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The effect of assembly tolerance on performance of a tape application task: A pilot study

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Abstract

Task characteristics such as visual and manual demands influence the postures employed and the muscular load during task execution. According to ergonomic experts at a car assembly plant, these demands are difficult to predict during product and production development and can easily be underestimated. One such task with combined visual and manual demands is the application of deco-tape to the door frame of cars. This precision task requires the exact manual positioning of the tape and a careful visual control in order to continuously adjust alignment and to check for any air bubbles fastened under the tape. This task has to be carried out within limited time determined by the pace of the assembly line, thus requiring both high precision and a certain speed.

The present study aimed at the question: how do different degrees of assembly tolerance affect the execution of a precision assembly task?

Deco-tape fixation was transformed into an experimental task in order to study the effect of different degrees of precision demands.

Ten subjects without previous assembly experience completed 60 experimental trials each. In each trial a tape was affixed in an area indicated on a frame. Thirty trials required high precision with minimal assembly tolerance—that is the tape was affixed in an area that had the same width as the tape. The remaining 30 trials were carried out with lower precision demands—the indicated area provided an assembly tolerance of 3 mm at a tape width of 19 mm.

Task completion time, the movement path of the right hand and head, and the occurrence of quality deficiencies were registered.

The study showed strong effects of the change in assembly tolerance on the speed, postural behaviour and movement paths during task execution:

Tasks with high precision demands required significantly longer completion times. Higher precision demands lead to a working posture with less variation in the distance between the right hand and head. During tasks with high precision, the movement path of the right hand was less economic—with smaller movement cycles of shorter duration—allowing for a more frequent control of results. It was concluded that precision demands play an important role for the speed, working posture and movement path during an assembly task. Considering these effects and their potential implication for the muscular load during task execution, it seems important to consider task characteristics such as precision

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demands in detail when designing products for assembly. A careful consideration of these task characteristics is essential when using simulation tools such as mannequins in extended phases of future product development processes.

Relevance to industry

Current ergonomic guidelines often focus on the physical layout of a workplace, while task characteristics such as visual and manual demands are considered to a lesser extent. However, these task characteristics may play an important role for assembly workers' postural behaviour and the muscular load during work. Increasing use of simulation tools instead of physical prototypes in the product and production development process makes it even more difficult to evaluate task characteristics such as precision demands. On this background, more knowledge about the effect of task characteristics on working posture and assembly paths is needed. The present pilot study provides a detailed analysis of the effect of different precision demands on the work posture and execution of an assembly task—deco-tape fixation.

Keywords: Ergonomics; Precision task; Work posture; Manual assembly; Movement path; Visual demand

1. Introduction

In recent years the character of manual assembly tasks in industry has changed towards increased demands of skill and flexibility (Heuer, 1999). According to Kroemer and Grandjean (1997) skilled jobs typically call for precise and quick movements, visual control, and concentration.

Li and Haslegrave (1999) point out, that most ergonomic guidelines focus on the physical arrangement of the workplace and neglect task characteristics such as precision demands. Predetermined time standards currently used in production planning foresee that task characteristics, e.g. assembly tolerances affect the duration of a task (e.g. the MTM tool differentiates between different types of reach movements depending on the precision required—Kanawaty, 1992). However, further effects of task characteristics are rarely considered although research findings indicate their relevance: Li and Haslegrave (1999) show that high visual and manual demands of tasks can cause poor work postures. Laville (1985) showed that high-speed precision work can lead to postural immobility during work. In addition, electromyography (EMG) studies revealed that even light manual precision work can increase shoulder muscle activity (Sporrong et al., 1998). Furthermore, field studies have shown an association between EMG variables that indicate sustained activity in low-threshold trapezius motor units and pain in the shoulder and neck (Veiersted and Westgaard, 1993). Thus, care should be taken when deciding on the precision demands in manual assembly work.

Current trends in product and production development are to replace the construction of early physical prototypes with computer models (Bullinger et al., 2000) in order to reduce time and cost. This implies that human-related factors such as the feasibility and cycle time of an assembly task also have to be evaluated on the basis of these computer models, if human factors are to be considered at early stages of the development. Today's tools for simulation of the human operator—so called "computer mannequins"—focus on verifying that manual assembly is possible. The computer mannequins are employed to visualize postures and movements of a human operator in the workspace—they are used to demonstrate the feasibility of a task given ideal components (Chaffin, 2001). Chryssolouris et al. (2000) point out that "intuitive natural motions of the operator" and the "randomness of the fitting paths" are not commonly considered in computerized mannequins. Furthermore, detailed analysis of precise hand movements and visual demands are not currently provided by the computer models. Given these simulations, especially persons without previous production experience may underestimate the skill needed for task performance (Dukic et al., 2002).

Thus, more explicit knowledge about the effect of task characteristics such as visual and precision demands on working posture and movement paths is of interest.

The aim of the present pilot study was to observe an assembly task—fixation of deco-tape on a car—with focus on the question: How do different degrees of assembly tolerance affect the performance of the precision task?

Relevant performance measures in a precision task such as deco-tape application include: completion time, frequency of quality deficiencies, working posture, location of hands and the movement paths on which the hands move during assembly.

1.1. The assembly task studied—deco-tape fixation

Fixation of deco-tape is a precision task that implies high visual demands and requires exact movements (see Fig. 1 for an illustration of this task). In this task an adhesive tape of about half a meter in length is fastened on a curved surface around a car window. Currently, the task is performed on an assembly line with work rotation between tape fixation on left/right side, in-/outside, and front/back door of the cars.

Fig. 1. Working posture during fixation of deco-tape in car assembly.

The task is usually initiated in the following way: one end of the tape is fastened with high precision on the upper end of the taping area. In numerous subsequent movement cycles, the remaining sections of the tape are aligned with one, usually the right hand and then pressed onto the surface with the other hand. The protective cover of the adhesive surface is removed to a large extent before the initial positioning of the tape.

Assembly workers perform the task sitting on a rolling stool without a backrest in various working postures. The task begins with the hands at approximately head level and continues as the taping hand and the smoothing hand move down to approximately elbow height. At the start of the taping task, the worker's head and eyes follow the taping hand as it moves to the initial application point. The trunk is bent forward and the head is nearly level, but the eyes, or in some—especially shorter—workers the eyes and head, are rotated upward.

As subsequent sections of the tape are applied, the arm is abducted. At elbow height, the tape placement location curves from approximately vertical to horizontal. This change in direction of the taping task causes the worker to abduct their upper arm to position the taping hand at the proper angle to apply the deco-tape. Head, eye, and arm postures are all extreme at times during the task.

A major difficulty with this task is that no tolerance is incorporated in the car design—even small deviations from the perfect alignment are marked as quality deficiencies. This precision task can currently be conducted by workers after a training period of about 1.5 months and there is no indication of this assembly work leading to increased physical workload or risk of physical symptoms. However, a considerable number of workers have difficulty developing sufficient skill in this precision task and move to other line divisions.

According to ergonomic experts at the car assembly plant, the difficulty of this kind of precision task is likely to be underestimated in production planning. For workers, the underestimation of task difficulty can imply high risk of failure and stress due to the following factors: lack of training, tight time schedules, and extreme demands of precision. Previous research has shown that aspects like speed and precision demands can cause increased muscle tension (Laursen et al., 1998). Thus, task characteristics of this kind should be considered carefully in production planning.

There is a large amount of research that investigates how precision demands affect elementary movements. Fitts' Law (Fitts, 1954) states that the movement time (MT) in elementary pointing tasks, e.g. moving a stylus from a start to an aim position, is related to the movement distance (D) and the width of the target (W) in the following way:

$$\mathrm{MT} = a + b \log_2 2D/W,$$

where a and b are empirically determined constants.

This law has shown to characterise a wide spectrum of aimed precision movements (Keele, 1981) and has been applied in different contexts (e.g. Baird et al., 2002).

In the tape fixation task, the initial positioning of the tape and perhaps even subsequent alignments of the tape imply elementary tasks similar to Fitts' aimed precision movements. Thus, it was assumed that higher precision requirements in the form of tighter tolerances for tape positioning would lead to slower task completion. In addition, it was assumed that higher precision demands would lead to increased control activities during movement (for a detailed description of the effects of precision requirements on movement control see e.g. Welford, 1968; Keele, 1981).

According to observations reported by Li and Haslegrave (1999) it was further assumed that higher precision requirements lead to changed work postures and postural immobilisation (Laville, 1985).

2. Method and materials

2.1. Experimental task

For experimental observation the assembly task was transformed into the following laboratory task: The subject was seated on a chair without a backrest (58 cm height). A tape (19 mm wide, 2 mm thick, 500 mm long) was to be fastened on an L-shaped metal frame (length of vertical portion 35 cm, 90° corner, length of horizontal portion 16.5 cm) installed on a table in front of the subject tilting 25° towards the subject. At the beginning of each task the subject rested in a start position with both hands on a clock (49 cm from the upper end of the frame), the right hand holding the tape. The test supervisor counted to three at which point the subject started the clock with the left hand and then fastened the tape in a target area outlined on the frame. The subject was instructed to fasten the tape such that it was inside the outlined area, with the area's borderlines remaining visible throughout. Afterwards, the participant resumed the initial posture and stopped the clock. This procedure provided a definition of the starting and stopping hand position and a readily available measure of the total completion time. Subjects were instructed to work as fast as possible at the given precision level (see the precision factor described in section "Experimental design" below). (Fig. 2 shows the task set up and working posture).

2.2. Subjects

The complete data of 10 subjects (three male, seven female) were included in the following data analysis. All subjects were right-handed and had normal or corrected to normal vision. Subjects had no previous experience in manual assembly work.

2.3. Apparatus

Movement paths of the right hand and head were recorded using Qualysis Pro reflex—an infrared-based motion capture system. Three cameras with a sampling frequency of 120 Hz were

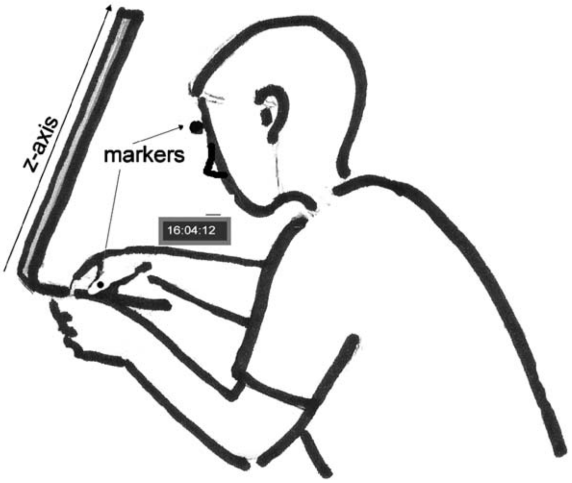

Fig. 2. Set up of experimental task. The arrow along the frame indicates the direction of the *z*-axis which had its origin in the corner of the frame. Markers on the right hand and head of the subject are indicated. The subject-operated clock—serving as start- and stop-position of the task is indicated (only rough position indicated).

used to detect the reflective markers that were fastened on the right hand (12 mm diameter) and forehead (40 mm diameter) of the subject. Markers were attached to the subjects' skin using double sided tape. Spatial acuity of measurements with the 12 mm markers was ±0.3 mm; for the 40 mm diameter marker the acuity is ±0.1 mm.

Cameras were connected to a Pentium III Crest computer with 128 MB RAM, 700 MHz.

2.4. Procedure of the experiment

The subject was informed about the purpose and background of the experiment. Afterwards, markers were fastened to the forehead and hand. The task was explained to the subject in the course of two pretrials. Then two blocks of 30 tasks each followed, where one block consisted of tasks with high precision and one of tasks with low precision. Repetitions of the same task were included in order to allow for the development of a stable and sufficiently skilled movement. The block sequence was altered between subjects. After every 15th trial subjects were given a short break.

2.5. Experimental design

Each subject carried out two blocks with 30 trials each in which the tape (width 19 mm) had to be fastened at one of the following levels of precision:

- High precision: Target area of 19 mm width indicated by lines with 0.6 mm breadth.
- Low precision: Target area of 22 mm width indicated by lines with 0.6 mm breadth.

Thus, the experimental factor precision was varied as a within subject factor with two levels, either low (large tolerance limits) or high (small tolerance limits) with a difference of 3 mm (ca. 13% of the larger target area) between the two.

The following dependent variables were recorded: total task completion time, number of quality deficiencies, and movement path.

- The *total task completion time* was recorded by the subject-operated clock (resolution: 1 s).
- *Quality deficiencies* were judged by visual inspection carried out by the experimenter. Deficiencies fell into two categories: If the tape was on or over the boundary lines defined for the precision level this was registered as a quality deficiency—*out of tolerance*. The second category of quality deficiencies included tape fixation where air *bubbles* were trapped under the tape or edges were loose. After each trial it was assessed whether a quality deficiency according to these criteria had occurred.
- The *movement paths* of the right hand and the head were registered throughout task execution. For motion capture, a marker (12 mm diameter) was attached on the right thumb—halfway between the interphalangeal joint and the nail-bed. For registration of the head position a second marker (40 mm diameter) was fastened to the forehead at 2 cm above the nasion approximately at the glabella.

In order to compare the movement paths in both levels of precision, the following phases were identified for each movement included in the data analyses:

- Phase 1: Initial positioning of the tape in a ballistic movement from the start position (on the clock) to the upper corner of the frame.
- Phase 2: Exact positioning of the tape with small adjustments of the tape on the upper corner of the frame.
- Phase 3: Fastening the tape along the vertical part of the frame—characteristically done by fastening the tape in a number of movement cycles (a movement cycle being defined as an acceleration of the hand downwards along the frame, followed by a distinct deceleration of the hand movement).

The remaining movement path (tape fixation in the curve and on the horizontal part of the frame) was not analysed.

For each of these three movement phases the duration was determined. For phase 3, the number of movement cycles was counted and the range of distances between the head and hand marker was calculated as an indicator for the degree to which movements of the hands were followed by movements of the head. Smaller ranges indicated that subjects kept a constant distance between head and hand to allow for optimal visual control during tasks with high visual demands.

Calculation of these parameters was carried out using a C-program—criteria for the identification of phases and parameters are given in Table 1.

Table 1
Definition of movement phases

	Definition
Phase 1	
Start	Distance of the right hand marker upwards in z-direction from the start position is larger than 5 mm
End	Movement of the right hand marker upwards in z-direction is less than 5 mm/s
Phase 2	
Start	End of phase 1
End	Movement of the right hand marker downwards in z-direction is faster than 5 mm/s
Phase 3	
Start	End of phase 2
End	Distance of the right hand marker from the position of the frame corner is less than 17 mm in z-direction
Movement cycle	Period of at least 30 ms without movement in z-direction followed by a movement of the right hand marker with a velocity of more than 5 mm/s downwards in z-direction

2.6. Data analysis

The dependent variable total task completion time was analysed using a repeated measurement ANOVA with blocking on subjects (2 levels of precision × 30 repetitions × 10 subjects).

Quality deficiencies were analysed as follows. For each subject, the number of trials in which each type of quality deficiency (bubbles respectively out of tolerance) occurred, were counted separately for both levels of precision (all 60 trials were included in this analysis). These counts were then analysed in *t*-tests for repeated measurements.

Data from the motion capture system were used to study the effect of precision demands on motor processes in more detail. As the detailed analysis of data registered with the motion capture system is highly time intensive (markers have to be identified manually in the registered data etc.), only half of the trials (every second trial) were analysed for each subject. A separate repeated measurement ANOVA with blocking on subjects (2 levels of precision × 15 repetitions × 10 subjects) was carried out for the following parameters: time for phase 1, time for phase 2, time for phase 3, number of movement cycles in phase 3, range of head-hand distances in phase 3, and maximal head-hand distance in phase 3.

3. Results

The following result presentation concentrates on the factor precision (see means presented in Table 2) as this experimental factor was focussed in the present pilot study. Tables 3 and 4 provide the statistical analysis results for both experimental factors (precision and trial) as well as

Table 2
Mean values of completion time, quality deficiencies, and movement path parameters by precision

	Completion time (in s)	Quality deficiencies		Movement path					
		Percentage trials with tape out of area	Percentage of trials with bubbles	Duration of phase 1 (in ms)	Duration of phase 2 (in ms)	Duration of phase 3 (in ms)	Number of movement cycles in phase 3	Range of hand/head distance in phase 3 (in mm)	Maximal hand/head distance in phase 3 (in mm)
Low precision	14	27%	43%	802	2395	5520	4.79	178	431
High precision	27	41%	44%	887	3258	11730	6.73	142	376

Significant differences between both levels of precision are shaded in gray.

Table 3
Repeated measurement ANOVA results of task completion time

	df	F	p
Precision	1, 9	109.59	0.000*
Trial	29, 261	3.14	0.000*
Precision* Trial	29, 261	1.57	0.036*

their interaction. The separate analysis of the dependent variables—total task completion time, number of quality deficiencies and movement paths revealed the following results.

Total task completion time: Total task completion time was based on the time between the subject starting the clock and stopping the clock after task completion (time in seconds recorded by the subject-operated clock). The reduction of the target area's width by 3 mm resulted in a doubling of mean task completion time (see Table 2). Repeated measurements ANOVA showed that precision had a significant influence on the total task completion time (see Table 3). Fig. 3 shows how task completion time depends on the level of precision and the number of trial repetitions.

Quality of task performance: Fig. 4 illustrates the percentage of quality deficiencies observed at both levels of precision. In the diagram, the two types of quality deficiencies (*out of tolerance* and *bubbles*) are shown separately. The number of trials with bubbles did not differ significantly between high vs. low precision ($t(\mathrm{df} = 9) = -0.237$, $p = 0.818$). However, the number of trials with tape outside the borderline differed significantly between blocks ($t(\mathrm{df} = 9) = -2.476$, $p = 0.035$). As Table 2 and Fig. 4 show, a higher percentage of trials with tape outside the border were observed in the block with high precision than in the block with low precision.

Pattern of movement: Fig. 5 presents the typical hand and head movement patterns observed during fixation of the tape—the upper diagram shows a typical example for movements in a task with high level of precision and the lower diagram depicts a pattern at low level of precision. Analysis of the movements focused on movements along the z-axis; the z-axis being defined as co-linear with the vertical part of the frame and with an origin corresponding to the inner corner of the frame (see Fig. 2).

Data analysis of the parameters for the three movement phases revealed the following results:

Initial positioning of the tape (*phase* 1): The duration of phase 1 was not affected by the level of precision ($F(\mathrm{df} : 1, 9) = 2.43$, $p = 0.153$). Thus, no significant influence of the precision level was observed for this phase of the movement.

Exact positioning of the upper end of the tape (*phase* 2): There was a significant effect of precision on the time needed for the exact positioning of the upper end of the tape ($F(\mathrm{df} : 1, 9) = 20.17$, $p = 0.002$). The mean duration of this phase was longer in trials with high precision than in trials with low precision (see mean values in Table 2).

Table 4
Repeated measurement ANOVA results of movement path parameters

		Duration of phase 1		Duration of phase 2		Duration of phase 3		Number of movement cycles in phase 3		Range of hand/head distance in phase 3		Maximal hand/head distance in phase 3	
	df	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Precision	1, 9	2.43	0.153	20.17	0.002*	80.21	0.000*	32.37	0.000*	9.57	0.012*	16.85	0.003*
Trial	14, 126	2.29	0.008*	2.23	0.009*	1.77	0.050*	1.54	0.107	1.14	0.331	1.49	0.121
Precision* Trial	14, 126	0.56	0.888	0.80	0.660	1.00	0.454	1.48	0.129	0.51	0.927	1.49	0.124

Significant differences are shaded in gray.

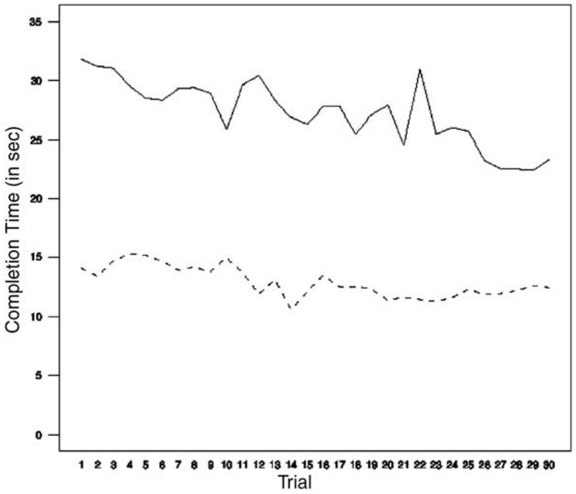

Fig. 3. Task completion time by precision and trial: … completion time in trials 1–30 with low precision, — completion time in trials 1–30 with high precision.

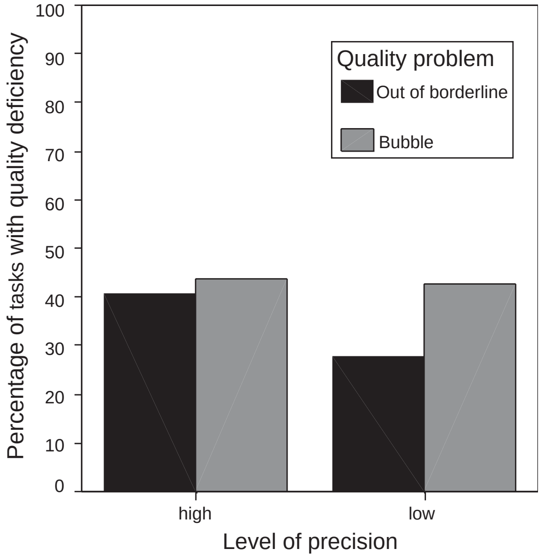

Fig. 4. Percentage of trials with quality deficiencies in tasks with high and low precision.

Stepwise alignment and fixation of the tape (*phase* 3): The time needed for the stepwise alignment and fixation of the tape was significantly affected by the level of precision ($F(\mathrm{df}:1,9) = 80.21$, $p = 0.000$). As the mean values in Table 2 show, the duration of this phase was longer for trials with high precision than for trials with low precision.

In addition, the number of movement cycles in phase 3 was significantly higher in tasks with high precision than in those with low precision ($F(\mathrm{df}:1,9) = 32.37$, $p = 0.000$).

Concerning the co-ordination of head and hand movements, it was observed that subjects kept a closer and less variable distance between head and hand in trials with high precision than in trials with low precision. The maximal distance between head and hand differed significantly with precision ($F(\mathrm{df}:1,9) = 16.85$, $p = 0.003$)—maximal distances were larger in trials with low precision (see Table 2). Furthermore, there was an effect of precision on the range of distances between head and hand during this phase ($F(\mathrm{df}:1,9) = 9.57$, $p = 0.013$) with larger ranges in trials with low precision than in trials with high precision (see Table 2).

Individual differences and learning effects: In all above named parameters a considerable

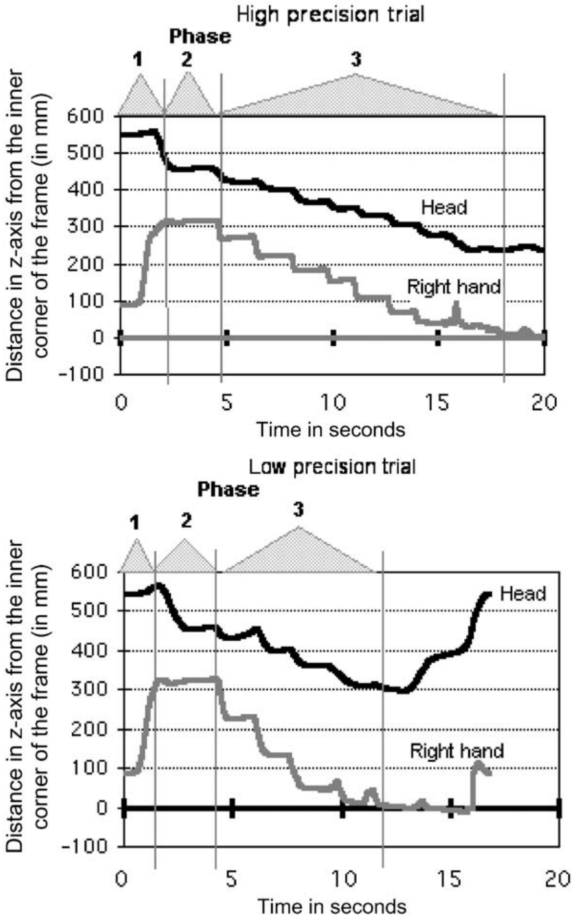

Fig. 5. Typical hand and head movement patterns during tape fixation with high/low precision demands.

inter-individual variation of movement times, movement pattern and quality of results was observed. As was to be expected, there were significant learning effects on the total completion time as well as the duration of the three separate movement phases (see effects of trial presented in Tables 3 and 4).

4. Discussion

Starting from previous research on precision demands and the experiences with specific assembly tasks reported by ergonomic experts at a car assembly plant, the present pilot study was conducted to give more detailed information about the role of precision demands on the working posture and movement pattern during task execution. A specific precision task—the fixation of adhesive deco-tape on car doors—was studied with focus on the following question:

How do different degrees of assembly tolerance affect the performance of the precision task?

It was observed that moderate increases in assembly tolerance lead to a clear reduction of task difficulty as indicated by significantly decreased total completion times.

The faster completion of tasks with lower precision demands was not achieved by a general disregard for the quality of results—the frequency of quality deficiencies due to incomplete tape fixation (bubbles) did not differ in both experimental conditions.

Although task completion times for trials with high precision were almost double the time of those with lower precision, there was a significantly higher percentage of trials in which the tape was outside the target area. Thus, it can be concluded that a more perfect completion of the tasks in the high precision demand condition would have required even longer completion times.

A detailed comparison of the movement patterns of the right hand and head during tasks revealed clear effects of precision demands on postural behaviour and movements:

Tasks with higher precision demands were executed in working postures with a smaller maximal distance between right hand and head and with less variation of this distance.

This observation is consistent with previous research findings that visual and manual task characteristics influence the working posture (Li and Haslegrave, 1999) and confirms the relevance of this research in the context of an actual assembly task. The observed behaviour may result in unfavourable and static working postures during these types of tasks corresponding to the postural immobilisation described by Laville (1985).

The present pilot study provided insight into the effect of precision demands on the movement path during task execution. Tasks with high precision demands were carried out in more and shorter movement cycles—indicating that task execution had to be controlled more frequently. This agreed with Keele's (1981) statement concerning single-movement control: "Movement time increases with distance and precision partly because the accuracy of translating visual perception of the distance to be covered into actual movement is limited. When the need for precision exceeds the inherent accuracy of this translation, then corrections based on visual feedback must be made as the target is neared, and those corrections take time." According to Schmidt (1991) the observed movements in more and shorter cycles during high precision tasks can be characterised as less "economic" than the larger movement cycles employed during tasks with low precision demands.

It ought to be stressed that the reported effects of precision demands could be shown with rather moderate changes of assembly tolerances between tasks with high and low precision demands. Furthermore, significant effects resulted with the small sample size of 10 subjects—further indicating a strong effect of the experimental factor.

The fact that assembly tolerances affect the difficulty of a task and its duration is considered in predetermined time standards currently used in production planning. In the literature on "Design for Manufacturability" the verification of visibility and visual feedback are seen as important criteria. Helander and Furtado (1992) state "Visibility and visual feedback play a vital role in assembly. Visual feedback occurs simultaneously with motions such as 'reach', 'move', 'position', and so forth. (In MTM it is not included in the analysis). All features should be fully visible and provide visual feedback. Hidden features complicate assembly." (p. 183). Present results that even minor changes in the tolerances to be observed during assembly lead to considerable effects on working posture and movement pattern confirm that visual and manual demands ought to be considered carefully when designing for assembly. This is highly relevant also when considering previous research reporting higher muscle load in precision tasks (Sporrong, 1998).

The major implication of these results is that it seems important to consider not only physical workplace layout but even detailed task characteristics in ergonomic evaluations. Further knowledge about the effect of task characteristics ought to be gathered in order to get a reliable basis for the formulation of detailed ergonomic guidelines concerning these task factors. Such guidelines appear to be even more relevant in the context of the changing product development process—the use of simulation techniques for ergonomic evaluation may otherwise lead to an increased risk of neglecting task factors in the course of product development.

One central aspect of line assembly is the time limit for task completion. This aspect was disregarded in the present study where subjects—apart from the instruction to work as fast as possible—were free to choose the speed they assumed to be appropriate. Previous research has shown that time pressure affects execution of hand movements (see Laville, 1985). Thus, it would be interesting to study the effect of time limitations on the above task completion in the future. Another open question is what effect extensive training—as is common in manual assembly tasks—has on the execution of precision tasks. Previous research in the field of skill acquisition indicates for example that extensive training may change the use of visual and other sensory information and the capability to detect errors (Schmidt, 1987).

Our recommendation from this pilot study is that further research be performed to examine the effects that task complexity and tolerances have on posture and muscular load. These task demands must be integrated into ergonomic evaluations and should be considered when using simulation techniques.

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