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Human Reliability Study in Manual Clamping of Turning Workpieces

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In many cases, technical problems or failures are not the primary causes for workpiece ejection during a turning operation. Often, clamping errors lead to those hazardous incidents. Therefore, one important question is whether the machine operator uses the clamping device correctly to reach the required clamping force. To answer this question, we conducted a between-subject study with 23 qualified machine users, with the available tool as an independent variable (conventional cuck key vs. electronic torque wrench). The task consisted (1) of checking the clamping system for possible errors before use and (2) of clamping a clamping force measuring device and a workpiece, either with a cuck key or an electronic torque wrench. The results show that a conventional chuck key is only suitable to a limited extend for applying a defined clamping force, in comparison with an electronic torque wrench. Consequently, the clamping safety, especially when high clamping forces are required, can be significantly increased by using an electronic torque wrench. Furthermore, the results show that the participants are rarely able to set the required clamping force with a conventional chuck key and are only able to assess their own performance correctly to a limited extent despite many years of professional experience.

Keywords: clamping safety, jaw-chuck, clamping experiments, user studies, technical-human reliability, safety instructions, statistical evaluation.

1. Human (un)reliability during manual workpiece clamping

Manual workpiece clamping consists of a variety of manual operations between an operator, the manually operated clamping system and a machine tool. Accordingly, the investigation and evaluation of human reliability is essential to determine the overall safety and reliability of a technical system, such as a workpiece clamping system. Therefore, our current research project does not only consider the technical reliability of manual workpiece clamping (Albero Rojas 2021), but especially the human reliability. According to the VDI guideline (VDI 4006 2015), human reliability is the capacity of a person to perform a task under given conditions for a given time interval within an acceptance range. Furthermore, Park (Park 1997) describes reliability as the antithesis of error probability. Thus, human reliability is defined as the probability that a human will perform a task without error for a given period of time. Essentially, humans differ from technology in their goal-oriented work, the capacity to self-monitor their actions as well as to correct erroneous action steps. However, the human is both a controlling component of the technical system, but at the same time also a vulnerable and protective element (Lolling 2003). Considering the human factor and its importance in relation to the percentage distribution of accident causes, it becomes clear that around 80 % of all workplace accidents are attributable to humans and thus to human (un)reliability. Among these, 70 % of the causes of human errors are due to "non-willingness" or "non-compliance" (e.g. underestimation of risk). Around 20 % are due to "non-knowledge" (e.g. insufficient experience or no instruction) and only 10 % to "non-capability" (e.g. no qualification or excessive demands) (Mertens 2017). Hence, the process of manual workpiece clamping presents the greatest risk potential in workpiece machining. In particular due to the hazard of ejection of clamping system components, but especially due to the previously clamped workpiece itself. To reduce the risk of an ejecting workpiece, it is therefore necessary to evaluate which problems arise when clamping manually. For this purpose a user study to identify and quantify human error during the manual workpiece clamping process, was carried out.

2. User Study

2.1. Participants

Overall 23 participants (1 female) participated in the experiment (average age: 41.96 years (SD = 13.05); average working experience: 17.38 years (SD = 13.69)). The sample consisted primarily of industrial mechanics (n = 8), metal-cutting machine operators (n = 6) and other qualifications (mechanic, mechanical engineering technician, CNC operator) with a focus on metal-cutting technology. The participants were randomly divided into two groups: Group 1 (n = 11) carried out the clamping tasks with a conventional chuck key (purely manually clamping without tool guidance/ or torque measurement on the tool). Group 2 (n = 12) performed the clamping tasks with an electronic torque wrench. All participants performed 3 tasks in a specific order. The full experimental session took approx. 40 minutes and all participants participated voluntarily and were allowed to abort the experiment at any time.

2.2. Equipment

The experiment took place partly (n = 12) at Chemnitz University of Technology in a separate area of a machine hall, in which the machine, all tools and a workplace for the experiment were set up. The machine was the universal machining centre DMC 80 EVO (Fig. 1, left) from DMG Mori GmbH. Due to the COVID-19 situation, parts of the experiment also took place at the project partner Gebr. Heller Maschinenfabrik GmbH under similar conditions (n = 11). The test setup was installed on the 5-axis machining center HF3500 (Fig 1, right). The 3-jaw chuck Duro-T 315 from RÖHM Group was installed on the respective machine. The manual clamping system was prepared in advance so that various errors had to be identified by the participants within the experiment. Figure 2 shows the 3-jaw chuck including screw designation.

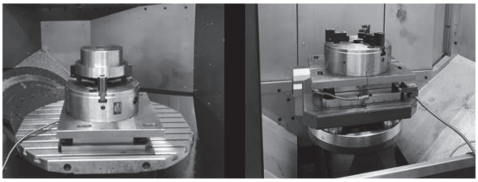

Fig. 1. Test setup at Chemnitz UT (left) and at Gebr. Heller Maschinenfabrik GmbH (right)

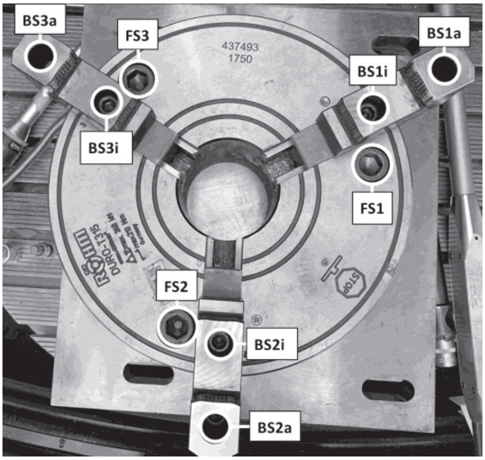

Fig. 2. 3-jaw chuck with screw designations

The following defects regarding chuck (table as well as base) and top jaws were prepared for each participant by the experimenters:

- FS1: strength class 8.8 installed (strength class 12.9 required)
- BS2i: screw thread damaged (see Fig. 3)
- BS3i: screw loose or not pretensioned
- Chuck guides soiled with shavings, lubrication condition to be checked (see Fig. 3)
- Impermissible clamping jaw position (see Fig. 3)

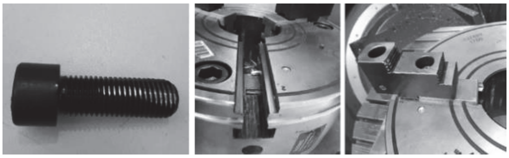

Fig. 3. BS2i (left), shaving in chuck guides (middle) and impermissible clamping jaw position (right)

2.3. Procedure

Two experimenters were present at each test run: one to carry out the technical tasks (technical experimenter) and one to direct the experiment and instruct the participants (instructor). To reduce unsystematic variance in the execution of the study, both experimenters followed a study protocol that exactly defined their specific proceedings. In this protocol, all deviations and remarks made by the participants while completing the tasks were noted. To avoid measurement errors and deviations when measuring the applied clamping force, the clamping system was checked before each participant and after each task, errors were corrected and reference measurements were carried out. For each participant and both groups, the following procedure was employed: Before each trial, the technical experimenter first determined the ratio between the clamping torque and the clamping force with the clamping force measuring device in order to know the actual efficiency of the clamping system. This consequently allowed to convert the clamping force specification of 160 kN into a corresponding clamping torque. After signing informed consent and filling out a short demographic questionnaire, the participants were instructed in written form about the upcoming tasks. Then the test environment was explained to each participant. The machine tool, the manual chuck, the available tools and instructions as well as normative specifications for the intended use of the clamping system were explained to each participant and then the first task was set.

First of all, the participants should put themselves in the following situation: "You receive the production order to process a workpiece (see sketch) by means of vertical turning. A machining centre (DMC 80 EVO or HF3500) is available to you for this purpose, which was previously installed by another employee, for another production task, both unknown to you. The machine or the assembled systems were not handed over to you by this employee." Task 1 consisted of preparing the machine and chuck for the specified production task on the machine in the same way as the participants would do in their everyday work. Within task 1, the participants should identify and correct the previously prepared deficiencies. This included replacing the damaged screw and the screw with the wrong strength class and screwing them in correctly, as well as installing the correct clamping jaws and cleaning the clamping system, as well as establishing the correct lubrication condition. The instructor then judged whether the deficiencies had been corrected completely or partly and the technical experimenter corrected the deficiencies unless this was done by the participant, so that there was an error-free starting situation for task 2. In task 2, the participants were asked to clamp the specified clamping force measuring device in the clamping system for the planned machining task. The instructor observed how and whether the participants aimed for a mathematical determination of the clamping force (given: cutting force = 3000 N; speed = 800 rpm predetermined). However, the participants did not carry out a detailed calculation of the clamping force. Thereafter, all participants were then given the required clamping force (160 kN), in order to have the same target value for all participants, independently of how the necessary clamping force was determined. Depending on the group affiliation, either the conventional chuck key or the electronic torque wrench had to be used to apply the clamping torque that generates a corresponding clamping force between the clamping jaws and the workpiece. The aim of the task was to apply at least a clamping force of 160kN. The technical experimenter then noted the values determined by the clamping force measuring device in the study protocol. The technical experimenter then removed the clamping force-measuring device and prepared the test workpiece for task 3. In task 3, the participants were instructed to clamp the specified workpiece with a clamping force of 160 kN. Group 1 again used the conventional chuck key and group 2 used the electronic torque wrench. During the task, the technical experimenter recorded the clamping torque using the measuring platform below the clamping system for both groups.

After the main experiment, the instructor interviewed each participant about the three tasks, to determine, whether there were interferences in the experiment that influenced the behaviour of the participants and whether the participants completed the tasks in terms of time and effort, as they would do in real working life. This information was used to assess whether the results of this laboratory study can be compared with behaviour in real working life or whether they have to be interpreted with limitations. Additionally, it was also surveyed how the participants assess their own performance in the tasks. This query was used to evaluate how well the participants can assess the applied clamping force without further technical equipment and what the relationship is between the subjective self-assessment and the actual performance. Subsequently, any questions the participants had about the experiment were answered and the starting situation for the next participant was created.

3. Results

The following values (per pre-set error) could be achieved for the identification/correction of the prepared defects on the manual chuck (task 1): correct identification of the error and its correction (1 point), partial correction or error was recognized but not completely corrected (e.g. chips removed but lubrication condition not checked or damage to screw thread recognized but not replaced) (0.5 point) and no error identification or correction (0 points).

The results show that only one participant identified and corrected the incorrect strength class of screw FS1. None of the participants identified the defective screw thread of screw BS2i or replaced the screw. 12 participants recognized that the BS3i screw was loose or not pretensioned. 10 participants received 0.5 points for recognizing soiling in the chuck guide and removing the chips, but only one participant received 1 point for also checking the lubrication condition. 17 participants identified and corrected the impermissible clamping jaw position completely, another 4 participants identified errors in the jaw position, but corrected them incompletely. Overall, only 1.9 points out of a possible 5 were achieved on average. Only 7 participants achieved more than half of the possible points.

For the second task, it was first recorded how the participants tried to determine the required clamping force. 47.8 % of the participants (11 people) stated that they wanted to apply the tension "by feel". 43.5 % of the participants (10 people) aimed to calculate the necessary clamping force or tried to use tables or specifications. For 2 people, it was not clear how they tried to determine the required clamping force or they stated that they did not know.

In task 2, the applied clamping force on the clamping force measuring device was determined. For this purpose, all participants received the specification that a clamping force of 160 kN is specified. In table 1 the mean values, standard deviations, the minima and maxima for both groups are shown and figure 4 shows the clamping force applied for both groups as a boxplot diagram. Figure 5 shows the distribution of applied clamping force for each participant and both groups. In both diagrams, the specified clamping force (160 kN) is marked as a dashed line. While in group 1 only 2 out of 11 participants achieved the required minimum clamping force, in group 2 9 out of 12 people achieved a clamping force of at least 160 kN.

Table 1. Mean value (M), standard deviation (SD), minima (min), maxima (max) of appl. clamping force

	Chuck key (Group 1)	Electronic torque wrench (Group 2)
M	102.42 kN	172.91 kN
SD	43.99 kN	19.84 kN
Min	28.00 kN	143.00 kN
Max	176.00 kN	212.00 kN

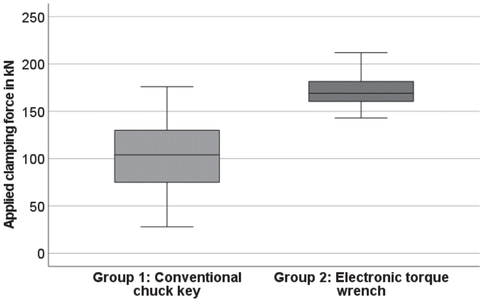

Fig. 4. Applied clamping force for both groups

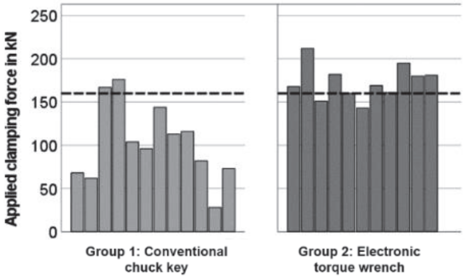

Fig. 5. Achieved clamping force in kN for both groups and specified clamping force (dashed line)

A Shapiro-Wilk test showed that the applied clamping force was normally distributed in both groups (p = .16). Therefore, the applied clamping force was analysed with a t-test for independent samples at the 5 % significance level. The test showed a statistically significant lower applied clamping force for group 1 with the conventional chuck key compared with the applied clamping force of group 2 with the electronic torque wrench

(95 %-CI[40.66, 100.32]), t(15.56) = 5.02, p < .001, d = 34.66. In addition to this comparison, a calculation was carried out to determine whether group 1 deviated significantly from the specified clamping force. For this purpose, a one-sample t-test was calculated against the value 160 (specified clamping force) and showed that group 1 deviated significantly from this given value (95%-CI[-85.53, -29.62]), t(11) = -4.53, p < .001, d = 43.99.

In order to evaluate whether the participants tended to behave differently when applying the clamping torque on the clamping force measuring device than when clamping a conventional workpiece, the applied clamping torque for the clamping force measuring device and for a workpiece clamped in task 3 was compared. The specified clamping force was 160 kN in both tasks (based on the determined ratio between the clamping torque and the clamping force). Figure 6 shows a comparison of the applied clamping torques for both clamping processes.

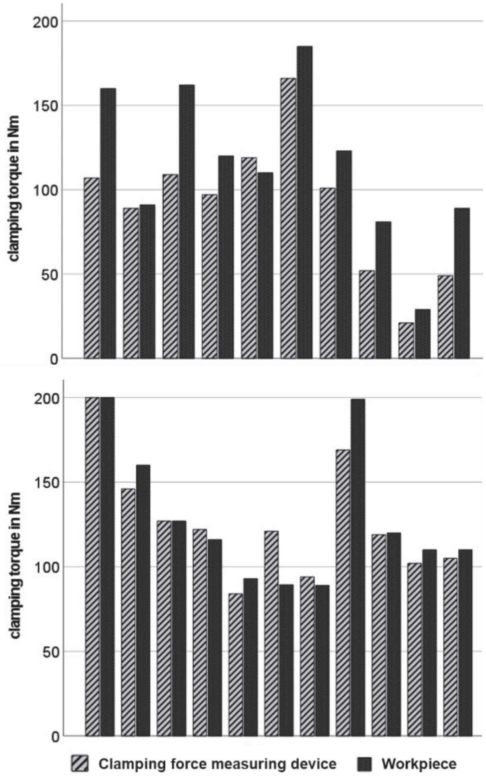

Fig. 6. Comparison of the clamping torque applied from tasks 2 and 3 for group 1 (above) and 2 (below). Due to technical problems, the applied clamping torques could only be recorded for 21 participants

In addition, the participants were asked whether they noticed a difference when clamping the clamping force measuring device compared to clamping the workpiece. In group 1, 2 participants and in group 2, 5 participants stated that they could not detect any difference between the clamping processes. 8 participants in group 1 and 5 participants in group 2 assessed the clamping of the workpiece as easier compared to the clamping force measuring device.

In the interview at the end of the study, participants were asked about their performance. A detailed analysis was carried out to determine how well the participants could assess their own performance in the tasks. Table 2 shows the individual statements of the participants and the difference from the specified clamping force for group 1. In group 2, 8 participants rated their performance as good to very good. 3 participants stated that they felt a little insecure and their performance was rather poor because they performed other tasks in their everyday work. The summarized results for both groups concerning the required time and the differences to normal everyday work are presented in Table 3.

Table 2. Comparison of subjective verbal assessment of own performance and clamping force differences in task 2 for group 1

"How do you rate your performance in the tasks?"	Clamping force difference
• "job done, normal"	-92
• "tasks accomplished"	-98
• "not so good; get acquainted with materials next time"	7
• "6 out of 10 points"	16
• "hope good"	-56
• "hard to say, torque not estimable	-64
• "8 out of 10 points"	-16
• "at least 8 out of 10 points"	-47
• "average"	-44
• "overall good, 7-8 out of 10 points"	-78
• "6-7 out of 10 points; tasks fulfilled, possible mistakes"	-132
• "7-8 out of 10 points"	-87

Question in the interview		Group 1 (n=12)	Group 2 (n=11)
"How do you estimate the time required for the examination in relation to your everyday work?"	• shorter than in everyday work	3 of 12	3 of 11
	• longer than in everyday work	2 of 12	4 of 11
	• identical	3 of 12	3 of 11
"What differences do you see between the tasks in the study and the work tasks in your everyday work?"	• other clamping devices, tools, …	8 of 12	3 of 11
	• other techniques for machining workpieces	1 of 12	5 of 11
"How do you rate your performance in the tasks?"	• good	7 of 12	8 of 11
	• not so good	4 of 12	2 of 11

4. Discussion

The results from task 1 show that the participants tended to neglect checking the initial state of the clamping system. Although the experimenter instructed the participants that the clamping system had previously been used and that the condition of the clamping system was therefore unknown to the participants, the inspection of the clamping system was mostly deficient. Most of the participants noticed the directly visible defects, such as the impermissible clamping jaw position and the chips in the chuck guides. However, only one participant checked the screw used. These results can be interpreted in different ways: On the one hand, one could assume that the participants did not anticipate the intentional installation of errors in the system and therefore assumed that the system was in perfect condition. On the other hand, the participants should put themselves in a typical work situation, which could have led to the participants behaving as they are used to at work, i.e. working with error-free, not sabotaged clamping systems. Another possible interpretation is that the participants felt under pressure from the test situation and thus made mistakes that would not occur in normal everyday work. However, it can be said, on the basis of the results, that a proper check of the clamping system did not take place when the initial situation was unknown. In addition, some of the participants stated that they do not regularly check clamping systems in their everyday work before use because there are special personnel or cycles for this in their company. Nevertheless, in the worst case, this lack of control could lead to a workpiece that is not correctly clamped, which may then become detached from the clamping system and result in an accident.

The results from task two show most participants determine the required clamping force by feel and do not determine it using specifications or calculations. As in previous surveys (Wittstock 2019), it is also evident here that the participants trust in their experience and simply tighten the workpiece sufficiently for their subjective feeling. The fact that in group 1 the clamping force on the measuring device was still low in some cases can be explained by the fact that the measuring device behaves differently than a workpiece when being clamped and the participants therefore also clamped more carefully. After all, 10 people aimed to calculate the required clamping force. However, it is questionable whether they also do this in everyday work or whether they only strive for a calculation based on the test situation in order to do well or to meet the suspected expectations of the experimenter.

The evaluation of the applied clamping force shows that the use of an electronic torque wrench ensures significantly better clamping forces than a conventional chuck key. Although these results are as expected, the values underline the fact that the participants are only partially able to correctly assess the applied clamping force when clamping with the conventional chuck key. The significant deviation of the applied clamping force from the specified clamping force underlines that, by tendency, too little clamping force is used and there is therefore a risk of the workpiece breaking out of the clamping system. Despite years of professional experience, it is therefore necessary to support the application of the clamping force with suitable aids, such as using an electronic torque wrench. The conventional chuck key as a standard tool is only suitable to a limited extent.

Although the results from task 3 show a better clamping performance than in task 2, the general tendency of a too low clamping force remains the same. However group 1 (except for one participant) shows that more clamping torque was applied to the workpiece compared to the clamping force measuring device. This could indicate that the participants tended to apply more clamping force to the workpiece than to the clamping force measuring device. However, it should be noted that clamping the workpiece was the second clamping process in the experiment and the participants were already familiar with the tools. In addition, it can be assumed that the participants are generally more familiar with the clamping of workpieces than with the clamping of clamping force measuring devices, as this occurs less frequently in everyday work.

4.1. Self-assessment of the applied clamping force

In addition to the performance in the individual tasks in the experiment, the assessment of the participants' own performance in the experiment is of particular interest. Statements can be made as to whether the participants are at all able to assess whether they have carried out their tasks correctly without further aids. The evaluation of the final interview for group 1 shows that most participants rate their performance as *good*, although they stretched with significantly too little tension. Only the two participants who achieved the required level of resilience assessed their performance as more average and critical. These results clearly show that most of the participants are not able to correctly assess their performance when tightening with a conventional chuck key, and that tightening "by feel" is therefore unacceptable in terms of machine operator safety. Statements from previous surveys (Wittstock 2019), in which the majority of machine operators say that the clamping force is only applied based on experience and intuition, are therefore extremely questionable from a safety point of view.

4.2. Limitations

Even if the results show strong differences between the two groups and significant deviations from the required clamping force, these results must be considered with some limitations: The study carried out is a laboratory study, which made it possible to control the initial situation for all participants and possible confounding variables, but also involves some observation of the participants. However, this also goes hand in hand with the fact that an attempt was made to depict a real work situation, but this does not guarantee completely natural behaviour of the participants. This is also reflected in the statements of the participants, because these statements indicate that some of them do not carry out certain work steps themselves in everyday life (e.g. determination of the required clamping force) and also work with other clamping systems or machines. Another limitation is that in group 1, some of the participants (4 people) clamp with an electronic torque wrench in their everyday work and are therefore not used to clamping with a conventional chuck key and therefore have no feeling for it.

In addition, a certain prior knowledge of the participants was presumed for the study, e.g. the correct handling of clamping systems, but some of the participants (4 people) stated that they usually work with other clamping systems. Overall, this leads to the need to evaluate the results with caution in relation to the transfer to the real work situation. This is also underpinned by the fact that the participants were told from the start that no real processing would take place. It could therefore be assumed that the participants did not see any compelling need to clamp correctly, as there was no danger of the workpiece being ejected from the work area. This could have reduced the motivation of the participants to apply the right tension. Overall, it can therefore be assumed that only some of the participants behaved as they would in a real work situation, since the motivation with regard to risk minimization and proper processing could have been low.

5. Conclusion

The study presented here examined the differences in clamping with a conventional chuck key and an electronic torque wrench. In addition, it was examined to what extend qualified operators execute specified safety-related control tasks during the installation and preparation of a manual three-jaw chuck. The results presented show that a conventional chuck key in comparison with an electronic torque wrench, is only suitable to a limited extend for applying a defined clamping force. Consequently, the clamping safety, especially when high clamping forces are required, can be significantly increased by using an electronic torque wrench. Furthermore, the results show that the participants are rarely able to set the required clamping force with a conventional chuck key despite many years of professional experience.

Due to the limitations of the study, future studies should continue to investigate this topic: First, the study should be repeated as a field study in order to be able to observe the real behaviour of the participants. However, because the results would be difficult to compare due to different tools, workpieces and machines, a standardized test workpiece and auxiliary equipment should first be classified, which could then be integrated into the normal work situation of the participants.

In this studies various errors were implemented, which differ in the severity of the caused risk when clamping the workpiece, but also in the way they are recognized. Future studies and developments could take up this problem and create a type of error classification (detection - visual, haptic, acoustic, immediately recognizable, only after dismantling) and an error weighting for the process. This could be included in future instructions for machine operators to highlight which errors could have serious consequences and thus need special attention and control.

In addition, a user-friendly calculation tool should be developed and made available to participants in future studies to determine its effectiveness and acceptance. Furthermore, studies show that perceptually engaging assembly instructions offer the highest potential for error reduction and performance improvement (Torres 2021), which is why the type of formulation and presentation of these should also be addressed in the future. The results presented further show that participants did not achieve the required clamping force. Therefore, real machining with insufficient clamping force, using a suitable safety and measurement concept, could be carried out in the future. This will allow to quantify the real consequences of insufficient clamping force. A further starting point for future studies is the comparison with a mechanical torque wrench, since electronic torque wrenches are currently hardly used in the manufacturing sector due to high investment costs. In contrast, a mechanical torque wrench is a standard tool, whereby the accuracy compared to an electronic torque wrench depends significantly on the handling. In summary, this study has identified many starting points for increasing the safety of machine operators. This includes the use of an electronic (or at least a mechanical) torque wrench, but also the need to easily determine or specify the required clamping force. It is also clear form the results that basic preparation and safety-related actions are forgotten or incompletely executed. For this reason, a safety data sheet is currently prepared as an additional instruction support, in which the most safety-relevant steps during manual clamping are illustrated clearly.

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