of tightening during the tightening period.

4. DEVELOPING A SKILL TRAINING SYSTEM

The authors have developed a training system for the purpose of imparting the above-mentioned skills by utilizing the device for measuring the performance of M3- or M4-size self-tapping screw-tightening operations (Shida et al., 2001). The training consists of two parts: “screwdriver operation training” and “screw-tightening training”. The former is a simulation training for a pre-training screwdriver operation, which does not include actual screw-tightening. The latter is an actual hands-on screw-tightening training. The contents and the procedures for each training session are outlined below.

Figure 7. Screwdriver operation training and screw-tightening training.
4.1 Screwdriver Operation Training

The screwdriver operation training consists of Step 1–Step 3, as shown in Figure 7, and enables an unskilled operator to acquire the necessary skills for operating a screwdriver, through simulations that allow an operator to experience a range of force applications, from the ideal level to the allowable limit, as specified in section 3. The training requires no actual screw-tightening operation. Low-level to mid-level operators are the subject of the training, and they are expected to learn the keys of operating the tools in terms of pressure application, vibration avoidance, work angle, and ideal to allowable limits through simulated experience. The training also enables an operator to acquire timing skills for lessening the pressure on a screwdriver.

4.1.1 Step 1: Training on Applying Desirable Pressure

In order for an operator to learn “how to apply desirable pressure on a screwdriver”, this training focuses on maintaining an applied pressure between the ideal and allowable levels through simulations.

The first part of this training allows an operator to learn how to apply desirable and appropriate pressure on a screwdriver, through simulated experiences of the ideal and allowable levels of pressures to be applied to a screwdriver, using computer screens and computer-operated voices as signals. The training instructions are as follows: First, position and place the bit of the screwdriver on the center of the device as preparation. Press the screwdriver toward the screw’s proceeding direction, and check on the screen to determine whether the applied force, shown in bar graphs indicating the magnitude of the applied pressure in real time, is appropriate. When the applied strength reaches the ideal (20.0 N) or allowable (30.0 N) limit, a buzzer rings to alert the operator. The operator practices these up-and-down movements several times to become familiar with the desirable pressure.

The next part of the training focuses on maintaining the desirable pressure for a certain period of time. The preparation procedure is the same as the previously mentioned action. The operator applies pressure on the screwdriver’s proceeding direction; the pressure is reflected in a waveform on the screen in real time. An operator practices how to keep the applied waveform between the ideal value and the allowable limit by operating a screwdriver several times.

The training is completed when the worker can apply 20.0-N and 30.0-N pressure within 5% without seeing the screen.

4.1.2 Step 2: Training on Vibration Avoidance and Work Angle

Here, training is implemented in order for the operator to learn “how to hold a screwdriver straight and avoid vibration”. The operator learns how vibration can be generated and the ideal (0 degree) and allowable (10 degrees) work angles through simulated experience. The training is designed to help an operator learn how to operate a screwdriver at the ideal work angle.

On the computer screen, the allowable range of work angles is shown in trajectories calculated from the allowable limit of work angle and the ideal applied pressure. The same preparation used in the training of applying maximum pressure is required, and an operator practices moving the screwdriver up and down using operation guide tools that allow him to operate a screwdriver only at ideal work angles. The screen displays a trajectory reflecting the waveform of vibration in real time. The operator moves the screwdriver up and down several times, checking the trajectories.

In the same manner, the operator can check the work angles at the allowable limit, with the trajectories showing vibration on the computer screen, reflecting the motions of the screwdriver moving back and forth and around.

The training is completed when the worker can apply pressure at a work angle of less than 1 degree without using guide tools or seeing the screen.

4.1.3 Step 3: Training to Lessen the Pressure on a Screwdriver and Twist the Wrist

In order to learn how to “weaken the pressure on a screwdriver during the tightening period” and “twist wrist in the direction of the screw’s rotation during the tightening period”, the operator practices replicating the ideal waveform, which is shown on the computer screen.

On the computer screen, an ideal waveform with a pressure start line, a pressure weakening line, a non-pressure line, and a twisting torque line is displayed. The same preparation used in the training on applying maximum pressure is required before this training; the operator needs to recreate the ideal waveform by applying pressure on the screwdriver at the press start point on the waveform, by lessening the applied pressure at the weakening point, by removing a screwdriver from the screw at the non-pressure point, and by twisting his wrist at the tightening point. The operator practices these series of movements repeatedly.

The training is complete when the worker can apply pressure with less than a 5% difference between the ideal waveform and the result without seeing the screen.

4.2 Screw-Tightening Training

Steps 4 and 5 of the training process represent the screw-tightening training portion of the training, as shown in Figure 7, in which the operator acquires knowledge of ideal execution of screw-tightening through feedback on the process and the result of actual operations. The operator of this training is originally unskilled but becomes a semi-skilled operator upon completing the screwdriver operation training, and even-
tually a skilled operator. The operator receives feedback on the process and outcome of the self-tapping screw-tightening operations that have been conducted, for the purpose of upgrading their current skills to a higher, ideal competency.

4.2.1 Step 4: Displaying Work Characteristic Waveforms of the Screw–Tightening Process

In this part of the training, the operator actuallytightens self-tapping screws while checking the work characteristic waveforms measured by the device, and displayed on the computer screen. The operator applies the screw to the end of the bit of a screwdriver and then screws it onto the center of the female thread member substitute, a part of the device for measuring the performance of self-tapping screw-tightening operation. The operator can monitor the waveforms showing the vibration, applied pressure, and torque in real time, as well as the work performance index on the computer screen.

4.2.2 Step 5: Displaying Evaluation Profiles of the Screw–Tightening Results

After completing a screw-tightening operation, the operator receives appropriate feedback through evaluation profiles of the self-tapping screw-tightening operation. The operator can objectively assess his own performance by checking the work performance indices, which helps the operator to self-diagnose problems and to know where to improve; he can also receive advice from a skilled worker.

The training is completed when the worker can attain an allowable work performance index (more than 77.7) three consecutive times.

4.3 Realization and Procedure of the Training System

The training procedures for each operator are described as follows: First, the operator performs the operation, from which an evaluation profile is generated to assess the operator’s level. Low-level operators start from Step 1 of the ‘screwdriver operation training’. Mid-level operators proceed to Step 3 of the ‘screwdriver operation training’. High-level operators go on to Step 4 of the ‘screw-tightening training’. After completing the assigned training step(s), the operator moves on to the next step of the training sequentially from 1, 2, 3, 4 and 5. Low-level to mid-level operators repeatedly take the ‘screwdriver operation training’ until their performance exceeds the allowable limit of the evaluation profiles. High-level operators receive training to move their level closer to the ideal, and terminate the training when they build enough confidence and feel ready to perform a satisfactory level of operation.

5. VALIDITY VERIFICATION OF THE DEVELOPED TRAINING SYSTEM

5.1 Validity Verification Test with Inexperienced Subjects

In order to verify the validity of the developed training system, the subjects were divided into two groups; the test group which received the developed training (hereafter referred to as the new training), and the control group which took the actual training (the existing training) provided on-site at an actual assembly factory (Matsumoto et al., 2003). In the existing training, a powered screwdriver, screws and a square steel plate with 225 holes were used as shown in Figure 8. A trainee was given instructions to “hold a screwdriver straight” and “tighten until it clicks.” Then, the tightening of the screws was repeated up to 15 times within 60 seconds. This training took about 15 minutes on average.

Twenty male and female college students participated in the validity test as subjects. The subjects were divided into two groups, each consisting of ten participants (8 males and 2 females). The subjects were divided according to their evaluation profiles so that there would be no outside factors affecting their work performance indices other than the self-tapping screw-tightening training to be given. The averages of the work performance indices for the two groups were 65.7 for the test group and 65.9 for the control group; thus, there were no statistically significant differences [F(1, 18) = 0.0538] prior to the training.

After implementing the validity test for the training, the average of the test group indices was 84.3, while that of the control group was 73.3, as shown in Figure 8. The difference exceeded a significance level of 1%; thus, the figures were significantly different [F(1, 18) = 73.87]. The differences in the tightening torque, maximum pressure and timing of the maximum pressure were at a significance level of 1%, and the other parameters exhibited no difference. Thus, the former three factors significantly contributed to the skill development. The factors from torque and pressure are causing and controllable ones, on the other hand vibration is resulting factor. The training took 15.5 minutes for the test group and 10.7 minutes for the control group on average. The average number of screws used in the test was 4.5 for the test group and 45.3 for the control group. The results show that although the new training may take 1.5 times longer than the existing training, it enables operators to acquire the required skills with fewer screws (10.0%) in actual tightening training. The validity test therefore demonstrates that while the existing training focuses on learning by doing without any supporting theories or proper instructions, the new training allows operators to think about working properly during the training process.
5.2 Validity Verification Test with Actual Workers

In this part of the validity test, 25 male and female participants aged 19–38, who had worked at the assembly factory as self-tapping screw-tightening workers for one to 14 months prior to the test, were selected as subjects.

The average training time of the participants was
12.3 minutes. The average work performance index of the subjects was 72.4 before the training, and after the training, this figure increased to 84.0, as shown in Figure 9. The results show that the difference exceeded a significance level of 1% [F(1, 48) = 54.29], and therefore, the validity of the training was verified. The differences in the maximum pressure and appearance of maximum pressure were at a significance level of 1%, and the other parameters displayed no difference. Thus, the former two factors significantly contributed to the skill development. To improve the rest factors continuous training especially Steps 4 and 5 is required. The training is thus shown to have enhanced the work, so that it was 1.2 times more effective in terms of work performance indices.

6. CONCLUSIONS

In this study, the authors developed and implemented a skill transfer system for a self-tapping screw-tightening operation, which occupies a considerable portion of ordinary assembly works at many factories. In order to quantitatively evaluate the self-tapping screw-tightening operation, first, three types of characteristic values regarding torque, pressure and vibration were specified and obtained, and a device to measure these values was specially designed and developed. The authors have also devised evaluation profiles, employing the tightening torque, the maximum pressure and timing, the vibration area during the processing and tightening period, and the work angle as parameters and, from the analyzed data, specified the skills that the best operators possess. A new training system, which consists of “screwdriver operation training” and “screw-tightening training”, was subsequently developed in order to systematically teach the featured skills. Finally, both new operators and actual workers received the developed training, and based on these results, the validity of the training system was verified.

In the future, it would be useful to simplify the mechanisms of the device developed for measuring the performance of self-tapping screw-tightening operations, such as downsizing the device into a screwdriver to make it more user-friendly.

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